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Survey and Bibliography on Attainment of Laminar Flow Control in Air Using Pressure Gradient and Suction

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PREFACE

This survey and bibliography on attainment of laminar flow in air through the use of favorable pressure gradient and suction consists of two volumes. Volume I contains the survey, summaries of data for both ground and flight experiments, and abstracts of referenced reports. Volume II (NASA TM-80108) comprises a bibliography and abstracts of the restricted and classified laminar flow control (LFC) literature. The first author conducted the survey and compiled summaries of data, and the second author compiled the bibliography. A selected bibliography of laminar flow control reports available to NASA personnel only can be secured upon request from the Scientific and Technical Information Facility by asking for BIB-79-01. An index of authors is found at the end of this volume.

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I. INTRODUCTION

A long-standing research emphasis upon reducing aircraft drag (e.g., ref. 1) received added impetus from the current and projected energy crisis (e.g., refs. 2 and 3). Laminar flow technology offers the possibility of providing a significant increase in aircraft fuel efficiency (25 to 40 percent depending upon the degree of application) for long-range conventional take-off and landing (CTOL) aircraft. The present NASA efforts in the area of natural and forced laminar flow (Energy Efficient Transport (EET) and Laminar Flow Control (LFC) portions of Aircraft Energy Efficiency Program (ACEE), respectively (ref. 3)) address certain critical unknowns (suction LFC for supercritical wings, natural laminar flow possibilities using latest numerical design tools, maintainability, reliability, impact of new materials and fabrication techniques, system optimization, etc.), but for maximum return from technical research investment, the new programs must be carried out with full recognition of the extensive previous efforts, both ground and flight. Since the present renewed laminar flow emphasis comes after a nearly 10-year hiatus in the field, and the previous laminar research encompassed considerable depth, breadth, time, and expense, it was believed that a brief survey and bibliography of laminar flow works might be of some use. In particular, the first author sought to unearth flight or low disturbance tunnel data suitable for "calibration" of advanced stability theories (relating theory to actual transition location, e.g., ref. 4).

Laminar flow control for CTOL wing application has been the subject of many review articles, probably because of its tremendous promise and practical difficulties. Section III of the present survey is an attempt to summarize the more cogent results and recommendations of these various reviews, and to provide a perspective on the results from 40 years of laminar flow control technology.

Section IV is a summary of much of the available low stream disturbance data suitable for calibration of advanced stability theories (relating stability theory to transition location using a disturbance amplitude or a similar criterion). Most of the data selected were taken in flight. However, propeller noise, surface vibration, roughness, etc., may still be present. The Ames 12-Foot Pressure Wind Tunnel was, according to reference 5, the lowest disturbance facility available which was suitable for three-dimensional wing LFC research; therefore, swept wing data from that facility are also included. Taken as a whole, the data subsume variations in (1) speed, (2) sweep, (3) laminarization technique (pressure gradient; suction-porous, slotted, or perforated; curvature, etc.), (4) geometry (wing, axisymmetric body), (5) surface waviness or finish, and (6) propeller slipstream (with or without). Some of these data were used in the original A. M. O. Smith and Gamberoni work on the e^9 method (ref. 6), but the analysis utilized simple parallel linear stability theory and similar boundary-layer profiles. A later version of the work (ref. 7) utilized mainly tunnel data; i.e., much of the flight data included originally in the analysis of reference 6 was evidently not included in reference 8. There exists a clear need for an updated study of the relationship between stability theory and transition using the latest tools (nonparallel stability theory, nonsimilar boundary-layer calculations) and data with the lowest background disturbance levels possible. The identification and collection of such data was one of the principal motivations for beginning the present bibliography. Once the stability theory is calibrated, the method can be used to optimize pressure gradient and suction amount and distribution for LFC.

Section V includes information, much of it quite early, which may be of some immediate use as background material for LFC applications. Topics include roughness, suction surface configuration, nonmetallic materials for surface smoothness, the insect contamination problem, alternate structural and suction concepts, experimental methodologies, noise effects, high lift, and environmental effects.

Section VI is a summary of much of the ground experimental information. Due to the extreme sensitivity of LFC to stream disturbances (flow quality), this information is often of limited usefulness, as problems can appear in ground testing which are either nonexistent or much less severe in flight. However, some of the ground experiments are documented fairly completely (including stream disturbance level, spectra, wall waviness, etc.) and therefore could be used in conjunction with stability theory to develop an analytical tool for estimating stream and surface disturbance effects upon LFC performance. Also, because detailed data are more easily obtainable in ground facilities (where redundant measurements and accuracy checks are possible), these ground test data contain a wealth of interesting phenomonology and flow physics, as well as practical experience in making the LFC system work for what is essentially a hostile environment.

Section VII contains some of the theoretical work necessary for design, analysis, and optimization of LFC systems. Recent developments, particularly in application of numerical procedures and computer technology, have supplanted much of the early analytical research, notably the integral boundary-layer procedures. Therefore, this theoretical section is not historically complete, particularly with respect to the earlier analytical techniques.

The two areas of natural laminar flow (pressure gradient) and suction laminar flow control are treated in this survey as essentially one subject, based upon the following reasoning: (1) favorable pressure gradient is as much a control device as suction (i.e., the flow over a laminar flow wing is no more naturally laminar than on a suction wing), (2) the critical issue for application is the same in both approaches, influence of surface waviness and roughness and the associated maintainability problems (although the pressure gradient control case is somewhat more sensitive than distributed suction), and (3) in many applications, the two approaches can perhaps be combined into an optimized system. Cooling could also be used as a laminar flow control technique, but is not included as such in this survey and bibliography.

The reference numbers used in the text of this report are the same as the bibliography entry numbers. Information regarding the availability of the bibliographic citations is found on pages 58 and 59.

II. SYMBOLS

A	disturbance amplitude
a/λ	ratio of amplitude to wavelength
C_f	skin-friction coefficient
C_L	lift coefficient
C_p	surface pressure coefficient
c	chord
c_d	section drag coefficient
dP/dx	pressure gradient
l	wetted surface length
M	Mach number
n	logarithm of the disturbance amplitude ratio
R	Reynolds number
R_L	Reynolds number based on wetted surface length
S	slot width
t/c	thickness-to-chord ratio
U	velocity
u	rms velocity fluctuation
V_w	wall suction velocity
$\bar{v}$	maximum cross-flow velocity
x	transition location
α	angle of attack
α'	wave number
δ	boundary-layer thickness
δ^*	displacement thickness
Λ	sweep angle
ν	dynamic viscosity

Subscripts:

c	chord
crit.	critical
e	local external to boundary layer
l	local
min	minimum
x	length to transition
δ	boundary-layer thickness
0	conditions at neutral curve
∞	free stream

III. OVERVIEW

Historical Perspective

Table I(a) summarizes the major countries, organizations, and researchers involved in LFC research. As indicated, the pressure gradient control work began in the United Kingdom, Germany, and the United States during the 1930's, with some actual applications attempted during World War II. This research peaked during the 1940's with the NACA 6-series wings and refinements of the Griffith wing, but was essentially stopped as a main-line activity due to the jet engine, which allowed flight speeds in the transonic/supersonic range. To obtain reasonable performance (low compressibility drag) in the high subsonic speed range with 1950's airfoils the local Mach numbers were kept low, which meant fairly thin wings and appreciable wing sweep. The essence of the natural laminar flow wing is a section which produces long runs of favorable pressure gradient, which damps disturbance growth in two-dimensional (unswept) boundary layers (figs. 1 and 2).[1] With the introduction of sweep, a new class of boundary-layer instabilities occurred; this was the "cross-flow" problem, which was actually aggravated (rather than helped) by a favorable pressure gradient. So the natural laminar flow wing, with its major problems of roughness and waviness (R & W), insect contamination, maintenance, micro surface damage, etc., still unresolved, was essentially set aside in favor of suction. Suction is a much more complicated scheme, but it is necessary for control of cross flow. Research on several of the original problems did continue, notably the NACA work on surface roughness criteria.

Laminar flow suction research began only a short while after the natural laminar flow work, but the effort during the 1940's was at a comparatively low

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[1] Figure 1 is from reference 9.

level. However, once the difficulties with the pressure gradient control airfoils became apparent, considerable research was concentrated on the suction approach, which could be used on swept wings. (See fig. 3 for detail of typical suction model.) The suction research (table I(b)) systematically identified and solved various problems associated with, for example, facility disturbances, suction surface configuration, and sweep (including spanwise contamination). The suction work culminated in the middle 1960's with two flight experiments on swept wings, one British (at Cranfield) and one American (the X-21). Basic technical feasibility of LFC was certainly shown, even to quite high Reynolds numbers (e.g., figs. 4 and 5).

The next logical step was optimization of the system and obtaining the all important practical data on maintainability and reliability. However, lack of a DOD mission, relatively low cost of fuel and the exigencies of the Southeast Asian conflict essentially stopped the American work, and the general debilitation of the English economy did the same to the U.K. effort. Therefore, there was a hiatus in LFC work for nearly 10 years except for basic, primarily theoretical efforts, much of which was Russian work.

The energy crisis, along with advances in allied technologies (fabrication techniques, materials, airfoil design), resurrected suction LFC. Along with the problems of maintainability, reliability, damage protection, insect impingement, etc., left over from the incomplete 1960's research, the application of suction LFC in the 1970's has a whole new area of research needs which are connected with application to supercritical wings. Particular problem areas include effects of concave curvature and possible downstream contamination from suction-induced disturbances produced in local flow regions of Mach number greater than one. As can be seen from table I(b), many groups have participated in the development of LFC, and many lessons have been learned. The present survey and bibliography is meant to focus attention on this previous work and make it more easily accessible to LFC researchers and practitioners.

Reviews and Evaluative Summaries

As stated in the Introduction, LFC has provided subject matter for multitudinous reviews. These reviews are surveyed and discussed herein as a source of consensus and as a convenient method of providing the reader with a broad entry into the LFC literature.

Transition.- Laminar flow control, whether attained through pressure gradient or suction (or a combination thereof), is essentially a delicate stability and transition problem. Therefore, the LFC practitioner should have some familiarity with the boundary-layer transition field in general, and in particular with the basic effects of pressure gradient, suction, curvature, three-dimensional (cross flow) and stream or surface disturbances. References 7 and 10 to 22 comprise a reasonably complete cross section of review papers in the transition area. A comprehensive manuscript on transition is currently under preparation by M. V. Morkovin.

Experimental research at the National Bureau of Standards during the 1940's (using a low-stream disturbance facility) confirmed the validity of conventional linear stability theory for the early stages of the transition process at flat-plate conditions (ref. 7). From this work and other comparisons with data (e.g., ref. 11), the conclusion is that stability theory can be used to predict the influence (trends) of various boundary condition modifications upon boundary-layer transition. For the two-dimensional case, suction, favorable pressure gradient, compressibility, and wall cooling (in air) all provide stabilization and thus longer runs of laminar flow. Injection, adverse pressure gradient, heating (in air), roughness, concave curvature, and free-stream disturbances (ref. 11) are destabilizing (fig. 6).

Detailed measurements at the National Bureau of Standards (ref. 12) indicate that the transition process consists of a series of stages starting with laminar flow. Linear amplification of small disturbances occurs next (above a lower critical Reynolds number), followed by nonlinear development and three-dimensionalization of the linear waves, and finally break down into turbulent bursts or spots. The commencement of spot formation is the usual definition of "transition." The linear amplification region generally has a much larger longitudinal extent than the nonlinear portion. For laminar flow control applications one generally strives for a situation where some amplification occurs, but not enough for the flow to be nonlinear and hence overly sensitive (subject to catastrophic behavior). Therefore, stability theory has considerable application to the LFC problem. Sufficient control (by suction, pressure gradient, etc.) to completely damp all disturbances (operation at or below the lower critical Reynolds number or neutral curve) leads to unnecessarily large performance penalties, although some early systems studies were predicated upon such an assumption (maintaining the flow below the lower critical Reynolds number).

Reference 6 constitutes some of the classic work relating transition to stability theory. This is the famous e^n method, which utilizes the natural log of the integrated disturbance amplitude ratio A/A_o, where A_o is the value on the lower branch of the neutral curve and A is the local amplitude at transition from linear theory. Comparison with experiment indicates that a value of around 9 for this natural logarithm correlates stability theory with a great deal of data, including effects of pressure gradient, wall temperature, and concave curvature. However, many of these correlations of stability theory with experiment were performed using early forms of both the stability and boundary-layer theories, and hence should be rechecked.

An overall feel for the transition process and sensitivities can be obtained from Morkovin's reviews (refs. 13 and 18). Although the emphasis in reference 18 is on the compressible case, both summaries include valuable insights into the physical processes. Of particular importance is the Morkovin principle of "dominant and multiple responsibility" for transition. The essential idea is that transition is a function of such a multitude of variables that once the dominant variable is suppressed (i.e., generally stream disturbances in the wind tunnel, noise, or roughness in flight), a new variable becomes dominant and must, in turn, be suppressed. The LFC practitioner should be prepared for surprises.

The survey of reference 14 provides a very useful summary of roughness sensitivities as of 1959. More recent references for roughness problems will be given in a later portion of this survey. Cross-flow effects (a significant instability mechanism in swept-wing flows) are discussed in references 16 and 17. Reference 4 presents an updated approach to the cross-flow problem which is of considerable importance for the present (late 1970's) LFC application effort on aircraft. Of particular interest in reference 17 is the discussion of combined effects, in this case three-dimensional roughness and wall cooling in air. Although theory indicates that wall cooling is stabilizing, experiment indicates that boundary-layer cooling aggravates the adverse three-dimensional roughness effects and the net cooling effect is destabilizing in the presence of three-dimensional roughness. This is another example of dominant and multiple responsibility. References 16 and 20 discuss transition prediction techniques (essentially data correlations) while reference 21 summarizes high-speed flight transition data on cones and missile-like configurations.

Laminar flow control - favorable pressure gradient.- Much of the information on favorable pressure gradient LFC airfoils is summarized in references 23 to 46. Research indicates that long runs of laminar flow are possible on bodies of revolution as well as airfoils, providing that stream or external disturbances are low enough (and not in an unfavorable frequency range) and that wall waviness and roughness are unusually small (roughness Reynolds number on the order of 300). For high fineness ratio bodies of revolution the maximum transition Reynolds number achieved was on the order of 6.5×10^6 (ref. 44). For low fineness ratio bodies and airfoils, laminar runs with Reynolds number on the order of 20×10^6 are possible (refs. 34 and 44).

The requirement for surface smoothness and vanishing small waviness cannot be overemphasized. It is the central theme throughout the LFC literature (both natural and forced) and is probably one of the most prevalent arguments against adoption of LFC on operational systems, especially for multipurpose applications (such as CTOL transport aircraft). These multipurpose aircraft are subjected to dirt and dust in the airport and runway environment, as well as rain, ice clouds, insect impingement, and distortion under aerodynamic and perhaps Sun loads. They also have surface anomalies associated with flaps, lights, attachments, wing access hatches, etc. Therefore, probably the most important LFC problem area is the production and maintenance of surfaces with appropriate roughness and waviness (criteria outlined in section IV). The criteria currently available are probably somewhat conservative, as they are primarily a result of wind-tunnel data (where stream disturbances may exacerbate roughness problems) rather than flight. Obviously a lower unit Reynolds number (higher altitude) can reduce the roughness problem, as a larger roughness can be tolerated (fig. 7).

Jones, in the first Wright Brothers Lecture (1938) was evidently one of the first to conclude, from flight transition experiments (ref. 23), that atmospheric turbulence was not a serious threat to laminarization. Transition in flight seemed to be determined by vehicle-generated disturbances (vibration, propulsion noise, roughness, waviness, steps, gaps, separations, etc.). As of 1939 (ref. 24), the state of the art in natural laminar flow airfoils was relatively advanced. (NACA research had obtained laminar flow up to Reynolds numbers of 6×10^6 from low disturbance tunnel data.) Successful flight tests of these airfoils in 1940 (ref. 25) again revealed a theme familiar in LFC research:

> "these [flight] tests have demonstrated that marked turbulence effects exist even in the low turbulence tunnel" [in an early configuration, not down to final disturbance levels], "with the result that the drag increase with Reynolds Number is shown by all wind-tunnel tests to occur at much too low a Reynolds Number. The practical result is that the airfoils now appear to be useable at a Reynolds Number of the order of twice that previously thought to limit their usefulness" (ref. 25).

Later NACA flight tests indicated less dramatic results, and the difficulties were ascribed to waviness induced by aerodynamic loading in flight (ref. 27). Reference 28 provides a summary of the NACA results up to 1945 and concludes that "the effects of surface condition on the lift and drag characteristics are at least as large as the effects of the airfoil shape." This report (ref. 28) is extremely detailed, still widely used, and includes the famous NACA 6-series low drag airfoils. All of this research is essentially for unswept and subsonic conditions. German work on laminar flow sections was considerably behind the NACA work (refs. 29, 30, and 32), but the Japanese were fairly well advanced (ref. 33), including flight tests (1940).[2]

The British, starting somewhat late, proved laminar flow up to a Reynolds number of 18×10^6 on the King Cobra (refs. 31 and 34) and ultimately developed the Griffith approach. Care should be taken when reading the Griffith literature to differentiate between Griffith suction wings and suction LFC. In the former case the suction was used (in later, more realistic designs) to prevent separation and provide some circulation control, rather than locally promote laminar flow (ref. 31). Since the Griffith type design optimizes LFC through a combination of increased thickness and suction and concave curvature separation control, the critical Mach number is quite low (tremendous expansion over upper surface; thickness-to-chord ratio t/c of approximately 30 to 40 percent, with maximum thickness at approximately 70-percent chord). Also, if one tries to alleviate the critical Mach number restriction by wing sweep, the favorable pressure gradient region becomes destabilizing due to cross flow and the section is probably more unfavorable for LFC than more conventional profiles. Therefore the Griffith work has application only to a limited range of parameters (low sweep, relatively low Mach number).

The premier summary of much of the Griffith work was done by Goldstein (ref. 34), whose purpose was to fill in details left out of reference 31. (See ref. 48 for developments after Goldstein's survey.) Goldstein gives relatively complete results on the King Cobra and Hurricane experiments, as well as the Griffith wing work. (See refs. 36 and 37 for further King Cobra and Hurricane details.) Some actual flight LFC maintenance information on smooth surfaces was obtained in the King Cobra program, with the only serious problem noted being due to insect impingement. However, at higher altitudes (above 6096 m (20 000 ft)), depending upon insect species, these can go "subcritical" for small sweep angle (ref. 44). It should be noted that the King Cobra tests occurred at relatively low altitudes (high unit Reynolds number, high roughness

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[2] Reference 47 provides background material on German wartime research work concerning Japanese, Russian, and American laminar flow wings.

sensitivity) and therefore their lack of particular or peculiar maintenance problems over a period of 6 months is quite important.

The Goldstein review of the Griffith airfoils (ref. 34) includes discussion of the Taylor-Görtler instability problem associated with the aft surface pressure recovery region. It also gives details of the slot and ducting design. Flight tests of Griffith wings in the United Kingdom (ref. 36) and Australia (refs. 35 and 48) indicated considerable sensitivity to slot suction details (slot width and suction variations, leaks). It should be noted that these slots were much larger than usually recommended for the "approach-to-distributed-suction" case where closely spaced slots are used to approximate a porous surface effect. The insect problem is also discussed in some detail in reference 36. Most of the information on U.K. low-drag airfoils is contained in published summaries (refs. 38 and 39). Research since the 1940's in the area of LFC wings which are pressure-gradient stabilized has been mainly for unswept, low-speed applications such as sailplanes and gliders (e.g., refs. 40 and 44).

Laminar flow control - suction, non-Northrop.- References 47 and 49 to 54 summarize the early (pre-1946) research on suction LFC. The work of Holstein (refs. 47 and 50), Pfenninger (refs. 51 and 52), and Von Doenhoff and Loftin (refs. 53 and 54) was evidently quite independent. With the three generic types of suction surfaces to choose from (porous, perforated, and slotted), all three investigators chose slotted surfaces (although Holstein did try perforated surfaces in his third test, with unfavorable results vis-a-vis the slotted surfaces). Results varied, due to differences in model design and facility disturbance level, but all three studies showed considerable laminarization was possible using slot suction (refs. 47, 52, and 54). All final experiments were on airfoil configurations, and the flow was kept laminar to at least 90-percent chord. Transition Reynolds numbers obtained vary from as low as 3×10^6 (ref. 51) to 7×10^6 (ref. 54). References 47 and 53 indicate that the required suction quantity was quite low, but that efficient slot flow with low pressure drop was essential to superior performance. Reference 52 is particularly detailed and provides an excellent summary (as of 1946) of the general features of transition and laminarization technology. Of the earlier works on suction, references 52 and 54 contain the most information.

In several of the tests reported in reference 52, Pfenninger attempted to make use of the favorable pressure gradient caused by the "sink effect" which occurs with slot suction. A. M. O. Smith in his 1950's research also attempted to use this effect (ref. 55). The results from both attempts agree. Increasing the sink effect increases the slot Reynolds number and aggravates the usual slot problems such as (1) thin, roughness-sensitive boundary layer downstream of the slot, and (2) destabilization effect of concave curvature associated with flow downstream of the slot rear stagnation region (ref. 55). References 53, 54, and 56 indicate that slot suction did not decrease the laminar flow sensitivity to roughness and waviness. In an attempt to reduce the sensitivity to surface irregularities and validate stability theory predictions for continuous suction, the next round of tests tried to approach area suction either through porous (refs. 56 to 59) or perforated (ref. 60) surfaces, or with closely spaced slots (ref. 61). The NACA porous suction experiments were the first to show:

> "The minimum experimental values of suction flow coefficient for full-chord laminar flow were of the same order of magnitude as the theoretical values and decreased with an increase in Reynolds number in the same manner as the theoretical values. It seems likely from the results that attainment of full-chord laminar flow by means of continuous suction through a porous surface will not be precluded by a further increase in Reynolds number provided that the airfoil surfaces are maintained sufficiently smooth and fair and provided that outflow of air through the surface is prevented" (ref. 59).

In an NACA flight test in the late thirties on a B-18 wing glove, slot suction was shown to maintain laminar flow up to a Reynolds number of 4×10^6 (ref. 61). This result is of special note considering the following relatively unfavorable circumstances: (1) conventional propeller engine mounted on the wing near the test surface and in operation during the test, (2) relatively high unit Reynolds number, and (3) residual roughness and high slot Reynolds number. It should be noted that in earlier tests the airfoil had already indicated a considerable laminar flow region.

Aside from the Pfenninger (Northrop) work, the first comprehensive look at the practical aspects of suction LFC is by Lachmann (refs. 58, 62, and 63). One of the major points in reference 62 is the extreme importance of unit Reynolds number vis-a-vis the roughness sensitivity problem. A quotation from reference 62 is:

> "research workers who have studied laminar boundary layer flow on large chord models in atmospheric low-turbulence tunnels, or in the free atmosphere, especially in the stratosphere, are considerably more optimistic about the practical possibilities of laminarization than those who have conducted experiments with small chord models in pressurized wind tunnels . . . the essential prerequisite for laminarized aircraft is a surface finish that is compatible with the maintenance of a laminar boundary layer thinned down by suction."

Reference 58 further provides some rather practical guidelines for suction surface design.

Lachmann conducted flight studies of his suction designs (ref. 64) using a glove on an essentially unswept Vampire wing. The suction surface geometry consisted of discrete spanwise perforated strips. These strips essentially took the place of the slots used in the corresponding, also unswept, U.S. flight experiments with the F-94 (ref. 65). According to reference 64 the U.K. flight experiments were successful, with an 82-percent reduction in skin friction over the test region. However, considerable difficulties were encountered with the performance of the perforated strips.

A somewhat parallel set of flight experiments by M. R. Head at Farnborough in the same time frame (mid fifties), also on an unswept Vampire using a porous surface, produced laminar flow at high subsonic speeds up to a Reynolds number of nearly 30×10^6 (refs. 66 and 67). These results are similar to those from the F-94 (ref. 68).

Schlichting (ref. 69) and Van Nes (ref. 70) give brief reviews of LFC up to 1956, while references 65, 71, and 72 provide summaries of LFC research endeavors as of the late fifties. Edwards, who was at Handley Page, recently authored an extensive review of LFC (ref. 66) covering particularly the U.K. research. Included in reference 66 is some discussion of the flight experiments at Cranfield on a large swept fin mounted on the fuselage of Lincoln and Lancaster aircraft. These experiments included fins with and without taper and suction, and were at relatively low speed. The time frame and general objective (flight LFC on swept wings) is similar to the American X-21 program, but the latter was considerably more ambitious, with much higher speed and Reynolds number. Of particular interest in the Cranfield experiments is the use of a large number of surface hot films for transition detection. They proved robust and worked quite well. The significance of the spanwise contamination problem for swept leading edges previously identified in the United Kingdom became fully appreciated at about the same time in both these U.K. and U.S. (X-21) flight tests (late 1963). British LFC work essentially stopped, as did the American, in the middle sixties.

According to reference 66, one of the main difficulties with the Lachmann Vampire flight studies was the formation of surface discontinuities at the perforated strip - smooth wing junction under aerodynamic loading in flight. In fact, Edwards provides what is probably the best and most complete generally available documentation ever made of the Handley Page flight experiments, which eventually achieved laminarization to a Reynolds number of 15 × 10^6 at full-scale unit Reynolds number (6.6 × 10^6 per meter (2 × 10^6 per foot)). Of particular interest are comments concerning possible strong three-dimensional effects (caused by wing taper) on what was essentially an unswept wing, and probable strong coupling between disturbances produced by the perforated hole pattern in this three-dimensional flow. Edwards gives Pfenninger complete credit for identifying the correct (relatively low) suction rates required to control the growth of cross-flow disturbances on swept wings, thereby showing that the LFC penalties associated with sweep are not unduly large. Reference 73 provides a recent review of LFC vis-a-vis the NASA ACEE program.

Laminar flow control - suction, Northrop.- The sheer magnitude of the Northrop effort on LFC (under Pfenninger) necessitates a separate section in the present survey. The Northrop Corporation research covers most phases of the LFC problem including structures, materials, propulsion, aerodynamics, aeroelasticity, and integrated systems (both experiment and theory). The effort included two flight tests (the F-94 and X-21) and covers approximately 16 to 18 years of research. Summaries of this work are available from journal articles and conference presentations (refs. 5, 68, and 74 to 88) and from Northrop summary and progress reports such as references 89 to 121. The following summary of the USAF and Navy sponsored Northrop LFC research on slot suction between 1949 and 1967 has been paraphrased from reference 5:

> One hundred percent laminar flow was observed on a slotted 15 percent thick wing in the Langley TDT tunnel at $R_c = 16.4 \times 10^6$, confirming slot suction laminarization at relatively high R_c when the external turbulence level is drastically reduced. A practical aerodynamically and structurally reasonably efficient LFC suction method, closely spaced fine slots, was developed and subsequently

applied to a second F-94 LFC wing glove in flight - 100 percent laminar flow was observed up to the F-94 test limit ($R_C = 37.5 \times 10^6$) with $M_l < 1.08$. The theoretically predicted boundary-layer stabilization at high Reynolds number by distributed suction was verified for axisymmetric bodies in the Ames 12-Foot Pressure Wind Tunnel on an 8 to 1 fineness ratio Reichardt LFC body of revolution with 114 suction slots located between $x/l = 0.03$ and 0.99: Complete laminar flow was achieved at $R = 57.8 \times 10^6$. In the Ames 12-Foot Tunnel experiments on a 30° swept modified NACA 66012 LFC wing with closely spaced slots, full-chord laminar flow was observed at $\alpha = 0^\circ, \pm 1^\circ$ up to $R_c = 29 \times 10^6$. Whenever strongly amplified oblique TS-oscillations (induced, for example, at $\alpha \gtrsim 1^\circ$ by freestream disturbances as well as external or internal duct noise) interacted nonlinearly with boundary-layer cross-flow disturbance vortices, linearized boundary-layer stability theory ceased to be valid. Boundary-layer cross-flow disturbance vortices on swept LFC wings then became unstable at substantially lower Reynolds number and grew considerably quicker as compared with small disturbance theory. Stabilization of the tangential boundary-layer component against TS-disturbances through increased suction and/or flow acceleration minimized such nonlinear interaction and substantially raised the permissible noise level on swept LFC wings.

Large attachment line disturbances, such as a large surface roughness or an initially turbulent boundary layer at the upstream end of the wing attachment line (wing-fuselage intersection), cause transition and spanwise turbulent contamination directly without the intermediate mechanism of amplified boundary-layer oscillations. Spanwise turbulent contamination can be eliminated relatively easily by local leading-edge extensions, leading-edge suction fences, or by removal of the entire turbulent attachment line boundary layer through local suction. As verified in the Norair 7- by 10-foot wind tunnel on a 45° swept blunt-nosed wing, a particularly high Reynolds number can be obtained by starting with an undisturbed laminar initial attachment line boundary layer and stabilizing by suction through closely spaced vertical nose slots.

Among suction-induced disturbances, slot wake oscillations downstream of the slot exit in the small spanwise plenum chambers underneath the slots at slot flow Reynolds numbers $\frac{\bar{v}S}{\nu} \gtrsim 100$ induce the flow fluctuations v' at the slot inlet, which, in turn, excite amplified boundary-layer oscillations on the external LFC surfaces to cause premature transition at higher chord Reynolds numbers. This disturbance influence was verified on the 15-percent-thick 33° swept Northrop LFC wing of the X-21 group. Such disturbances vanish when the slot wake flow is viscous and steady at $\frac{\bar{v}S}{\nu} \lesssim 100$; indeed, no difficulties from such disturbances had previously been observed up to $R_L = 58 \times 10^6$ when $\frac{\bar{v}S}{\nu} < 100$. With perforated LFC surfaces suction-hole-induced streamwise or horseshoe vortices shed from the suction holes had often caused premature transition either directly or as a result of amplified TS-oscillations, especially when the streamwise spacing of rows of suction holes was comparable to the wave length of amplified TS-oscillations (as verified during transition experiments at the attachment line of a 45° swept blunt-nosed wing). Perforated LFC surfaces are acceptable at high Reynolds numbers when the suction-hole-induced three-dimensional aerodynamic roughness and the resulting streamwise disturbance vorticity are too weak to significantly affect transition, which requires a very large number of closely spaced small suction holes. Such suction-hole-induced disturbance vorticity must be minimized, particularly on swept LFC wings where it will superimpose with the streamwise boundary-layer mean and disturbance vorticity induced by spanwise pressure gradients.

Permissible two- and three-dimensional surface disturbances for laminar flow (steps, gaps, waves, roughness) were established on straight and swept LFC wings. Properly placed weak local suction in the rear flow reattachment region downstream of rear facing two-dimensional surface steps has doubled the permissible step height Reynolds number.

As verified by supersonic low-drag suction experiments in the AEDC von Kármán Gas Dynamics Facility Tunnel A on a laminar suction plate and a suction ogive of revolution with a large number of closely spaced slots, full-length laminarization at supersonic speeds by means of boundary-layer suction was surprisingly easy in the absence of shock waves and boundary-layer cross flow up to high length Reynolds numbers ($R_L = 51 \times 10^6$ at $M = 3$ on the LFC ogive of revolution) in spite of severe acoustic disturbances radiated from the turbulent tunnel wall boundary layers. This result is explainable by the higher TS-stability limit Reynolds numbers of supersonic laminar boundary layers. In the presence of incident shock waves at supersonic speeds, carefully laid out boundary-layer suction in the boundary-layer—shock-interaction region of a flat suction plate eliminated laminar separation and premature transition in this area to enable full-length laminar plate flow up to plate length Reynolds numbers $R_L = 26 \times 10^6$ at $M = 3$ and 1.6 pressure ratio across the shock.

Structural investigations of slotted LFC wings with many closely spaced slots were conducted, leading from structural tests on small-scale panels to investigations of progressively larger structural panels, and finally to the structural investigation of an LFC wing box. Many of the results of these studies were incorporated later in the X-21 wing design. These structural investigations showed that the structural weight penalty of LFC wings can be kept small by carefully integrating the suction ducting system with the wing structural layout, by using a load-carrying LFC wing surface instead of a non-load-carrying LFC wing glove, by using a careful structural overall design and detail design, and by using the fact that a substantially steeper rear pressure rise is possible on the upper wing surface by means of suction in this area to allow (under otherwise the same conditions) thicker and thus structurally lighter wings.

This summary does not include the X-21 results, which are already summarized quite well in references 85, 93, 94, and 122. Once the spanwise contamination problem was isolated and corrected (e.g., ref. 123), the X-21 performed satisfactorily (laminar flow up to R_x on the order of 40×10^6) except for roughness and waviness problems associated with filler in hollow spots near panel splices. The conventional picture of the current status of suction LFC feasibility is given in references 73, 85, and 88. "LFC's technical feasibility is now a fact, and many attractive applications to future aircraft seem likely - provided operational [and manufacturing] feasibility can also be demonstrated. The last clause is the crux of the problem"

Supercritical wing sections developed since the 1966 to 1970 time frame give rise to new LFC technical problems such as concave curvature (lower surface) and sonic-line reflection and subsequent boundary-layer disturbances caused by suction-induced waves in the supercritical region (upper surface). These new issues are not yet satisfactorily resolved, but research is under way.

Application Studies

Subsonic/transonic.- The prime motivation behind LFC research is obviously the large performance gains possible. Over the years many authors have examined the magnitude of such gains, and the best method of realizing them, for a multitude of missions. Most of the subsonic and transonic application studies (unclassified) are given in references 35, 37, 62, 85, and 124 to 163. One general and obvious consensus of this literature is that the entire aircraft should be redesigned rather than LFC just "added on" to an existing design. This permits a much more efficient aircraft by resizing of the aircraft and propulsion units, etc. Most studies do not include laminarization on the fuselage, due primarily to the larger Reynolds numbers and presence of multitudinous roughness sites (windows, windshield wipers, doors, antenna, towing handles, etc.).

One of the first "system studies" of suction LFC dates back to 1937 (ref. 124), even before such a concept was proven feasible (or even possible). Shenstone presents a detailed drawing of an aircraft completely covered with suction holes, estimates the system parameters required, and concludes that a speed increase from 105 to 156 m/sec (235 to 350 mph) might be possible on a De Havilland airplane (circa 1937). For natural laminar flow, the major design or system considerations on 1940's aircraft were smoothness and waviness (ref. 125) and presence or absence of propeller slipstream (ref. 126). (See ref. 127 for an interesting early study (1947) using prop jets.) Richards (ref. 37) lists the requirements for LFC as: "the wing must be made sufficiently free from waviness, roughness, and steps to allow extensive laminar flow under ideal conditions; then provision must be made to eliminate the effects of rain, mud and flies near the leading edge and the wing must be maintainable at a high level of finish from week to week and from year to year." With these caveats, Richards estimates a doubling of payload using LFC on conventional aircraft (1950 vintage).

"Flying-wing" designs, especially attractive for LFC application, were quite popular in the early fifties (refs. 35 and 37) and on into the sixties. (See Handley Page 117 design in refs. 136, 137, and 152.) By 1953, Courtney's analysis (ref. 129) indicated that a high-speed, wing-body combination would be better than a lower speed, thick-sectioned all-wing aircraft, if fuselage laminarization were possible. Courtney quotes a possible 70-percent increase in passenger payload. Reference 129 is relatively complete and is among the first of the "modern" LFC system studies. Lachmann in 1954 (ref. 62) quotes a range increase of 45 percent for an aircraft with 50-percent wetted surface laminarization.

Thus far in the discussion the usual LFC application considered has been to the long-haul passenger mission. In the early to middle fifties, Pfenninger considered this case (refs. 132 and 133) in considerable detail (including structural and aeroelastic effects) and advocated strut-braced wings to obtain the necessary reduction in drag due to lift required for aircraft optimization with lower skin friction. Reference 131 and especially the company report (ref. 134) are quite informative as is reference 135 by Lachmann on LFC design. As of 1962, Handley Page (United Kingdom) was still in the LFC business and a new design was discussed in reference 136, along with a beautiful cutaway drawing of the Cranfield swept fin LFC experiment. The article quotes optimistic numbers such as "the L/D is approximately doubled" for the LFC aircraft. (See ref. 66 for subsequent Handley Page developments.) Northrop produced a series of fairly detailed LFC system mission studies in the early sixties (refs. 137 to 146 and 164) which culminated in a quick look at putting suction LFC on a C-5 class vehicle (ref. 146).

Vehicle classes investigated (using early 1960's technology) include not only passenger, but also cargo, multipurpose (long-endurance, see also ref. 147) and nuclear, as well as several supersonic missions covered in the next section. Results from these studies are more optimistic than the recent work in the same vein (12 to 14 years later, refs. 150 to 163), probably due to the increase in performance of the basic turbulent aircraft which occurred in the meantime (supercritical wings, etc.). For Mach 0.8 with take-off weight of 121 109 kg (267 000 lb), range increases of 30 to 60 percent are quoted (refs. 137 and 138), along with decreases in direct operating cost (DOC) on the order of 20 percent. Somewhat later (ref. 143) Northrop quotes a 70-percent range increase for relatively small payloads (22 680 kg (50 000 lb)). Reference 143 is recommended as a particularly straightforward summary of the Northrop studies in the early sixties.

The demise of the Air Force-funded Northrop design efforts in the middle sixties started a long hiatus in LFC research, broken only by scattered studies such as at Boeing (ref. 148) and a rather detailed Russian analysis (ref. 149). The Russian interest in LFC has evidently continued, as evidenced by a recent paper (ref. 150). Reference 148 states, "Below transcontinental design ranges, the application of LFC to a commercial transport does not appear practical."

The energy crisis has triggered a whole new spate of LFC application studies sponsored by the U.S. Air Force (refs. 151, 160, and 162) and by NASA (refs. 153 to 159, and 165). Reference 151 suggests a "shopping list" of required LFC research and development. This list includes (1) further stability studies, (2) acoustic criteria, (3) further roughness influence research, (4) relative humidity effects, (5) refinement of slot and duct details, (6) incorporation of high lift capability, (7) wing-mounted nacelle research for LFC, and (8) designs incorporating consideration of visual inspection and maintainability. The British contribution to the recent literature (ref. 152) states that "on a fuselage the roughness and irregularity of windows, doors, etc., make it impossible to have laminar flow on that component" (deduced from Handley Page research).

The recent studies for LFC on CTOL aircraft indicate improvements of 22 to 30 percent in fuel consumption and 8 to 15 percent in DOC (refs. 154 to 160 and 166). Reference 161 states that "the primary operational requirements of LFC systems are those related to smoothness and cleanliness of the surfaces and to the operation and control of the suction system." Reference 161 should be consulted by readers interested in actual LFC operations.

Supersonic/hypersonic.- Detailed studies of LFC applied to the SST class vehicle were conducted by Northrop (refs. 137, 138, 143, and 167). There also exists an unclassified British contribution (ref. 168). Even though skin-friction drag is a somewhat smaller percentage of total drag at supersonic speeds, LFC can still provide a major benefit (in increased payload) because of the large fraction of initial weight devoted to fuel, i.e., relatively small decreases in fuel weight (from LFC drag reduction) can lead to rather large percentage increases in payload fraction. An additional benefit is a lower equilibrium skin temperature (approximately 83 K (150° F) reduction) due to the lower recovery factor and Stanton number associated with laminar flow. The estimated range increase from use of LFC on a Mach 3 transport is 20 percent (e.g., ref. 143). An LFC advantage peculiar to the SST (aside from the lower skin temperature) is the possibility of lower sonic boom due to reduced weight. Of particular interest in the SST problem is the reduced roughness sensitivity compared with the subsonic case (ref. 17).

Because of the continuing decrease in roughness sensitivity with increasing Mach number, natural laminar flow hypersonic aircraft have been considered (refs. 169 and unpublished study by Bertram) along with suction LFC for hypersonic reentry vehicles (ref. 170). In the latter case the normally low base pressure could be used as the suction source. Application studies of LFC on SST vehicles using late 1970's technology are not yet available.

Previous Bibliographies

Aside from the reference lists contained in the various review articles, there are some older bibliographies (refs. 171 to 173). Two new LFC bibliographies (author and title only) are also available (refs. 174 (Air Force, primarily X-21) and 175).

IV. SUMMARY OF FLIGHT AND LOW DISTURBANCE TUNNEL DATA ESPECIALLY SUITABLE FOR RELATING STABILITY THEORY TO TRANSITION

As stated in the Introduction, one of the primary purposes for the present review and bibliography is the identification of low-stream disturbance transition data suitable for the calibration of linear stability theories as predictive techniques for transition location (which is the result of both linear and non-linear processes). Once calibrated, the theories can be employed as analysis methods (but in a design mode) to predict optimized wall suction rates required for LFC. The best low-stream disturbance data supposedly comes from flight experiments, as the scale of the atmospheric turbulence is generally too large to influence the body transition location to first order. In addition to flight data, several swept wing studies are cited in this section which were conducted in the Ames 12-Foot Pressure Wind Tunnel, which has one of the lowest stream fluctuating vorticity levels of any free-world facility suitable for testing large-scale three-dimensional configurations. However, the Ames facility does contain low-level acoustic disturbances. Therefore, these ground data are still subject to question.

Once the stream disturbances are reduced, as in the flight case, the problem becomes one of reducing the body-generated disturbances such as vibration, noise (propulsion, air frame, and boundary layer), roughness (including insects, joints, etc.), and (especially insidious) waviness. A surface which looks and feels smooth (low roughness) may still contain sufficient waviness to cause premature transition, and, especially for the earlier flight data where relatively thin skins may have been used, such waviness may occur under aerodynamic flight loading and not be present upon ground inspection.

The flight and Ames 12-Foot Pressure Wind Tunnel transition studies identified in the present review are summarized in table II. These studies cover the period from 1937 to 1972 and cover a wide variation of parameters including: (1) large Reynolds number range with and without suction, (2) sweep, (3) compressibility, (4) variations in type of suction surface and aircraft propulsion (noise), and (5) geometry (both wings and axisymmetric bodies). In most of these investigations an attempt was made to reduce surface waviness and roughness and the data may be used with some confidence as being indicative of boundary-layer behavior in an actual LFC application (except for concave curvature and extensive compressibility influences which have not yet been flight tested). The extensive ground studies on LFC (other than those in the Ames 12-Foot Pressure Wind Tunnel) are covered in section V of the present survey.

Previous stability theory calibrations (refs. 6 and 8) have used a limited sample of the flight data summarized in table II, but these analyses were restricted to the two-dimensional, no suction case and did not employ the full set of data available for this restricted case. Of particular interest in table II is that the NACA flight tested a slotted LFC suction experiment in 1941 at Reynolds number to 30×10^6 at a time when the ground research on LFC was just beginning elsewhere. Also, spoiler experiments were included in some of the flight studies, i.e., various known disturbance fields, such as propeller slipstream, waviness, roughness, atmospheric turbulence, and acoustic environment, were independently varied. The four-part series of experiments at Cranfield are especially well documented and useful, having a range of Reynolds number (but unfortunately not very high in an absolute sense) with and without wing taper and suction. (See ref. 176 for a review of earlier flight tests.)

The data quality of the entries in table II obviously varies and several entries may be of little use except as interesting checks. However, it is suggested that the calibration of stability theory with flight data may be more productive for later application to flight design than using ground data. Many more studies of flight transition in the high supersonic and hypersonic range exist (e.g., refs. 21 and 177 to 182), but since the thrust of the present review and bibliography is LFC for CTOL and SST aircraft, these works are not discussed in detail.

V. DETAILED APPLICATION ISSUES FOR LAMINAR FLOW CONTROL

Roughness and Waviness (R & W)

As stated previously, roughness and waviness are the key issues in the application of laminar flow, either natural or forced. There are two separate problems: the first is the efficient production (manufacture) of a smooth and low waviness surface; the second is the maintenance of that surface, particularly in the presence of insects, possible runway rubble impingement, cyclic loading, corrosion and erosion, etc. Furthermore, attainment of the close tolerances permissible in the leading-edge region is made considerably more difficult by the extreme measurement accuracy required. The roughness problem has received research attention from the standpoint of conventional transition, as well as the extension of laminar flow, and considerable literature exists. Much of the R & W research is contained in references 17, 36, 37, 71, 93 (section 10), and 183 to 226. The insect problem is considered in references 34, 36, 44, 166, 195, and 227 to 239. Except for special situations (such as roughness and waviness in concave curvature regions), sufficient information exists to provide engineering guidelines (criteria) for R & W in LFC manufacturing and maintenance. An optimal three-dimensional wing design should consider means of keeping surface insect impingements to a minimum.

Waviness is less easily noticeable or detectable than roughness, yet 1 part in 2000 ($a/\lambda = 1/2000 = 0.0005$) has caused premature transition in laminar flow experiments. Obviously, the amount of R & W which can be tolerated on a wing is a function of parameters such as boundary-layer history, including disturbances prior to R & W location, unit Reynolds number, local flow conditions, subsequent boundary-layer development (whether or not an R & W disturbance or induced disturbance can ever grow to transition), surface curvature, R & W geometry, and three-dimensional flow aspects. Therefore, stating a value of roughness or amount of waviness actually makes little sense without also stating the detailed conditions associated with the experiment (or calculation).

Roughness and waviness affect transition through several mechanisms, many of which compete through Morkovin's principle of dominant and multiple responsibility for transition. These mechanisms include (1) flow separation and consequent free shear-layer instability (at least an order of magnitude less stable than attached flows), (2) local regions of adverse pressure gradient which can trip the boundary layer before the usually related region of favorable pressure gradient can affect the flow, (3) both positive and negative pressure perturbations induced by R & W, which, in three-dimensional mean flow (swept wings), can be destabilizing, (4) local concave streamline curvature causing transition via the Görtler bypass, and (5) local three-dimensional perturbations (usually organized vortex motion) which hasten the nonlinear breakup and burst formation. The amount of waviness required is small due to the large pressure gradients produced by small wavelength waves, even for quite small ratios of amplitude to wavelength; i.e., a larger a/λ can probably be tolerated if the λ is large. As discussed in reference 17, for example, the action of two-dimensional and three-dimensional disturbances can be quite different, with the nonlinear effects of the three-dimensional disturbance being much more critical to LFC design. The direct use (for flight design) of wind-tunnel data on permissible R & W is probably conservative, due to the interaction between stream and facility disturbances and R & W generated motions. In general, anything that thins the boundary layer exacerbates the R & W problem (e.g., refs. 194, 231, and 232). There exist no systematic studies of combined R & W effects.

Particularly recommended on this subject are references 17, 34, 36, 186, and 195 (actual flight maintenance experience); 196 and 200 (especially for detailed physics of roughness effects and flight verification (unswept)); 210 and figure 9 of reference 71 (extensive tests and analysis); 208 (multiple elements); 211 (waviness for swept wings); 218 (note on scaling law); section 10 of reference 93 (summary for X-21 three-dimensional compressible flows); 223 (local suction to increase allowable step height); and 229 and 233 (summary of insect problem). A brief comment which arose during the discussion in reference 68 is of interest:

> "The leading edge must be smooth, but in general the [distributed surface] roughness which can be permitted in a laminar boundary layer is much greater than the roughness that gives a drag increase in a turbulent boundary layer."

In the laminar case, however, isolated roughness or the larger peaks and valleys in the distributed roughness can cause transition over the entire downstream surface, depending upon location.

Suction-Surface Configuration

Several approaches exist for suction LFC, and the decision of which approach to apply must be based upon structural as well as aerodynamic efficiency. The three major possibilities are (1) porous, (2) perforated, and (3) slotted. Slotted surfaces are by nature discrete rather than distributed (continuous) suction. Porous and perforated surfaces can be applied either continuously or in strips. The bulk of the U.S. LFC research has heretofore been focused upon slotted surfaces, whereas the U.K. work has been concentrated on porous and perforated (both continuous and strips) surfaces.

Recent unpublished calculations by Nayfeh at Virginia Polytechnic Institute and State University (VPI&SU) and Lockheed-Georgia Company on two-dimensional mean flows indicate that porous or perforated strips, if placed in the near field of each other (less than O(10) strip widths between suction strips) may be as optimal, from a stability standpoint, as distributed (porous) suction. Prior to the Nayfeh results discrete suction was always considered less efficient, aerodynamically, than continuous suction. In particular, in the slot experiments, usually the slots were O(100) slot widths apart and therefore not in the near field.

A major consideration in suction-surface design is the requirement for relatively uniform flow (spanwise) into the suction surface. Therefore, slots or perforated strips and associated suction ducts should usually be located along isobars, and the wing should be designed with straight isobars. This circumvents the problem of nonuniform inflow, or even outflow, due to feedback forced by external static pressure variations.

An excellent, and still quite up-to-date, review of suction-surface options, trade-offs, and physics is given in reference 240. This paper is highly recommended. The suction power required is proportional to both the suction mass flow (quantity of suction required) and the local pressure level. Therefore, in some instances, designs necessitating higher suction may be more efficient, if the local pressure level is higher, i.e., one should minimize suction requirements in low pressure regions. Since reference 240 provides such an excellent background to suction-surface design, other references available are merely quoted and a few brief remarks are made, based primarily on knowledge or options not available in 1961 (time period of ref. 240). The work on slots is considered first, followed by the porous and perforated cases. The latter two are discussed together, as a perforated surface with small, closely spaced holes is essentially a porous surface. The data base on porous materials was developed for the separation boundary-layer control (BLC) case, as well as for LFC.

Slotted surfaces.- Most of the basic slotted-surface research is contained in references 52, 54, section 3 of reference 93, and 241 to 262. (See also ref. 263.) Additional information is of course available from both the slotted flight tests already discussed (see table II) and the slotted wind-tunnel studies summarized in table III (discussed in the next section of the present review). Initial slot research focused upon the ideal flow into fairly large slots and identification of the sink effect; i.e., the existence of favorable streamwise pressure gradients both upstream and downstream of the slot (with a stagnation point at the downstream slot lip (refs. 54 and 241 to 246)). Such large slots seemed favorable initially. By using rounded slot lips and internal diffuser contours and by keeping viscous loss small, the momentum of the sucked air could be recovered, thus reducing the pumping power. The stabilizing sink effect should reduce the suction requirements.

In actual practice, large contoured slots have proven quite unfavorable. The flow in such a slot tends to exhibit relatively violent, unstable separated flow regions at off-design conditions (due to the smooth contour, the separation point is not anchored by surface discontinuity). Also, the deceleration in the slot entrance flow tends to produce highly unstable inflected profiles with resultant large-amplitude disturbances downstream of the slot, and the concave streamline curvature immediately aft of the slot can be sufficient to cause large streamwise growth factors. Therefore, the Northrop group under Pfenninger eventually settled upon the antithesis of the original approach, that is, narrow, sharp-edged slots with highly viscous flow (slot Reynolds number O(100)). The sharp edge anchors the separation point and the low Reynolds number dampens disturbances produced within the slot plenums or the slot vicinity. Flow in such small slots has relatively high velocity compared with a porous surface and the slots are spaced quite far apart, in terms of slot widths (refs. 247 to 252, 254, and section 3 of ref. 93). This situation is quite different from the porous surface case, the latter being the only case which classical stability theory can handle.

Porous and perforated surfaces.- The problems with porous surfaces (refs. 173 and 263 to 283) are mainly structural and materials problems such as (1) structural support and fastening, a problem especially for distributed (continuous) suction, (2) weight (early sintered metal surfaces were quite heavy), (3) uniformity of porosity, (4) surface roughness, especially for a boundary layer in the leading-edge region thinned by suction, (5) clogging, (6) porosity tailoring to meet suction requirements, and (7) internal compartmentation for inflow-outflow control. If porous strips are employed, then the porous/nonporous joint can cause difficulty (forward or backward facing step). Additional problems with porous surfaces include low strength and possible porosity distortion when machined or otherwise surface finished.

Of particular interest is a result from a flight study of porous leading-edge-region suction (ref. 269) which shows that "clogging due to atmospheric dust did not appear to be a problem." However, since the study was not an LFC effort there may be questions concerning a lack of sensitivity; i.e., what is not a problem under a turbulent or transitional flow may well be a problem for the super-sensitive LFC leading-edge case (thin boundary layer). (See also ref. 279.) The more recent porous work evaluated nonmetallic materials such as porous fiberglass, which were found to be better in terms of strength-to-weight ratio, uniformity, and smoothness (refs. 173, 223, and 284). The Navy is presently pursuing a renewed effort in boundary-layer LFC for possible torpedo application and is generating new results for porous surface options or possibilities. Preliminary results from this ongoing research are given in references 276 and 277. The NASA ACEE-LFC effort has also sparked renewed interest in porous surfaces (e.g., ref. 278).

Perforated surfaces, references 1, 263, 264, 280, and 285 to 301, are composed of an array of small holes. The principal difficulties concern allowable hole sizes and spacing or array geometry. The British found (ref. 66) that the holes should not be spaced behind each other in order to avoid reinforcement of vortices or wakes shed from upstream suction holes. Indeed, they should not be spaced in any regular pattern at all, except on a noninterference basis, which is possible for a small number of rows of holes. The extreme importance of the interrelationship between spacing, hole size, and suction was dramatized in both the U.K. work summarized in reference 240 and particularly that of Pfenninger's group at Northrop (refs. 287 to 294) who mapped out the regions in parameter space for various phenomena including (1) standing vortex bridges between holes, (2) shed horseshoe vortices, and (3) stationary longitudinal vortices. Figure 5 of reference 5 provides criteria for the existence and growth or decay of these flow structures.

Reference 264 states that the perforated-surface technology as of 1948 was to "punch" the holes with the minimum hole size depending upon the metal thickness. The latest technology (ref. 301) allows hole sizes down to 0.0127 m (0.005 in.) (or smaller) using electron beam drillings. An alternate approach is to use woven mats (ref. 278).

Acoustic Effects

In LFC applications, at least four acoustic sources are generally present: (1) propulsion noise (propeller, jet exhaust, or compressor), (2) airframe noise (separated flow and turbulent boundary-layer noise, the latter primarily from the fuselage), (3) sound produced by the suction surface, especially for the transonic and supersonic cases where strong waves can form, and (4) suction ducting and compressors.

Fundamental studies of the influence of sound upon transition (e.g., refs. 302 to 305) indicated that sound can have a first-order spoiler effect, depending upon frequency content. Sound frequencies near those for the most unstable waves in the boundary layer (in two dimensions, generally Tollmien-Schlichting waves) are particularly unfavorable to efficient operation of an LFC system. However, quite high noise levels can be tolerated if the frequency is far from the unstable region of the viscous flow. In examining the experiments for the influence of noise, two issues should be borne in mind: (1) the critical boundary-layer frequency range is a function of the flow history and local conditions, and therefore sound input which does not effect one portion of a wing may have a large effect elsewhere on the same wing, and (2) from the principle of dominant and multiple responsibility for transition, the transition location in a given experiment may be forced by roughness, waviness, etc., and, therefore, while occurring early, may not be sensitive to changes in sound.

The initial studies on noise effects (refs. 306 to 308) concerned propeller aircraft. (See refs. 259 and 309 to 312 for propeller noise characteristics.) The general conclusion was that propeller sound fields do not seem to appreciably influence transition location. Obviously, if the surface was behind the propeller in the slipstream, the huge fluctuating vorticity levels of the stream had a first-order influence, but for surfaces outside the slipstream, and for pusher propellers, no appreciable effect was noted. The next set of tests (refs. 313 and 314) concerned differences in jet-engine exhaust noise (with and without afterburning), and somewhat different conclusions were reached than in the propeller case; i.e., afterburning did cause boundary-layer destabilization. (See page 3-4 and fig. 6 of ref. 315.) These tests were on a fighter airplane and the situation probably would be worse for the engine-on-wing transport case. Reference 316 provides an excellent first look at noise effects, particularly for the X-21 project. Concerns for the possible noise problems on the X-21 (refs. 315 and 316) led to several wind-tunnel and flight tests. (See refs. 267

and 317 to 322.) In particular, the flight tests (ref. 321) showed that, transonically, the radiated turbulent boundary-layer noise was larger than the propulsion noise.

The results from the Northrop wind-tunnel studies of noise influence upon LFC systems (refs. 262, 320, 322, 323, and section 11 of ref. 93, pp. 155-156) indicated that increased suction could successfully stabilize low-speed boundary layers excited by sound disturbances, and that the critical sound frequency range was relatively broad. Both external and internal (duct noise) sound had similar effects upon transition. References 324 to 326 contain more recent work on noise problems.

Other Application Issues and Information

Methods for transition determination in flight.- References 327 to 334 provide evaluation of several techniques suitable for measuring transition location in flight. Possibilities include (1) liquid crystals, (2) surface hot films (ref. 332), and (3) surface microphones. Older (and quite accurate but more difficult) methods were surface pitot traverses and china clay (e.g., ref. 330).

Suction ducting design.- Most of the research on suction ducting design (refs. 240, 335 to 350, and sections 4 and 5 of ref. 93) was conducted in the 1950's at Northrop. The major design problem is to keep the duct losses small so that suction is approximately constant along isobars. An equally important goal is the production of a quiet, stable duct flow to avoid disturbance feedback through the suction surface and consequent flow destabilization. "Organ-pipe" resonances and shear-layer noise coupling, leading to large disturbances, can occur if the design is not well done. Acoustic treatment within the suction ducts may also be necessary.

Incorporation of high lift for take-off and landing.- Efficient CTOL aircraft generally employ high lift devices (e.g., refs. 351 to 358), usually in the leading-edge region, for take-off and landing. The incorporation of such devices in an LFC wing is difficult, particularly near the leading edge, because of the LFC roughness and waviness requirements and the necessity for suction through the surface over the retracted flap in cruise. One approach, currently under study by Pfenninger, is to reduce the leading-edge-region unit Reynolds number and radius, so that some reasonable discontinuities can be tolerated. In this approach, the suction requirement is reduced, and a Krueger nose flap can be used.

An alternate approach is to combine a high-lift BLC (boundary-layer control) suction scheme with the LFC suction hardware (refs. 354 to 358). For unswept wings the required suction distributions are quite different for the two purposes (reducing leading-edge separation (BLC) and keeping flow laminar (LFC)). However, for the three-dimensional case considerable suction is required in the leading-edge region to stabilize cross flow; therefore, the two systems may perhaps be compatible. Extensive literature exists on suction BLC but is not referred to herein in the interests of space. This literature is easily accessible. A possible problem with LFC suction system operation during take-off and landing is clogging from low-altitude (airport-region) particles and runway dirt, pollution, debris, and rain.

Environmental effects.- Several considerations are included in this catch-all section (see especially ref. 359): (1) effects of rain upon LFC performance (LFC generally lost in rain, but regained shortly after leaving rainy area, ref. 360), and (2) influence of ice clouds, humidity, and local region of small-scale atmospheric turbulence (refs. 361, 362, and p. 27 of ref. 94), weathering effects upon surface quality (refs. 363 to 365), and ice protection (section 14 of ref. 93).

Surface geometry.- There are at least two problem areas, wing-fuselage juncture-region design and concave curvature destabilization causing early transition. For the juncture-region problem the wing isobars should probably be kept as straight as possible, at least until the "turbulent wedge" from the generally unlaminarized fuselage and wing are laminarized. The intersection (and the suction system) must then be designed to keep laminar flow in the immediate vicinity of the corner as well as downstream on the fuselage where the wing wake is a particular problem. Most of the intersection research was again done by Northrop (refs. 311, 312, 315, 316, 320, 321, and 366 to 372), with the addition of a well-documented U.K. study (ref. 373). Considerably more research is required on this problem, as indeed is the case for the ordinary situation, where both surfaces have turbulent flow entering the corner.

The concave curvature problem (e.g., refs. 244 and 374 to 388) also requires much more research. There is no real agreement, even about the correct computed neutral stability curve (ref. 388). The basic physics for concave surfaces involves formation of stationary Görtler vortices within the boundary layer (ref. 375). For the two-dimensional (unswept), incompressible, no-suction parallel-flow case, A. M. O. Smith (ref. 376) showed that an e^n approach (relating stability theory for concave surfaces to experiment through a surface-integrated amplification rate) worked quite well, and this 1955 work is still the state of the art. Kobayashi (refs. 386 and 387) has shown that suction should be stabilizing in the Görtler case also, but there is a need, particularly for supercritical airfoil applications, to extend the Görtler research, both experimental and theoretical, to the compressible, nonparallel, suction, and swept leading-edge (three-dimensional) cases.

Structures, materials, and propulsion and pumping systems.- These areas have problems which are just as critical to the development of an optimized LFC aircraft as the aerodynamic issues. An LFC application can probably accrue considerable benefit from a synergistic design where propulsion, structures, materials, and aerodynamics and boundary-layer theory are considered and optimized simultaneously. The reason for the emphasis thus far in this report on the aerodynamic side is that LFC must first be obtained, easily and repeatedly, before it makes sense to look at optimized systems. For example, the type of suction surface, or the smoothness requirements, can dictate and narrow structural and material options.

For the natural laminar flow case, where a key problem is roughness and waviness, the use of smooth molded or plastic wings is an attractive concept (refs. 389 to 391). The early structural research on laminar flow wings was mainly concerned with minimizing distortion (waviness) under load (refs. 392 and 393). For the suction case, the structural design of both perforated (refs. 284 and 394) and slotted surfaces (refs. 395 to 399 and section 15 of ref. 93) has been considered, the latter in the most detail. The manufacturing problems of LFC panels and wings are discussed in references 278, 306, and 400 to 404.

In the propulsion area, the available information covers the range from propellers (ref. 405) to cycle calculations for an LFC SST. The studies cover two areas, main propulsion (refs. 406 to 412) and suction systems (refs. 413 to 417), including consideration of "engine out" conditions (ref. 418).

VI. SUMMARY OF LAMINAR FLOW AERODYNAMIC GROUND STUDIES

Historically there have been two basic reasons for LFC wind-tunnel testing: feasibility and design checks and basic studies of phenomenology and physics. By far the bulk of the available data belong to the first category, with detailed local measurements (second category) made generally as a last resort when difficulties are encountered. Problems which engendered considerable basic "micromeasurements" are the spanwise turbulence contamination issue and the swept-wing transition phenomena in general (which are quite different from the two-dimensional case (refs. 419 to 424)). References 425 to 429 provide typical examples of other basic research studies in the LFC area involving detailed fluctuation measurements. (See also section entitled "Acoustic Effects.") There is an important need for further detailed measurements to (1) validate the new generation of stability theories through direct comparison with amplification rates and amplified frequencies, and (2) provide physical insight into the physics of situations such as the possible superposition or interaction of Görtler vortices and stationary disturbance vortices (concave curvature regions on supercritical swept wings).

As stated earlier, the wind-tunnel LFC data are subject to question concerning the influence of various facility disturbance modes such as vorticity, acoustic, and temperature fluctuations. All of the data are suspect in terms of the validity of linear stability theory, but in greater or lesser degree depending upon the level, scale, spectra, and orientation of the stream disturbances. The special difficulty comes when it is realized that stream disturbance data are generally either not well documented or nonexistent. (See refs. 430 to 433 for one of the better studies in this area.) One of the reasons for the early NACA success with natural laminar flow airfoils was the early development by NACA of a low disturbance tunnel (ref. 28). The importance of documenting and reducing stream disturbances cannot be overemphasized for LFC wind-tunnel studies.

Tables III to VI contain a summary of much of the available laminar flow wind-tunnel data. The Ames 12-Foot Pressure Wind Tunnel data are covered in table II, and the Northrop 33° wing tests are covered in the section entitled "Acoustic Effects."

The content of tables III to VI is as follows:

Table III - Natural laminar flow investigations (see also refs. 24 to 46).

More recent research on natural laminar flow airfoils for low Reynolds number application is given, for example, in references 434 and 435.

Table IV - Subsonic tube experiments with suction.

Table V - External flow subsonic suction experiments.

Table VI - Supersonic suction experiments.

VII. ANALYTICAL DETERMINATION OF SUCTION AND PRESSURE-GRADIENT REQUIREMENTS FOR LAMINAR FLOW

Early Approaches

The estimation of suction and pressure-gradient requirements and their optimization is essentially a three-step process: (1) calculation of mean (viscous) flow development, (2) calculation of the unsteady, or stability, characteristics of these profiles, and (3) relation of the stability theory results (generally linear) to the transition location (nonlinear). The last item is empirical, but postponing the introduction of empiricism until as late a stage as possible in the analysis generally leads to more reliable results. For example, empirical input could take the place of the entire process. One could run tests and correlate transition-length Reynolds number with suction rate or pressure gradient. There are no boundary-layer or stability theory calculations anywhere in such a procedure, but of course, neither is there any possibility of generalizing the result to the airfoil case, where rate processes and history effects are important. Because of this history aspect of the airfoil problem, boundary-layer and stability calculations are quite necessary for good laminar flow design.

The early nonsimilar boundary-layer solutions were generally either of the integral type (e.g., ref. 436) or involved other approximations (ref. 437). Once boundary-layer profiles are available, the next step involves application of stability theory. The initial approach involved use of the neutral curve only, and in particular, the lower critical Reynolds number (refs. 438 and 439). This Reynolds number was corrected empirically by relating some function of the lower critical Reynolds number to the observed transition location (refs. 440, 441, and section 2 of ref. 93). Reference 442 is recommended as a relatively detailed summary of pre-1968 mean-flow calculations for suction application, while references 443 to 445 are indicative of more recent research in the same vein.

Mean-Flow Calculations

The availability of large computational machinery since the middle 1960's has revolutionized mean-flow (and stability) calculations. The essential change is the use of direct numerical solution techniques for the complete nonlinear governing equations (e.g., ref. 446). This allows inclusion of history effects as well as full Navier-Stokes calculations (when required). More approximate techniques are still sometimes used, particularly for simple parametric studies (ref. 447), extraction of analytical functional dependencies (ref. 448), or three-dimensional flows (ref. 449). However, the newer numerical techniques and development of faster machines has brought complete numerical boundary-layer solutions well within the range of all but the smallest budgets. Reference 446 contains a review and listing of most of the numerical-solution programs applicable to the compressible wing problem. Several even newer methods are still under development.

Other flow calculations of interest to LFC, besides distributed suction, include details of the flow near a suction slot (refs. 450 to 453), suction in streamwise corner (intersection) regions (ref. 454), and spanwise perturbations in suction (ref. 455).

Stability Theory

Details of the stability theory approach and its application are the most important part of an LFC design procedure. The prerequisite mean-flow calculation, while sometimes difficult, is at least relatively straightforward as long as the flow is laminar. The stability theory question is not so straightforward. Until the early 1970's, several important assumptions were commonly made in such calculations, including linear (less than O(1 percent)) perturbations, and locally parallel mean flow. For low-stream and surface disturbance levels (both steady and unsteady) where a high-intensity bypass does not occur, the actual transition process (at least on a flat plate) does have a large (streamwise) linear region with exponential amplification. The question then, in regard to the linear assumption, is how to relate a linear calculation to a nonlinear physical process (transition). The locally parallel flow assumption conventionally consists of two parts, neglect of the transverse (normal to the wall) velocity, and neglect of streamwise derivative terms. Recent calculations at VPI&SU by Saric and Nayfeh (ref. 456) indicate that the parallel flow assumption(s) can easily introduce an error on the order of 20 percent in the computed amplification rate, with the nonparallel being lower for the suction case.

References 457 and 458 provide a useful background in stability theory. Because of the penalty associated with keeping the flow completely stable (below the lower critical Reynolds number), some disturbance amplification should be allowed to occur, but its amplitude must not be allowed to reach a level sufficient to induce catastrophic (transitional) growth. Use of the amplification region of the stability diagrams allows determination of the growth rates required to evaluate whether amplified disturbances remain within bounds. A. M. O. Smith (refs. 6 and 8) was among the first to propose the e^9 or e^n method for two-dimensional flows with and without pressure gradients. The basic approach is to keep the A/A_0 ratio below e^n. Here A is the local disturbance amplitude (for a particular frequency), obtained by integrating the spatial amplification rates, and A_0 is the value at the neutral stability point. This approach has been extended to suction (ref. 459), bodies of revolution (ref. 460), compressible flow (ref. 461, which stresses the crucial influence of external disturbances upon the value of n), and three-dimensional wings (ref. 4). Reference 462 provides a recent evaluation of the e^9 method. Although highly empirical, the e^n approach is generally quite accurate, at least in the absence of large imposed disturbances which can produce a high-intensity or nonlinear bypass. (See ref. 463 for variation of n with stream disturbance level.) One explanation for the success of this approach is that most of the boundary-layer transitional process (at least for the two-dimensional, $dP/dx \simeq 0$ case) is linear, with the nonlinear region being fairly short. This is not the case for a free shear-flow transition region.

References 464 to 473 document stability theory developments of particular interest to LFC. Extensions include (1) axisymmetric geometry (ref. 474), (2) wall cooling or heating (refs. 475 to 479), (3) external turbulence (ref. 480), and (4) surface permeability (refs. 481 and 482). The forthcoming monograph of M. V. Morkovin should be consulted for a detailed exposition of stability theory variants and transition.

Analytical Optimization

Considerable analytical effort went into optimization of natural laminar flow airfoils and bodies (refs. 28 (NACA 6-series), 40, 52, and 483 to 493). The Griffith-profile analytical research (e.g., refs. 483 to 487) sought first to design optimal thick wings and later to compute fixes to the original designs as tests indicated difficulties. Major problems with the Griffith sections included a low critical stream Mach number and instabilities and high pumping losses associated with transitional flow into the suction slots. One design technique for low C_f is to keep the boundary layer close to separation in the pressure recovery region. Because of the sensitivity of laminar flows and transition to adverse dP/dx, this is accomplished most easily with turbulent flows (ref. 489). As stated previously, most of the current natural laminar flow research is focused on small, relatively low-speed aircraft (refs. 42 and 492).

The optimization of suction LFC surfaces, where the airfoil contour and instability growth are considered simultaneously, has not yet received sufficient careful attention. Since the conventional design method (e^n) involves a path integral of the local amplification rate, the problem of determining an optimum suction mass flow distribution using this approach is not unique. Options include (1) performing moderate suction early, followed by maintenance levels, or (2) low levels of suction early, followed by large levels when disturbances begin to build up. The former approach has generally proven to be superior. Besides the determination of an optimum suction level and distribution (currently via trial and error using analysis techniques), gains can probably be made by combining favorable pressure gradients with suction and by taking into account the discrete nature of porous strip and slot suction. References 494 to 500 document various approaches to suction optimization.

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March 26, 1979

NOTATION USED IN TABLE I

AEDC	Arnold Engineering Development Center
ARC	Aeronautical Research Council
ARI	Aeronautical Research Institute, University of Tokyo
ARL	Aeronautical Research Laboratory
A.V.A. Göttingen	Aerodynamische Versuchsanstalt Göttingen
LETS	Low Energy Transportation Systems
MSU	Mississippi State University
NAARI	North American Aviation Rockwell Institute
NBS	National Bureau of Standards
NOTS/ONR	Naval Ordnance Test Station/Office of Naval Research
NPL	National Physical Laboratory
NUC	Naval Undersea Center
ONERA	Office National d'Etudes et de Recherches Aerospatiales
R.A.E.	Royal Aircraft Establishment
T.H.	Technische Hochscule
+++	Pfenninger's path
---	Carmichael's path

TABLE I.- PRINCIPAL INVESTIGATORS

[Arrow indicates continuing interest]

(a) Natural laminar flow wings

	1930	1935	1940	1945	1950	1955	1960	1965	1970	1975
Japan			ARI Tani							
U.S.S.R.		Work on LFC airfoils (referred to by Holstein)						Kozlov		
Germany		A.V.A. Göttingen Holstein Doneis Doetsch	Bussmann			T.H. Stuttgart Riegels → Eppler → Wortmann →		Stuttgart Univ. Althaus →		
United Kingdom		Griffith N.A.V. Miles Cambridge Jones	NPL Piercy Richards → Gregory → Fage → Walker → ARC Goldstein → Smith and Higton → Gray → Pringle → King Cobra Plascott →	NPL Preston → Pearcey → Rogers → (lecture) R.A.E. Hurricane		NPL Pankhurst				
United States		NBS Dryden →	North American Mustang, P-51 NACA Jacobs → Loftin → Abbott →	Von Doenhoff → Braslow →	Ross & Johnson (RJ-5 sailplane)	MSU (Navy) Raspet, Gyorgyfalvy (Phoenix sailplane)			Boeing Co. George-Falvey McDonnell-Douglas Liebeck →	NASA-Langley (ACEE) - (EET) Peterson →
Australia				Dept. of Supply, ARL Keeble → Atkins (GLAS II)	DHG2 glider					
France									Société Bertin et CIE De Lagarde De Loof	
Switzerland			Pfenninger							

TABLE I.- Concluded

(b) LFC with suction

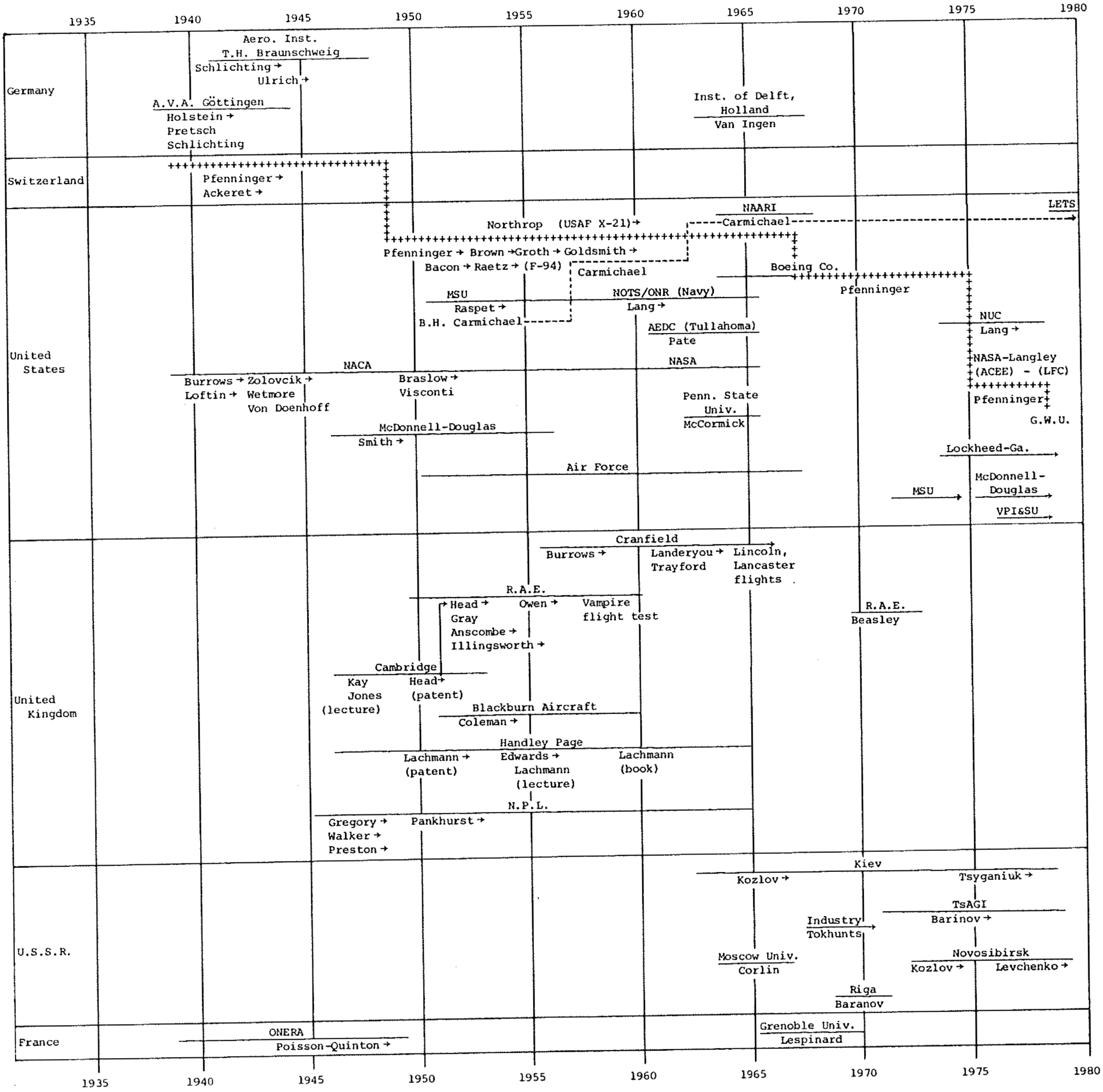


TABLE II.- SUMMARY OF FLIGHT AND LOW DISTURBANCE GROUND TRANSITION

Principal investigator(s)	Reference(s)	Aircraft or tunnel	Configuration	Λ, deg	Suction type	Speed or Reynolds number
(a) Serby, et al.	501	Hawcon aircraft	14% and 25% thick airfoils, gloved	≈ 0 (mean), tapered wing	No suction	≈ 76 m/sec (250 ft/sec), R_c up to 8×10^6
(b) Stephens and Haslam	502	Snark aircraft	17.5% thick airfoil	≈ 0 (mean), tapered wing	No suction	≈ 61 m/sec (200 ft/sec)
(c) Young and Morris	503, 504	Anson aircraft Courier aircraft	Thin glove to 50% chord	≈ 0 (mean), tapered wing	No suction	≈ 55 m/sec (180 ft/sec)
(d) Bicknell	505	Northrop A-17A aircraft	Thin glove, ≈ 2.7-m (9-ft) chord	≈ 0 (mean), tapered wing	No suction	≈ 82 m/sec (270 ft/sec)
(e) Wetmore, et al.	306	Douglas B-18 aircraft	Wing glove outside of slipstream, NACA 35-215 profile	0	No suction	R_c up to 30×10^6
(f) Zalovcik	27	Several aircraft	Eight airfoils	0 (some tapered)	No suction	$4 \times 10^6 < R_c < 30 \times 10^6$
(g) Zalovcik, et al.	53, 506	Douglas B-18 aircraft	Wing glove outside of slipstream, NACA 35-215 profile	0	9 slots and 17 slots	R_c up to 30×10^6
(h) Zalovcik, et al.	507 (XP-47F) 307 (XP-47D)	Republic P-47D, P-47F aircraft	P-47D Republic S-3 airfoil, t/c = 11% to 14.6%, 3 smooth test panels XP-47F NACA 66- and 67-series airfoils, 2 panels	0 (tapered)	No suction	R_c up to 20×10^6 P-47D tests up to M_{crit}.
(i) Smith and Higton	34, 36, 37, 509	King Cobra aircraft	Smooth wing, NACA 662x-116 to NACA 662x-216	0 (tapered)	No suction	R_c up to 18×10^6

[a] Private communication from Nigel Gregory, British Embassy, Washington, D.C.

DATA SUITABLE FOR RELATING STABILITY THEORY AND TRANSITION LOCATION

Disturbance variation	Measurements	Comments, additional information	Results
Waviness varied (not controlled or measured)	Local pitot, profile drag from wake momentum loss, some surface static	14% thick up to 1.7-m (5.7-ft) chord 25% thick up to 2.1-m (7-ft) chord Wing section coordinates given Glove surface stiffened and polished	$x/c \approx$ 0(0.3 up to 0.4)
	Surface pitot, "raised" pitot	Waviness measured (fig. 29 of ref. 502) Data obtained as $f(C_L)$ Local edge velocities given Wing section coordinates given Surface may have distorted under load	For high C_L, transition observed within adverse pressure-gradient region, R_x up to 5×10^6
With and without propeller slipstream (strength varied)	Pitot distribution	Anson - NACA 2218 at root,[a] NACA 2209 at tip Courier - NACA 2219 at root,[a] NACA 2212 at tip Special smooth skin used, up to ≈1.7 m (5.5 ft) from leading edge Surface pressure distribution not given	Transition location given as f(spanwise location) $x/c \approx 0.05$ in slipstream $x/c \approx 0.25$ outside of slipstream
Atmospheric turbulence (no effect noted)	Wake surveys, local pitot static in boundary layer	Profile coordinates given Limited external velocity data C_L varied	Transition occurred at 17.5% chord, in a local adverse pressure-gradient region, independent of C_L
Waviness and propeller noise varied	Surface pressure, velocity profiles, drag	Airfoil coordinates given Waviness measured 5.2-m (17-ft) chord	Transition at $R_c = 26 \times 10^6$ $x/c \approx 42\%$ (engine off, small waviness) $x/c \approx 39\%$ (engine on, small waviness) $x/c \approx 32.5\%$ (factor of 5 larger waviness)
	Profile drag	Summary of several flight studies (various aircraft, wing profiles) Insufficient details given for stability theory application	Natural laminar flow airfoils had 0(27%) lower drag in flight than conventional airfoils
	Suction distribution, velocity profiles	Waviness measured 5.2-m (17-ft) chord Airfoil coordinates given Suction slot details given Surface deteriorated during experiments	Transition moved back from $x/c \approx 0.4$ to $x/c \approx 0.45$ (start of adverse pressure gradient) by slot suction (9 slots) "Over suction" not beneficial
Power setting, with and without propeller slipstream Surface finish (XP-47F)	Limited surface pressure distributions Boundary-layer profiles Wake surveys	2.1-m (7-ft) chord Surface waviness measured S-3 airfoil coordinates given in ref. 508 Airfoil coordinates given for XP-47F	Laminar for x/c up to 20% (in slipstream) XP-47D Laminar for x/c up to 50% (outside of slipstream) Laminar for x/c of 20 to 25% (in slipstream) Outside of slipstream Transition not f(power setting) } XP-47F
Surface waviness, surface finish, flies, dust, water	Wake surveys	1.8-m (6-ft) chord "Filler" used, performed satisfactorily Identified the insect problem Waviness measured	Transition occurred at 60 to 65% chord for low waviness

TABLE II.-

Principal investigator(s)	Reference(s)	Aircraft or tunnel	Configuration	Λ, deg	Suction type	Speed or Reynolds number
(j) Plascott, et al.	34, 36, 37, 510, 511	Hurricane II aircraft	Special low-drag wing, coordinates given in ref. 511	0 (tapered)	No suction	R_c up to 20×10^6
(k) Keeble	512	D.H.G.2 glider	Modified GLAS II wing (Griffith type)	0 (outer portion tapered)	Suction for separation control (Griffith)	Up to 54.9 m/sec (180 ft/sec)
(l) Carmichael and Raspet	285, 513, 514	TG-3A sailplane	NACA 4416 section wing	0	Perforated surface	Up to 37.5 m/sec (123 ft/sec) $2 \times 10^6 \leq R_c \leq 4 \times 10^6$
(m) Head	515	Avron Anson aircraft	15% t/c low-drag airfoil mounted as fin under fuselage	0	Porous surface	R_c up to 3.3×10^6
(n) Head, et al.	67	Vampire aircraft	Upper-surface wing glove	0 (mean, tapered) with leading edge at 11.5°	Porous surface	R_c up to 29×10^6 ($M_\infty \approx 0.7$)
(o) Pfenninger, et al.	313, 314, 516 to 519	F94 aircraft	Upper-surface wing glove	0 (tapered)	Slotted surface (12, 69, and 81 slots)	R_c up to 36×10^6 ($M_\infty \approx 0.726$)
(p) Burrows (later Landeryou and Porter)	520 to 525 (see also 526)	Anson, Lancaster, and later Lincoln aircraft	Dorsal fin mounted on upper fuselage (geometry given in reports)	45, 42.6	No suction initially, later slots	R_c up to 14×10^6, on the order of 91.4 m/sec (300 ft/sec)
(q) Groth	527 (see also 528, 529)	F94 aircraft	Three bodies of revolution, mounted under wing	---	No suction	R_c up to 30×10^6

Continued

Disturbance variation	Measurements	Comments, additional information	Results
Surface waviness	Surface pressure Wake surveys	Waviness measured Limited surface C_p Data available	Transition beyond 50% chord
Flies	Wake surveys Surface pressure Limited boundary-layer profiles	Airfoil coordinates given Waviness measured 2.4-m (8-ft) chord Boundary layer evidently tripped by slot (if not before)	Boundary-layer behavior may be dominated by waviness, slot flow instabilities Transition evidently occurred at x/c of 0.61 up to 0.63 (see fig. 42 of ref. 512, flight 17 results)
Perforation spacing	Transition location with stethoscope Boundary-layer profiles Surface shear	Location/amount of suction varied Well-documented study (ref. 285) 1.5-m (5-ft) chord	Transition location given as f(amount and location of suction) Achieved stabilization in adverse pressure gradient region
Roughness	Boundary-layer profiles Limited surface pressure data Waviness measured Local suction velocity Surface pitot	Airfoil coordinates given Well documented With and without local pressure gradient Approximately 99-cm (39-in.) chord	Suction does not alleviate transition roughness sensitivity Full-chord laminar flow achieved
	Surface pressure Boundary-layer profiles	Approximately 2.4-m (8-ft) chord Airfoil coordinates given Waviness measured Some surface roughness problems	Achieved full-chord laminar flow at R_c up to 29×10^6
Aircraft vibration noise (with and without afterburner) gusty weather, flight maneuvers Roughness and waviness (ref. 517)	Surface pressure Suction distribution Boundary layer measured Electronic stethoscope	2.3-m (7.5-ft) chord "Critical" conditions documented (minimum suction for laminar flow) NACA 65-213 profile (similar to) Some surface pressure information given Surface waviness small Bug contamination not a problem above altitude of 7.6 km (25 000 ft)	No roughness problems up to Reynolds number of 12.1×10^6 per meter (3.7×10^6 per foot) Full-chord laminarization up to $R_c = 36 \times 10^6$
	Surface pitot Boundary-layer profiles	Well documented, an interesting and excellent set of experiments with sweep Essentially three separate studies: (1) Ref. 522; 122-cm (48-in.) chord, unsucked, Anson; (2) Refs. 523 and 527; 218-cm (88-in.) chord, unsucked, Lancaster; (3) Ref. 525; 254-cm (100-in.) chord, tapering to 173 cm (68 in.), slot suction, Lincoln Detailed surface pressure given	Transition location given as $f(R_c, \alpha, \text{span})$
	Boundary-layer profiles	2.4-m (8-ft) length Body coordinates given	$R_x \approx O(6 \times 10^6)$

TABLE II.-

Principal investigator(s)	Reference(s)	Aircraft or tunnel	Configuration	Λ, deg	Suction type	Speed or Reynolds number
(r) Banner, et al.	530, 531	Fighter aircraft	Wing glove, biconvex with $t/c = 3.4\%$ (sharp leading edge) Radius = 0.254 cm (0.1 in.)	27	No suction	$1.2 < M_\infty < 2$
(s) Raspet and Gyorgyfalvy	532	Phoenix sailplane	Eppler (laminar) airfoil	0	No suction	R_c up to 2.8×10^6
(t) Pfenninger and Gault	533 to 537	Ames 12-Foot Pressure Wind Tunnel	NACA 66-012 wing	30	93 spanwise slots	R_c up to 29×10^6, low speed
(u) Boltz, Kenyon, and Allen	538, 539	Ames 12-Foot Pressure Wind Tunnel	Two bodies of revolution, plate, unswept, and swept wings	0, 10, 20, 30, 40, 50	No suction	R_c up to 40×10^6, low speed to $M_\infty \approx 0.47$
(v) Hyde	540	Lancaster aircraft	Swept/tapered wing RAE 102 symmetric section Coordinates given in ref. 541	40 (quarter chord)	No suction	On the order of 91.4 m/sec (300 ft/sec)
(w) Carlson, Pfenninger, and Bacon	317 to 319, 323, 542	Ames 12-Foot Pressure Wind Tunnel (ref. 318) conducted in Norair 7- by 10-foot wind tunnel)	Swept wing, NACA 64016 section	33	Spanwise slots	R_c up to 53×10^6 (low speed)
(x) Stark	93, 94, 122, 543	X-21 aircraft	Swept wing (C_p variation given in fig. 6.1 of ref. 93)	30	Spanwise slots	R_c up to 47×10^6 (transonic)
(y) Zozulya and Cheranovskiy	544	Remotely piloted vehicle	Unswept wing (airfoil may have to be scaled from sketch in fig. 2 of ref. 544)	0	Spanwise slots	40 m/sec (131 ft/sec)

Concluded

Disturbance variation	Measurements	Comments, additional information	Results
Surface finish	Transition location from sublimation and surface gages	Two transition detection methods used Limited, but unique, data	R_x up to 8×10^6 at $M = 2$ on swept wing
	Boundary-layer profiles Surface pressure	Small waviness Airfoil coordinates given 0.97-m (3.2-ft) chord	Transition location given as $f(C_L)$ for both upper and lower surfaces
	Surface pressure Suction distribution Wake surveys Microphones	Contoured end plates used Airfoil coordinates given	Achieved full-chord laminar flow (with suction) at R_c up to 29×10^6
	Surface pressure Microphones (for transition detection) Surface hot wires	Surface waviness measured Transition location f(fan blade angle, sound level in tunnel) NACA 64_2A015 section (unswept and swept wings) Well documented	R_x up to 15×10^6
	Surface pressures Boundary-layer profiles	Chord tapers from 236 cm (93 in.) down to 127 cm (50 in.) Surface pressures tabulated and plotted This is actually another in the Cranfield series and came between refs. 524 and 525	Transition onset in essential agreement with Owen/Randall criteria
Sound environment	Microphone data Surface pressure	3-m (10-ft) chord Slots or surface finish may not be optimized in this experiment Surface pressure has spatial oscillation around $x/c \approx 0.08$	x/c given as $f(R_c)$
Roughness Suction duct noise Wing vibration	Wake drag Microphones Hot film	Detailed knowledge of local suction rates evidently lacking, some estimates available (see p. 42 of ref. 543)	R_x up to 47×10^6
	Free-stream turbulence Suction rates Wake drag Local hot wire	Low Reynolds number Soviet flight experiment Corresponding ground data shown, flight results much better Waviness quoted	Laminar to x/c up to 0.8

TABLE III.- NATURAL LAMINAR FLOW INVESTIGATIONS

[$\Lambda \approx 0$, low speed except as noted]

Principal investigator(s)	Reference(s)	Configuration	Comments	Results
(a) Jacobs	24	Many	A "must-read" classic paper, summary of early NACA work	R_x up to 6×10^6
(b) Frick and McCullough	545	NACA 65,2-016	Conducted in Ames 7- by 10-Foot Wind Tunnel, 2.1-m (7-ft) chord	Heating the surface near pressure minimum destabilized the boundary layer (expected result)
(c) Bussmann	546	Six laminar-flow airfoil sections (maximum thickness of 0.5 to 0.65x/c), one conventional	Early German work, obtained NACA 27215 coordinates from secret French report	Laminar flow sections did much better than conventional ones, but transition Reynolds number low for all configurations (suggesting high stream disturbances)
(d) Richards	244	Griffith profile t/c = 16%	First large-scale Griffith test Waviness measured Conducted in NPL 13 ft by 9 ft wind tunnel	Concave instability identified downstream of suction (separation control) slot
(e) Richards, et al.	547, 548 (Gregory and Walker). (See also 549 for earlier experiments)	30% thick Griffith	Later tests with flap reported in ref. 548 Griffith approach for thicker airfoils, trying mainly for structural advantage Conducted in NPL 13 ft by 9 ft wind tunnel	Single-position suction delayed separation

TABLE III.- Continued

Principal investigator(s)	Reference(s)	Configuration	Comments	Results
(f) Fage and Walker	550	EQH1260 laminar airfoil (maximum t/c at x/c = 0.6)	Calibration tests for NPL 13 ft by 9 ft wind tunnel (only has 4:1 contraction ratio, ref. 551) Waviness measured	Transition occurred near predicted separation point
(g) Preston, et al.	552	16% thick Griffith section	Blowing rather than suction attempted for separation control	Suction scheme deemed better, same c_d requires 7 times as much air for blowing as for suction
(h) Braslow and Visconti	553	NACA $65_{(215)}$-114	δ defined using velocity ratio of 0.707 Tests conducted in Langley low-turbulence pressure tunnel	$R_\delta = 6700$ up to 8000 Tests up to $R_c = 40 \times 10^6$
(i) Several	554 to 560 (ref. 560 has 55.5° sweep)	GLAS II 31.5% thick, Griffith type large suction slot 0.69c	Many problem areas identified, primarily associated with suction and slot systems Many of the studies made to support GLAS II flights (ref. 512) Ref. 560 used holes as well as slots for suction	Tripping boundary layer going into slot greatly helped slot flow efficiency and decreased aerodynamic instabilities
(j) Gregory, et al.	561	30% thick Griffith section	Blowing rather than suction (follow-on to ref. 552)	Factor of three more mass flow required (than for suction) to obtain same c_d (separation control)

TABLE III.- Concluded

Principal investigator(s)	Reference(s)	Configuration	Comments	Results
(k) Preston and Gregory	551	NACA 65.3.018	Tested in NPL 13 ft by 9 ft wind tunnel Curvature measured	Laminar flow obtained beyond minimum pressure point (x/c = 0.45) at $R_c = 9 \times 10^6$
(l) Pearcey and Rogers	562	22% thick Griffith section	Compressibility sensitivity test NPL 20 in. by 8 in. High Speed Tunnel Various slot modifications tried	As might be expected, airfoil and suction system performed poorly near critical conditions
(m) Cumming, et al.	563	13% thick low-drag section (maximum thickness at approximately 0.55x/c)	Used single slot to reestablish laminar flow These are really initial results in a different subject area - relaminarization (see ref. 564)	Could relaminarize in favorable dP/dx, suction of complete turbulent boundary layer required
(n) Gregory, et al.	565	30% thick Griffith section	Porous suction over nose region of Griffith section This is a link between the natural and forced laminar flow studies (both used together)	Distributed suction increased performance of Griffith suction

TABLE IV.- SUBSONIC TUBE EXPERIMENTS WITH SUCTION

[All of these studies were carried out at Northrop under Pfenninger (entry region flow, not developed pipe flow)]

Principal investigator(s)	Reference(s)	Configuration	Comments	Results
(a) Pfenninger	566, 567	5.08-cm (2-in.) diameter tube, 12.2 m (40 ft) long	"Tare" experiments, no suction Sonic throat at end of tube Honeycomb and 13 damping screens ahead of tube	R_x up to 19×10^6 (slightly favorable dP/dx)
(b) Pfenninger	568	Slotted section added to original 5.08-cm (2-in.) diameter tube	Initially had problems with flow characteristics and peculiarities associated with confined flow One suction slot only	Suction through slot destabilized flow without favorable pressure gradient immediately downstream (obtained by reducing tube diameter)
(c) Pfenninger	569	Same as ref. 568, but with all 8 slots functioning		Obtained some pressure recovery in the slot diffusers
(d) Pfenninger and Meyer	570, 571	2.54-cm (1-in.) and 5.08-cm (2-in.) diameter tubes	No suction	R_x up to 53×10^6 with flow acceleration

TABLE IV.- Concluded

Principal investigator(s)	Reference(s)	Configuration	Comments	Results
(e) Goldsmith and Meyer	283, 287, 289, 290, 347, 572	5.08-cm (2-in.) tube with hole suction	Summary for detailed studies of hole suction including effects of adjacent holes (figs. 14 to 17 of ref. 89)	See fig. 13, p. 32 of ref. 89 for critical suction condition (3-D disturbances from hole destabilizing)
(f) Meyer	573	20.32-cm (8-in.) diameter tube	Flow visualization experiments for hole suction	Identified trailing vortices from holes
(g) Pfenninger, et al.	574 to 576	5.08-cm (2-in.) tube with 80 slots		R_x up to 21×10^6 with suction in presence of adverse dP/dx 27% less suction required with 80 slots than with 8 slots

TABLE V.- EXTERNAL FLOW SUBSONIC SUCTION EXPERIMENTS

$[\Lambda \approx 0$, low speed except as noted$]$

Principal investigator(s)	Reference(s)	Configuration	Comments	Results
(a) Holstein	47, 577	15% thick Karman-Trefftzt, rounded edge slots NACA 0012-64 slots Flat plate with perforated surface	Tunnel turbulence not very low Problems with roughness sensitivity ("over suction")	R_x up to 3.2×10^6
(b) Pfenninger	52, 578	Several, including detailed study of several suction slot geometries and a 17% thick laminar airfoil	Tunnel turbulence of O(0.4%) Tried to use sink effect and obtain pressure recovery in slot flow	R_x up to 2.5×10^6
(c) Loftin and Burrows	54	Several including NACA 18-212, 0007-34 and 27-215	Detailed profile measured in vicinity of slot Tunnel turbulence varied from 0.02 to 0.2% Varied slot geometry and external pressure gradient	R_x up to 7×10^6
(d) Braslow, et al.	59, 579	NACA 64A010 Porous (porosity varied between 459 and 579)	Model in ref. 579 had appreciable surface waviness, irregularities	In ref. 59, $R_x > 20 \times 10^6$ Measured velocity profile near porous surface at various suction rates

TABLE V.- Continued

Principal investigator(s)	Reference(s)	Configuration	Comments	Results
(e) Loftin and Horton	580, 581	NACA 66_2-(1.8)15 Slot suction	Extreme roughness sensitivity Surface pressure distributions given Ref. 581 quite detailed	R_x up to 17×10^6
(f) Burrows and Schwartzberg	582	NACA 64A010 Slot suction	Extreme surface roughness sensitivity	R_x up to 10×10^6
(g) A. M. O. Smith	583 to 585	DESA-2 airfoil Slot suction	Hypersensitive to roughness (ref. 583) Tried to use "sink effect" to extend performance	R_x up to 5.8×10^6
(h) Kay	586	Flat plate Porous suction	Detailed boundary-layer measurements Deals mainly with asymptotic suction profile	V_w/U_e up to 0.001 required to stabilize (with existing tunnel and plate disturbances)
(i) Groth and Pfenninger	587 to 589	Axisymmetric fineness ratio 9 Slot suction	Obtained laminarization at up to 3° angle of attack	R_x up to 14×10^6
(j) Pfenninger, et al.	590, 591	12% thick 30° swept wing Slot suction	This wing was later tested in the Ames 12-Foot Pressure Wind Tunnel (refs. 534 and 535) Flow quality quite good in this tunnel (5-ft by 7-ft Michigan wind tunnel)	R_c up to 12×10^6

TABLE V.- Continued

Principal investigator(s)	Reference(s)	Configuration	Comments	Results
(k) A. M. O. Smith	1	Flat plate Porous suction	Obtained laminarization quite easily	R_x up to 8×10^6 with relatively low suction rates
(l) McCormick	592	"Pop up" axisymmetric body tests Slot suction	Water tunnel and sea tests Problems included nonuniform circumferential suction	R_x up to 4×10^6
(m) Gross	593, 594	9:1 fineness ratio body of revolution	12-ft model with 102 slots	R_x up to 20×10^6
(n) Gregory and Love	595	Slender delta wing ($\Lambda = 76^\circ$) Porous suction (upper surface)	Large cross flow Sharp leading edge	Some laminarization achieved
(o) Gross	596	4% thick wing Slot suction (100 slots)		R_x up to 26×10^6

TABLE V.- Concluded

Principal investigator(s)	Reference(s)	Configuration	Comments	Results
(p) Gross	597	Sears-Haack body of revolution Slot suction		R_x up to 20×10^6
(q) Van Ingen	598	15% thick airfoil Porous suction	Detailed data, extensive boundary-layer profiles	R_c up to 9×10^6, transition location in approximate agreement with e^n method
(r) Lespinard	599		Detailed basic study	
(s) George-Falvy	326, 600	30° swept wing Slot suction	Detailed data Surface imperfection study	R_c up to 20×10^6, but suction over first 30% only $\therefore R_x = O(6 \times 10^6)$
(t) Kozlov and Tsyganyuk	601	Body of revolution Porous suction	Water tests	R_x up to 3.5×10^6

TABLE VI.- SUPERSONIC SUCTION EXPERIMENTS

Principal investigator(s)	Reference(s)	Configuration	Comments	Results	
(a) Groth	602, 603	Ogive-cylinder body of revolution Slot suction	M_∞ = 2.5, 3, 3.5 Slots relatively far apart Tested at AEDC	R_x 10.6×10^6 4.7×10^6	M_∞ 2.5 3.5
(b) Groth	604, 605	5% biconvex wing Slot suction	M = 2.23 and 2.77	R_x up to 12.5×10^6	
(c) Groth	606, 607	Ogive-cylinder body of revolution Slot suction	Similar to (a), but with more slots and better suction	R_x 15×10^6 12×10^6 7×10^6	M_∞ 2.5 3.0 3.5
(d) Pate	608	50° swept wing Slot suction (67 slots)	Back of model unswept	R_x 17×10^6 12×10^6 9×10^6	M_∞ 2.5 3.0 3.5

TABLE VI.- Concluded

Principal investigator(s)	Reference(s)	Configuration	Comments	Results
(e) Groth	609 to 611	Flat plate Slot suction (76 slots)		R_x M_∞ 21.8×10^6 2.5 25.7×10^6 3.0 21.4×10^6 3.5
(f) Groth	612 to 614	Flat plate with external shock generator Slot suction (90 slots)	Experiment to determine suction increase required to laminarize through a shock wave	Factor of approximately 2 increase in suction required for weak shocks
(g) Groth	615	36° swept biconvex wing, 3% thick Slot suction		R_x M_∞ 17×10^6 2.5 25×10^6 3.0 20×10^6 3.5
(h) Goldsmith	616	72° swept wing Slot suction	Leading-edge swept behind Mach angle Large sweep angle	Laminarization still possible at extremely high sweep angle

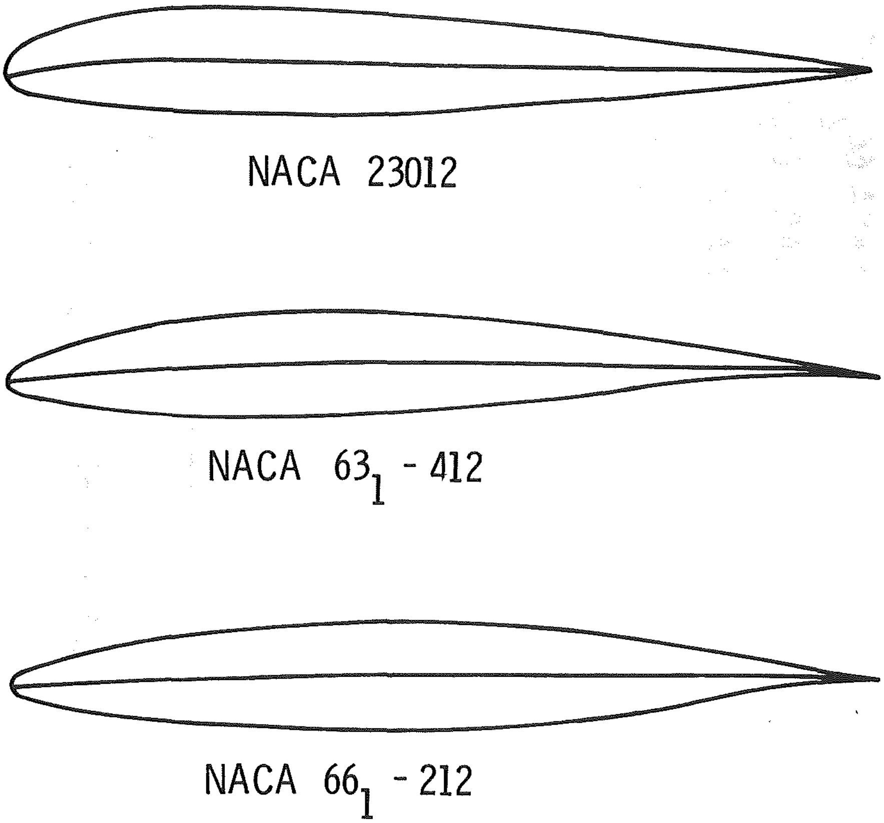


Figure 1.- Comparison of shape of two NACA low-drag airfoil sections with the NACA 23012 airfoil section (from ref. 9).

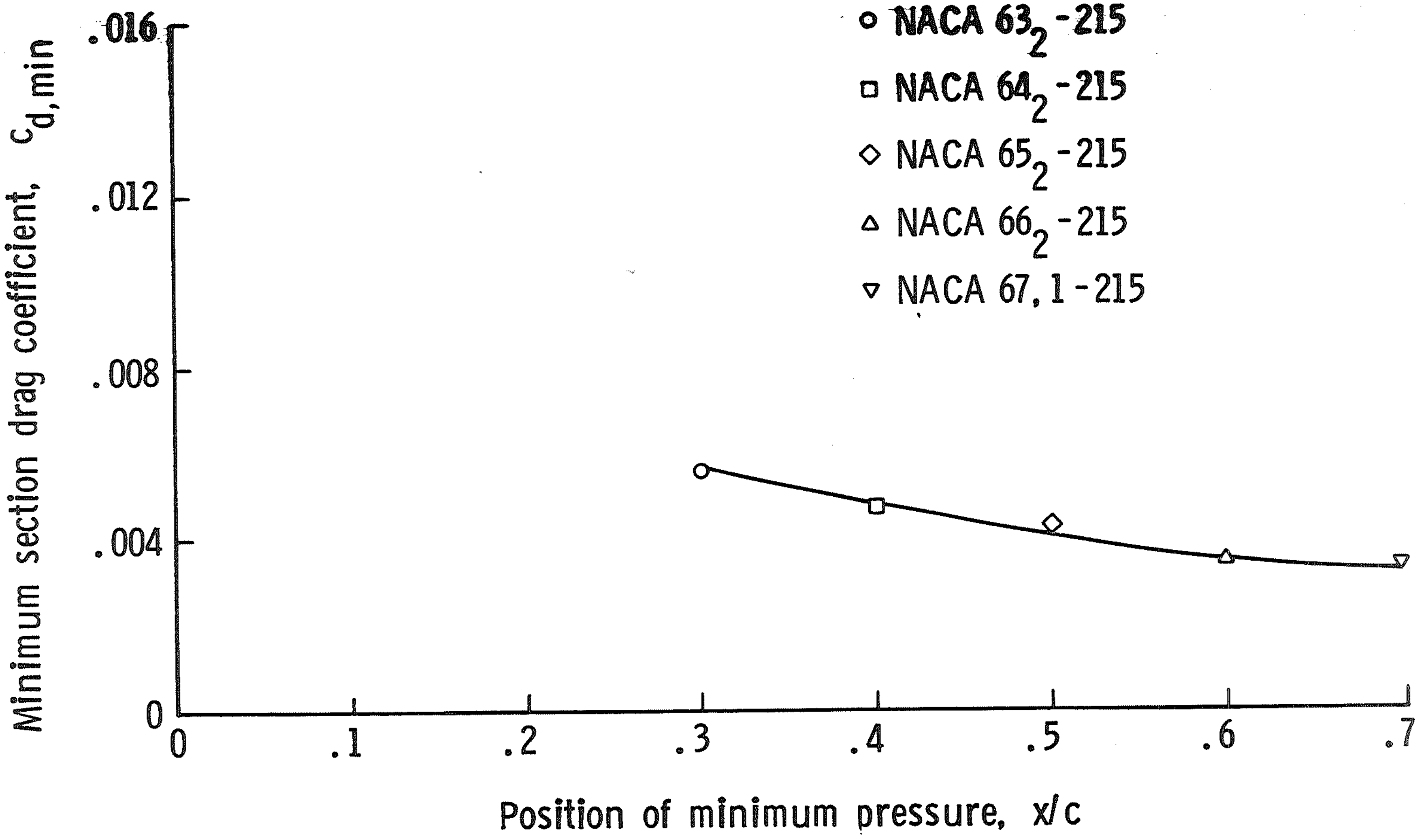
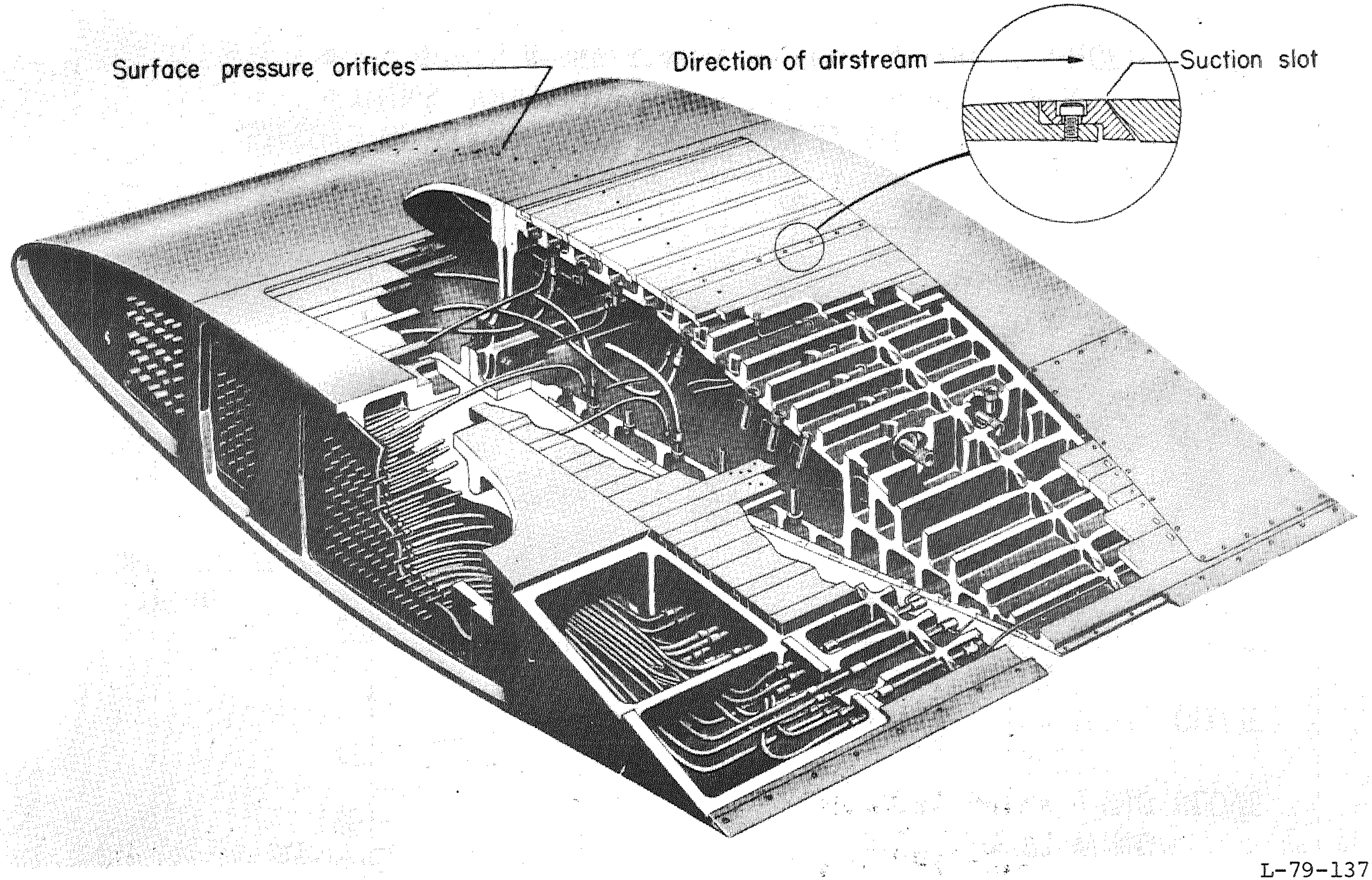
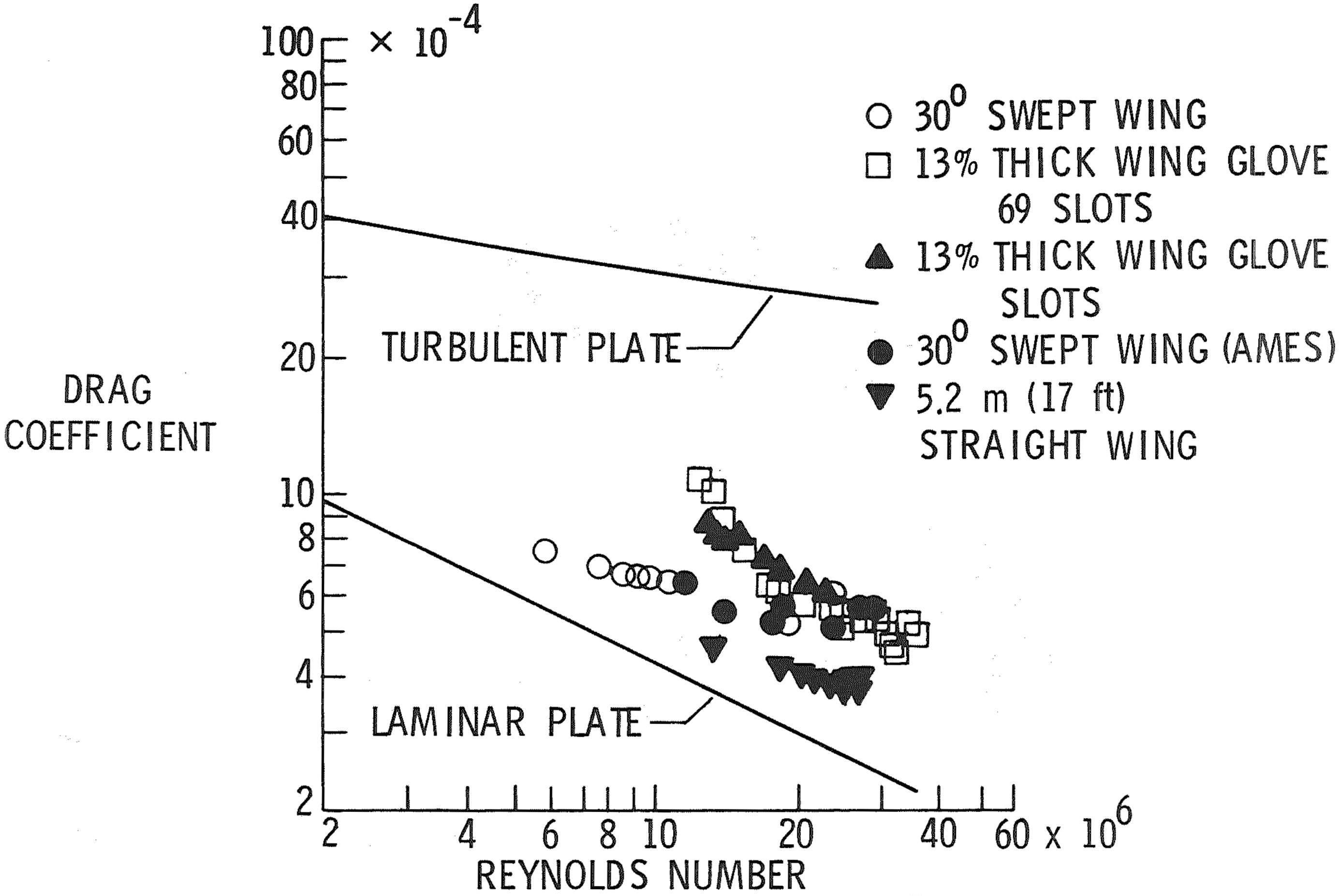


Figure 2.- Variation of minimum section drag coefficient with position of minimum pressure for some NACA 6-series airfoils of the same camber and thickness. $R = 6 \times 10^6$ (from ref. 28).



L-79-137

Figure 3.- Cutaway diagram showing details of boundary-layer suction model (from ref. 580).



EFFECTS OF SUCTION ON BOUNDARY LAYER

- THINS BOUNDARY LAYER-REDUCES EFFECTIVE R
- PRODUCES MORE STABLE (FULLER) VELOCITY PROFILE

Figure 4.- Summary of subsonic LFC results using surface suction (from ref. 81).

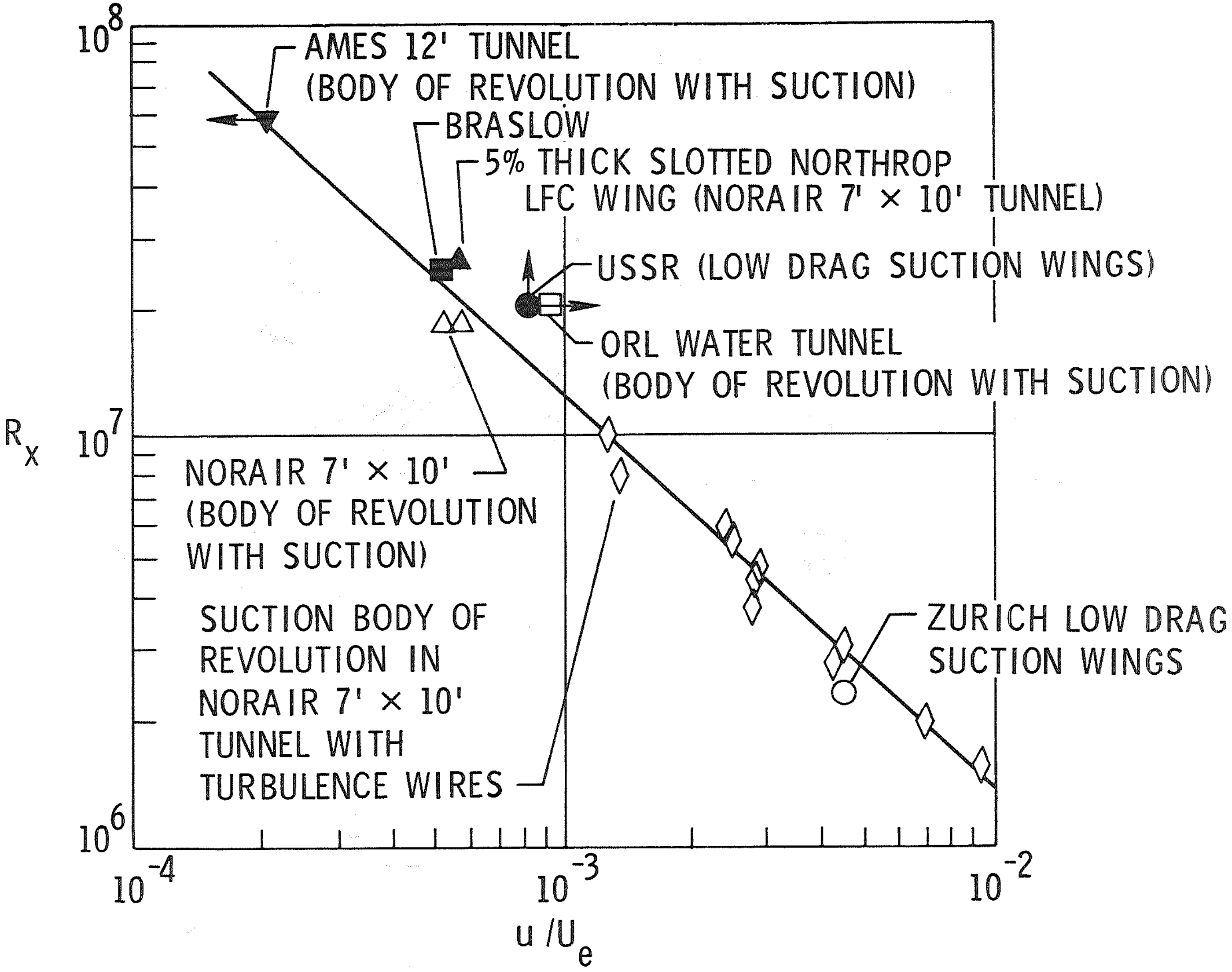


Figure 5.- Maximum length Reynolds number R_x with full laminar flow versus u/U_e for low-drag suction wings and bodies of revolution (from ref. 5).

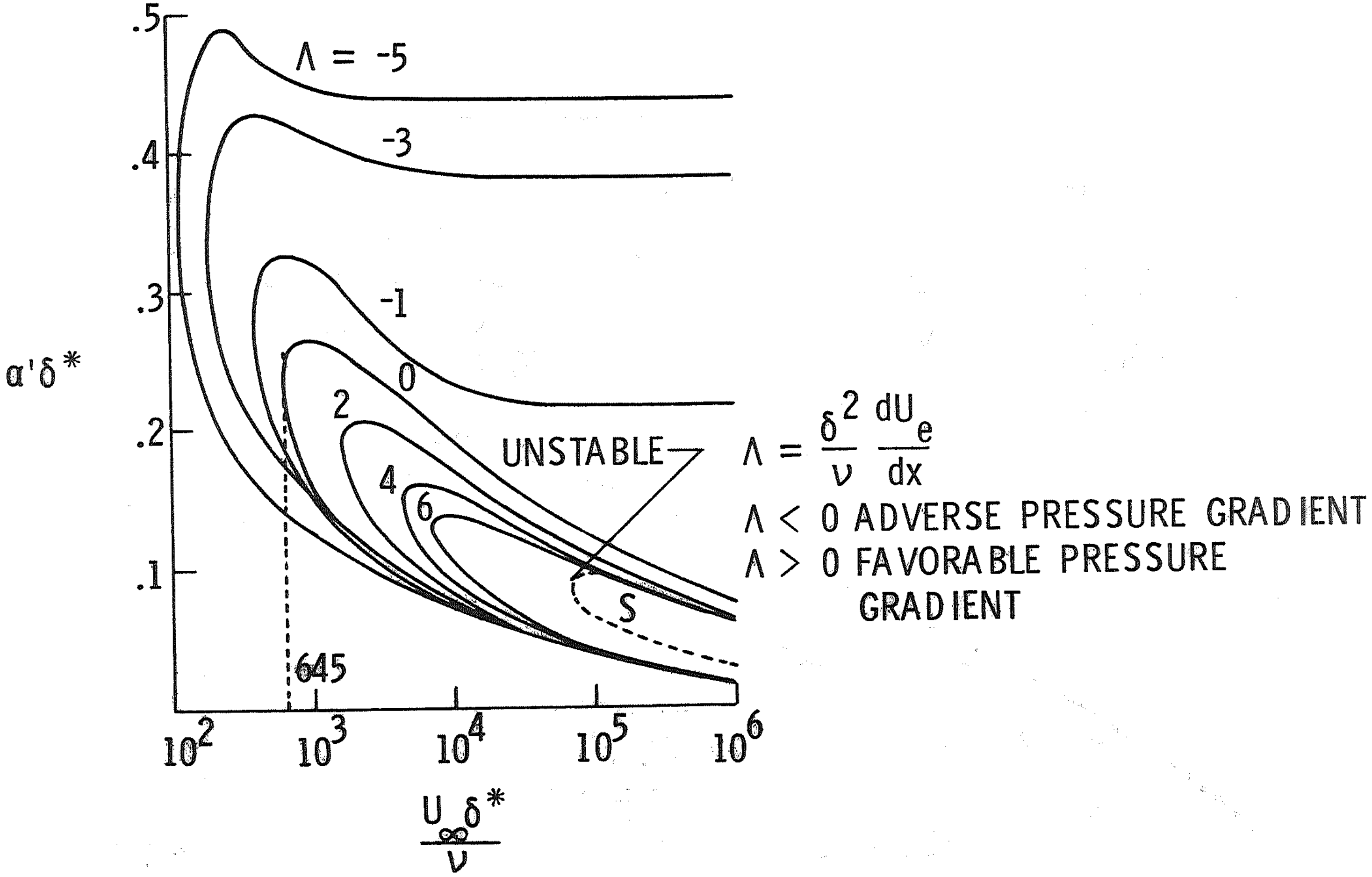


Figure 6.- Effect of pressure gradient on boundary-layer stability characteristics (from ref. 2, paper 1).

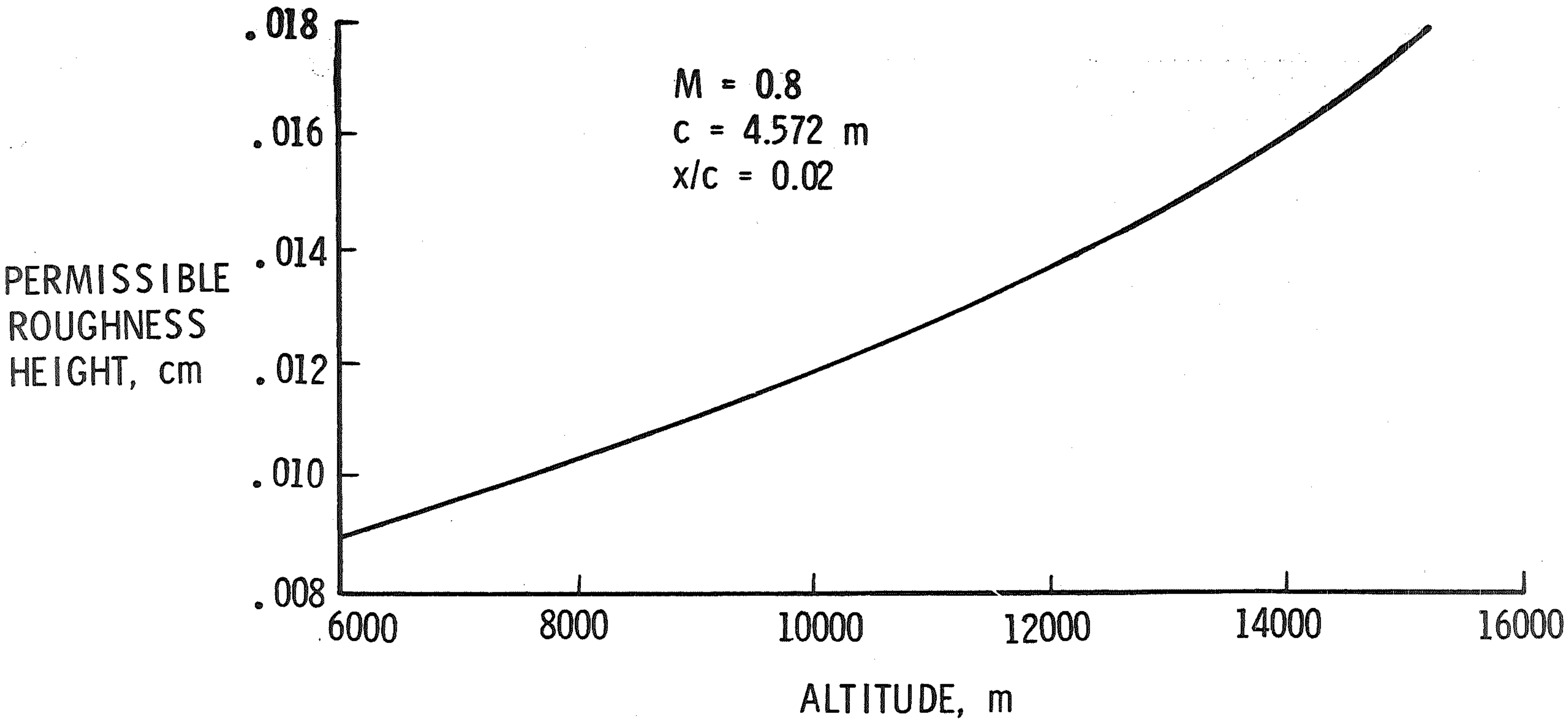


Figure 7.- Permissible three-dimensional roughness height as a function of altitude (from ref. 73).

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The items in this reference list and bibliography are arranged in the order in which they are discussed in the survey; information given includes not only title and author, but also abstract and detailed document source and location information. References contained in the reference lists of the included documents are not necessarily repeated in this bibliography.

Abstracts from the NASA announcement publications Scientific and Technical Aerospace Reports (STAR) and International Aerospace Abstracts (IAA) have been used when available. Many author's abstracts or summaries have also been used. Some of these have been shortened by including only certain paragraphs or sentences considered of interest to the subject of this bibliography.

Availability of journal articles, books, and other open literature has not been included as this type of material is available at many libraries or may be secured through interlibrary loan. Significant and identifying information on the material other than open literature has been given in order to facilitate access. This information, which includes call numbers from the various cataloging systems, should be included when requesting documents from a library or other facility. Addresses for these facilities are as follows:

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NTIS - National Technical Information Service
5285 Port Royal Road
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STIF - NASA Scientific and Technical Information Facility
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Consult the following example for information on how to locate the source of a document.

Example

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NACA- documents	

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Example:

167. Pfenninger, W.; and Bacon, John W., Jr.: Note About the Range Performance of Future Long Range Low Drag Suction Airplanes With Partially Supersonic Range. Summary of Laminar Boundary Layer Control Research, WADC Tech. Rep. 56-111, Apr. 1957, pp. 339-351. (Available from DDC as AD 130 759.)

Availability: N78-75293; CN-56122; N78-76390; N-53889; AD 130 759.

BIBLIOGRAPHY

1. Smith, A. M. O.; and Clutter, D. W.: Studies and Experiments in Drag Reduction by Boundary Layer Control. Rep. No. ES 26354 (Contract No. NOas 54-773-c), Douglas Aircraft Co., Inc., July 31, 1956.

Various wind tunnel studies were made of methods of obtaining drag reduction. The experiments were performed in the Douglas El Segundo Wind Tunnel on a large model designed to give large extents of laminar flow. The natural x-Reynolds number of transition for the model varied from 2.0×10^6 to 7.2×10^6 depending on model position and tunnel speed. The model could be modified for a variety of experiments.

A study was made of the use of a plastic veneer as a means for producing a smooth surface and for fairing out discontinuities such as joints, rivet heads, screw head dimples, etc. Experiments were performed on the extension of laminar flow by sucking through strips of perforations. The experiments confirmed the design criteria given by the British up to a Reynolds number of 10^6 per foot.

Attempts were made to artificially thicken the boundary layer at the leading edge of the model to reduce the sensitivity of the boundary-layer flow to surface roughness. Experiments were performed to learn whether an acoustic absorbing device, a Helmholtz resonator, would damp boundary-layer disturbances. An experiment was designed to study the effect of chord-wise surface corrugations on disturbances in the boundary layer.

Experiments with distributed suction through a porous plate, extending almost the full chord of the model, allowed transition Reynolds numbers up to 8×10^6 to be obtained with a minimum of effort in keeping the surface finish smooth or the surface fairings within small tolerances.

A study was also made of a possible method of reducing the drag of a turbulent flow by boundary layer control. Wake drag and total drag were measured with various distributions of suction, blowing, and combined suction and blowing through the porous surface of the model. The results indicate that no combination of suction and blowing is feasible for reducing the drag of turbulent flow.
Author

Availability:
N78-78051
N-56745

2. Special Course on Concepts for Drag Reduction. AGARD-R-654, June 1977.

The results of aerodynamic research and development in aircraft design to reduce drag, boundary layer control, and optimization of gas turbine intake system are evaluated in relation with fuel consumption. The following papers are included in this document:

Hefner, Jerry N.; and Bushnell, D. M.: An Overview of Concepts for Aircraft Drag Reduction.

Whitcomb, R. T.: Methods for Reducing Subsonic Drag Due to Lift.

Pfenninger, Werner: Laminar Flow Control Laminarization.

Edwards, Brian: Laminar Flow Control - Concepts, Experiences, Speculations.

Cary, A. M., Jr.; Bushnell, D. M.; and Hefner, J. N.: Slot Injection for Skin-Friction Drag Reduction.

Adkins, R. C.: Diffusers and Their Performance Improvement by Means of Boundary Layer Control.

Zimmermann, G.: Drag Reduction by Compliant Walls: Theory.

Dinkelacker, A.: On the Problem of Drag Reduction by Means of Compliant Walls.

Bushnell, Dennis M.; Hefner, Jerry N.; and Ash, Robert L.: Effect of Compliant Wall Motion on Turbulent Boundary Layers.

Availability:
N77-32091

3. Aircraft Fuel Conservation Technology - Task Force Report. OAST, NASA, Sept. 10, 1975. (Available as NASA TM X-74295.)

The Task Force developed the final technical program plan, which is the body of this report. A background of the fuel shortage as it pertains to the airline industry is presented. The proposed NASA Aircraft Fuel Conservation Technology Program is then described, including technical content, development schedules and resource requirements. In the final section, an estimate is made of the potential fuel savings associated with the implementation of the different technologies. The suggested program for development of Laminar Flow Control is described on pages 68-78. A practical system could possibly be demonstrated by 1985, and an LFC aircraft might be introduced into service by 1990.

Availability:
N77-11055

4. Srokowski, A. J.: Mass Flow Requirements for LFC Wing Design. AIAA Paper 77-1222, Aug. 1977.

The problem of determining optimum suction mass flow requirements for LFC wings is addressed. Some previous methods for predicting the extent of laminar flow over swept wings with suction are briefly reviewed. These range from the purely empirical to those utilizing tabulated linear stability computations. The present method is described. This method solves the linear, incompressible stability equations by spectral techniques. The maximum temporal amplification of boundary layer crossflow and 2-D disturbances is determined for waves of a given frequency. Group velocities are used to integrate these amplification rates along the wing to yield the logarithmic amplitude ratio or 'N factor' of the disturbance. The 'N factor' calibration of a computer code utilizing this method is described, using experimentally determined transition data. The method is shown to be as consistent as previously used 'fixed wavelength' methods.

Author

Availability:
A77-44323

5. Pfenninger, Werner: Laminar Flow Control Laminarization. Special Course on Concepts for Drag Reduction, AGARD-R-654, June 1977, pp. 3-1 - 3-75.

A practical aerodynamically and structurally reasonably efficient laminar flow control (LFC) suction method, removing the slowest boundary layer particles through many closed spaced fine slots, was developed and subsequently applied to a second F94 LFC wing glove in flight: 100 percent laminar flow was observed up to the F94 test limit. Laminar flow on LFC wings in flight is thus possible at a much higher Reynolds number than even in the best low turbulence tunnels as a result of the negligible influence of the atmospheric microscale turbulence on transition. The F94 LFC glove comparison experiments, with suction starting at 0.03c and 0.4c, verified the theoretically predicted boundary layer stabilization by suction starting at 0.08c, thus maintaining laminar flow at substantially higher C sub L numbers as compared to boundary layer stabilization by flow acceleration; i.e., geometry alone without suction upstream of 0.4c.

Author

Availability:
N77-32094

6. Smith, A. M. O.; and Gamberoni, Nathalie: Transition, Pressure Gradient and Stability Theory. Rep. No. ES 26388, Douglas Aircraft Co., Inc., Aug. 31, 1956. (Also available in IX Congrès International de Mécanique Appliquée, Tome IV, Université de Bruxelles, 1957, pp. 234-244.)

This presents a method of predicting transition that is founded upon the theory of boundary-layer stability. It considers both plane and axially symmetric flows of a very low-turbulence incompressible stream past very smooth bodies. According to stability theory, self-energized disturbances form in the boundary layer and slowly grow in strength while moving downstream, until they ultimately cause the boundary layer to become turbulent, by a process as yet unknown. J. Pretsch has computed a family of charts by means of which the apparent growth of these waves can be calculated so that correlation with experiment becomes possible. The theory and its implications are reviewed and discussed. Nearly all the applicable experimental transition data have been studied and correlated with the calculations made with the aid of Pretsch's charts. A strong relation of experimental results with this theory was discovered. In fact, to first order, Tollmien-Schlichting waves were found to undergo an apparent amplification ratio $\exp \int \beta_i \, dt$ equal to about e^9 by the time transition began. This value was then used to predict transition for a considerable variety of flows, both in wind tunnels and in flight. The predictions agree quite well with experiment. In contrast, $R_{\delta*}$ or R_θ at the beginning of transition vary greatly with pressure gradient and are not at all suitable alone as fundamental guides for locating transition. As a measure of transition on bodies of revolution $R_{\delta*}$ is even less satisfactory than it is for two-dimensional flows. However, the method based on stability theory correlates both types of flow with equal accuracy. A short-cut empirical method of predicting transition, due to Michel, has been studied.

Author

Availability:
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N78-78048

7. Dryden, Hugh L.: Recent Advances in the Mechanics of Boundary Layer Flow. Volume I of Advances in Applied Mechanics, Richard von Mises and Theodore von Kármán, eds., Academic Press, Inc., 1948, pp. 1-40.

This paper summarizes and references some of the more important papers published since 1936 that contribute to a better understanding of the mechanics of boundary layer flow. Most of the work cited relates to incompressible flow although references are given to such papers as are available on compressible flow.

CONTENTS

8. Jaffe, N. A.; Okamura, T. T.; and Smith, A. M. O.: Determination of Spatial Amplification Factors and Their Application to Predicting Transition. AIAA J., vol. 8, no. 2, Feb. 1970, pp. 301-308.

A method for applying stability theory to the problem of prediction transition is described. The Orr-Sommerfeld equation is employed to perform a stability analysis on laminar boundary-layer velocity profiles that have been obtained numerically for two-dimensional and axisymmetric flows. An orthogonalization technique capable of handling Reynolds numbers, based on displacement thickness, up to at least the order of 10^5 is used to obtain spatial amplification rates of small disturbances over a select frequency band at various streamwise locations. For each of the frequencies considered, the amplification rate is integrated with respect to surface distance downstream from the point of neutral stability in order to obtain an amplification factor. The disturbance whose frequency produces a maximum amplification factor at transition is considered for correlation purposes.

Author

Availability:
A70-23219

9. Loftin, Laurence K., Jr.: Development of Airfoils and High-Lift Devices. NACA-Industry Conference on Personal Aircraft Research - A Compilation of the Papers Presented by NACA Staff Members. NASA, Sept. 20, 1946, pp. 47-50.

During the course of the war years, a new type of airfoil section, known as the NACA low-drag or 6-series section, was developed at the Langley Laboratory. Low-drag airfoils differ from the older NACA 4- and 5-digit series airfoils, such as the NACA 2412 and 23012, in that they were theoretically derived by potential-flow methods to have pressure distributions of a type permitting extensive laminar flow in the boundary layer and thus very low profile-drag coefficients. A comparison of an NACA 23012 with two of the newer low-drag airfoil sections is shown in figure 1. Two low-drag sections, the NACA 63_1-412 and the NACA 66_1-212, are designed to permit laminar flow over the airfoil surfaces to 30- and 60-percent chord, respectively.

In order to provide the airplane designer with systematic aerodynamic data from which to choose low-drag airfoils suitable for different applications, a series of approximately 100 related low-drag airfoils was derived and tested in a specialized two-dimensional wind tunnel permitting the attainment of full-scale Reynolds numbers and having a turbulence level approaching that of free air. The lift, drag, and pitching-moment characteristics of all the airfoils were obtained at Reynolds numbers of 3, 6, and 9 million, and, in addition, tests were made with each airfoil to determine the effect upon the aerodynamic characteristics of surface roughness.

An idea of the drag characteristics of these newer airfoil sections may be obtained from figure 2 which shows drag results for a typical low-drag airfoil section (63_1-412) of 12-percent thickness and 0.4 design lift coefficient.

Author

Availability:
N66-81716

10. NACA Conference on Boundary Layers - A Compilation of the Papers Presented. NASA, Aug. 14, 1947.

This document contains reproductions of technical papers on some of the recent research results on boundary layers from the NACA Laboratories and under the sponsorship of the NACA at the National Bureau of Standards and the California Institute of Technology. These papers were presented at the NACA conference held at the Langley Memorial Aeronautical Laboratory August 14, 1947. The purpose of this conference was to convey to those involved in the study of aircraft and aerodynamic problems these recent research results and to provide those attending an opportunity for discussion of the results and of the work planned for the future.

The papers in this document are in the same form in which they were presented at the conference so that distribution of them might be prompt. The original presentation and this record are considered as complementary to, rather than as substitutes for, the Committee's system of complete and final reports.

A list of the conferees is included (from the Introduction).

(This document is included in this collection because of historical interest and to make this bibliography more complete.)

Availability:
N78-78047

11. Gazley, Carl, Jr.: Boundary-Layer Stability and Transition in Subsonic and Supersonic Flow. A Review of Available Information With New Data in the Supersonic Range. 1952 Heat Transfer and Fluid Mechanics Institute, Stanford Univ. Press, June 1952, pp. 73-93. (Also available in J. Aeronaut. Sci., vol. 20, no. 1, Jan. 1953, pp. 19-28.)

This paper presents the available data in subsonic and supersonic flow for the effects of free-stream turbulence, surface curvature, pressure gradient, surface roughness, surface temperature, and Mach number on the transition position. New supersonic data are included from rocket flights, firing-range tests, and wind-tunnel tests. The effects of the several variables on transition are compared with the theoretically predicted effects on boundary-layer stability.

In general the experimental data for transition confirm the trends indicated by the stability theory. Perhaps the most significant deviation from the trend expected from the stability theory is the relative insensitivity of supersonic transition to surface-temperature variation. The transition Reynolds-number range appears to increase with increasing Mach number in both firing-range tests where relatively low surface temperatures occur and in wind-tunnel tests where relatively high surface temperatures occur.

Author

Availability:
N78-78202
N-24166

12. Schubauer, G. B.; and Skramstad, H. K.: Laminar-Boundary-Layer Oscillations and Transition on a Flat Plate. NACA Rep. 909, 1948.

This is an account of an investigation in which oscillations were discovered in the laminar boundary layer along a flat plate. These oscillations were found during the course of an experiment in which transition from laminar to turbulent flow was being studied on the plate as the turbulence in the wind stream was being reduced to unusually low values by means of damping screens. The first part of the paper deals with experimental methods and apparatus, measurements of turbulence and sound, and studies of transition. A description is then given of the manner in which oscillations were discovered and how they were found to be related to transition, and then how controlled oscillations were produced and studied in detail. The oscillations are shown to be the velocity variations accompanying a wave motion in the boundary layer, this wave motion having all the characteristics predicted by a stability theory based on the exponential growth of small disturbances. A review of this theory is given. The work is thus experimental confirmation of a mathematical theory of stability which had been in the process of development for a period of approximately 40 years, mainly by German investigators.

Author

13. Morkovin, M. V.: Transition From Laminar to Turbulent Shear Flow - A Review of Some Recent Advances in Its Understanding. Trans. ASME, vol. 80, no. 5, July 1958, pp. 1121-1128.

Recent experimental studies of transition from laminar to turbulent shear flows are reviewed. Certain common features are emphasized and related to the stability theories of viscous shear layers. The 3-dimensional character, the unsteadiness, and the nonlinear and random behavior of the latter stages of the transition process are also examined.

Author

Availability:
N-64069

14. Dryden, H. L.: Transition From Laminar to Turbulent Flow. Turbulent Flows and Heat Transfer, C. C. Lin, ed., Princeton Univ. Press, 1959, pp. 3-74.

Transition at low subsonic speeds is discussed in Articles 2 through 23. Articles 24, 25, and 26 deal with transition at supersonic speed. This is an excellent review with much data in chart form.

15. Shaw, T. E.: A Brief Review of Boundary Layer Transition. AET Memo No. 197 (Contract No. AF 04 (647)-269), General Electric Co., 1961. (Available from DDC as AD 350 225.)

A brief review is made of the state-of-the-art of boundary layer transition. To date, no reliable theoretical or empirical prediction technique exists for the prediction of boundary layer transition for practical engineering problems, particularly those involving high speed flight. In the absence of

other disturbances, it was found that transition aft of two- and three-dimensional roughness appeared to be reasonably well correlated as a function of the half power of the roughness Reynolds number. Experimental data on transition, involving the effect of boundary layer cooling on laminar flow stability, was found to be quite contradictory. The strongest evidence that boundary layer stability is unaffected by extreme cooling was obtained from Mach 2 heat sink flight tests. The effect of ablation on boundary layer transition was deduced from RVX-1 and Mark 3 flight tests in which it was found that a Reynolds number of transition of 150,000 represented a reasonable criteria.
Author

Availability:
N74-74848
AD 350 225

16. Bridge, J. F.: A Summary of Parameters Influencing Boundary Layer Transition. Doc. No. D2-22052, Boeing Airplane Co., 1963. (Available from DDC as AD 444 658.)

Availability:
X65-80325
AD 444 658

17. Braslow, Albert L.: A Review of Factors Affecting Boundary-Layer Transition. NASA TN D-3384, 1966.

A brief review is made of the current state of the art of boundary-layer transition. Discussed, in various degrees of detail, are experimentally determined effects on transition of pressure gradients, surface to free-stream temperature ratio, free-stream Mach number, free-stream turbulence, noise, two- and three-dimensional-type surface roughness, and laminar boundary-layer control through suction. Certain aspects of the theoretical approach to transition are discussed and some comparisons with experiment are made. The review is intended primarily for the engineer or scientist desiring a general understanding of boundary-layer transition phenomena rather than for the active researcher in the field of fluid mechanics. Some needs for further research are indicated.
Author

Availability:
N66-32940

18. Morkovin, Mark V.: Critical Evaluation of Transition From Laminar to Turbulent Shear Layers With Emphasis on Hypersonically Traveling Bodies. AFFDL-TR-68-149, U.S. Air Force, Mar. 1969. (Available from DDC as AD 686 178.)

The review report represents an attempt to evaluate critically the available data on high-speed boundary layer transition to turbulence and to interpret the apparent agreements and contradictions within some rational framework. Special attention was paid to the more documentable discrepancies between reported results as touchstones of conceptual models and instability theories.

Experiments with microscopic information are used as backbone of conceptual models, both linear and nonlinear. Linear instability results are used as a point of departure for the examination of current controversial questions of transition reversal with cooling, unit Reynolds number effect, effect of aerodynamic noise in supersonic wind tunnels, etc.

Author

Availability:
N69-31309
AD 686 178

19. Tani, Itiro: Boundary Layer Transition. Annual Review of Fluid Mechanics, Volume I, William R. Sears and Milton Van Dyke, eds., Annual Rev., Inc., 1969, pp. 169-196.

Review of current interpretations of the fundamental mechanism involved in the transition from laminar to turbulent flow in a boundary layer. Supersonic and hypersonic flow regimes are considered, with emphasis on the low-speed regime. Boundary-layer transition on a flat plate without a pressure gradient is considered, and the effects of pressure gradient, surface curvature, freestream turbulence, and surface roughness are discussed. Three-dimensional boundary layers are examined, as well as unsteady boundary layers. Transition at high speeds is considered, and methods for predicting boundary-layer transition are reviewed.

Availability:
A69-34920

20. Hairston, David E.: Survey and Evaluation of Current Boundary Layer Transition Prediction Techniques. AIAA Paper No. 71-985, Oct. 1971.

A survey has been conducted of current literature on prediction of laminar boundary layer transition. Techniques based on empirical formulations as well as those founded on Schlichting-Tollmien stability criterion have been investigated. Based on correlations of published results, Bennett's semi-empirical procedure and Deem's fully-empirical technique have been incorporated into a boundary layer analysis computer program. Transition has been predicted for several airfoil cases in which the location of transition has been experimentally observed. These studies indicate that the chosen prediction techniques are limited to specific freestream Mach number ranges.

Author

Availability:
A71-44581

21. Berkowitz, A. M.; Kyriss, C. L.; and Martellucci, A.: Boundary Layer Transition Flight Test Observations. AIAA Paper 77-125, Jan. 1977.

A historical review regarding the evolution of flight test boundary layer transition correlations in connection with the development of operational ballistic reentry vehicles in the U.S. is presented, taking into account the time periods from 1956 to 1961, from 1961 to 1971, and from 1971 to the present time. Questions of transition data evaluation are discussed, taking into account transition data selection criteria, angle of attack effects, vehicle geometry characteristics, on-board sensors, redundant transition altitude sensors, vehicle classifications, and aspects of local flow property determination. A correlation evaluation is also conducted, giving attention to the ground test, the flight test, wall cooling effects, nose related parameters, and bluntness correlations.

Availability:
A77-22231

22. Reshotko, Eli: Boundary-Layer Stability and Transition. Annual Review of Fluid Mechanics, Volume 8, Milton Van Dyke, Walter G. Vincenti, and J. V. Wehausen, eds., Annual Rev., Inc., 1969, pp. 311-349.

The use of normal-modes procedures for the study of boundary layers is examined, taking into account aspects of formulation, the parallel-flow assumption, the form of disturbance, and the properties of the disturbance equations. A description is presented of the results of normal-modes calculations. Nonparallel-flow effects are considered along with flat-plate boundary layers in air and water and the effect of surface curvature. An investigation of receptivity is conducted. Receptivity denotes the means by which a particular forced disturbance enters the boundary layer. Attention is given to the prediction of transition and the directions of current and future investigations.

Availability:
A76-20822

23. Jones, B. Melvill: Flight Experiments on the Boundary Layer. J. Aeronaut. Sci., vol. 5, no. 3, Jan. 1938, pp. 81-101. (Also available as The Boundary Layer in Flight, Aircr. Eng., vol. X, no. 111, May 1938, pp. 135-141.)

The title of the lecture is Flight Experiments on the Boundary Layer and it deals more specifically with the transition of the layer from the laminar to the turbulent form.

The material from which the lecture has been constructed is drawn mainly from experiments made in flight at Cambridge, but in order to make it as complete as possible, results from Government Research Establishments with which we work in close cooperation are quoted.

This is the experimental evidence so far available in England upon the position of the point where turbulence begins in the boundary layer of smooth wings in flight. It shows conclusively that it is possible to retain a laminar layer over at least one-third of the whole wing surface, even when the Reynolds Number is as high as eight millions. Experiments are now being made at Farnborough to carry observations of this kind up to larger Reynolds Numbers, but conclusive results are not to hand at the time of writing. Drag experiments which have been already made at high Reynolds Numbers by the pitot-traverse method suggest, however, that though the points of transition may move forward somewhat at the higher numbers, they certainly do not move right forward to the leading edge and the laminar form of the boundary layer can still be retained over a considerable proportion of the wing surface.

It remains to consider in rather more detail the circumstances in which transition occurred in the experiments which have been described, in order to see whether any light can be thrown upon the factors which influence it.

Author

24. Jacobs, Eastman N.: Preliminary Report on Laminar-Flow Airfoils and New Methods Adopted for Airfoil and Boundary-Layer Investigations. NACA WR L-345, 1939. (Formerly NACA ACR.)

Recent developments in airfoil-testing methods and fundamental air-flow investigations, as applied to airfoils at the N.A.C.A. laboratory, are discussed. Preliminary test results, obtained under conditions relatively free from stream turbulence and other disturbances, are presented. Suitable airfoils and airfoil-design principles were developed to take advantage of the unusually extensive laminar-boundary layers that may be maintained under the improved testing conditions.

For practical consideration, these preliminary results presented are of interest mainly in the lower Reynolds Number range below 6,000,000. Within this Reynolds Number range the new laminar-flow airfoils and the new airfoil-design principles may be expected to yield drag coefficients on actual wings of a markedly smaller order than those heretofore obtained. For example, drag coefficients as low as 0.0022 and profile L/D values as high as 290 were measured.

Author

Availability:
N78-78514

25. Jacobs, Eastman N.: Immediate Use of New Airfoil Sections of the Laminar-Flow Type. NACA WR L-521, 1940. (Formerly NACA MR.)

In view of the work that had been done on laminar airfoils and the possibilities for drag reduction at high Reynolds Numbers, it was recommended that the new experimental military aircraft try out the new low-drag airfoils.

Availability:
N78-78210

26. Young, A. D.: Notes on the Aerodynamic Properties of Low Drag Wing Sections. Tech. Note No. Aero. 1019, British R.A.E., Sept. 1942.

This report summarises the available information on the general aerodynamic properties of low drag wing sections. It includes discussions of their drag, lift, pitching moment, aileron control and stalling characteristics and the effect of flaps. It is concluded that the use of low drag aerofoils of thickness between 15% and 20% involves no serious disadvantages as compared with conventional aerofoils. A detailed list of conclusions is given.

Author

Availability:
N78-78791

27. Zalovcik, John A.: Profile-Drag Coefficients of Conventional and Low-Drag Airfoils as Obtained in Flight. NACA WR L-139, 1944. (Formerly NACA ACR L4E31.)

The results of flight investigations of the profile drag of several carefully finished conventional and low-drag airfoils are presented. The results indicated that in all cases lower profile-drag coefficients were obtained with the low-drag than with the conventional airfoils over the range of lift coefficient tested and that, for comparable conditions of lift coefficient and Reynolds number, the low-drag airfoils may have profile-drag coefficients which are at least 27 percent lower than the profile-drag coefficients of the conventional airfoils.

Author

Availability:
N78-78515

28. Abbott, Ira H.; Von Doenhoff, Albert E.; and Stivers, Louis S., Jr.: Summary of Airfoil Data. NACA Rep. 824, 1945.

Recent airfoil data for both flight and wind-tunnel tests have been collected and correlated insofar as possible. The flight data consist largely of drag measurements made by the wake-survey method. Most of the data on airfoil section characteristics were obtained in the Langley two-dimensional low-turbulence pressure tunnel. Detail data necessary for the application of NACA 6-series airfoils to wing design are presented in supplementary figures, together with recent data for the NACA 00-, 14-, 24-, 44-, and 230-series airfoils. The general methods used to derive the basic thickness forms for NACA 6- and 7-series airfoils and their corresponding pressure distributions are presented. Data and methods are given for rapidly obtaining the approximate pressure distributions for NACA four-digit, five-digit, 6-, and 7-series airfoils.

The report includes an analysis of the lift, drag, pitching-moment, and critical-speed characteristics of the airfoils, together with a discussion of the effects of surface conditions. Data on high-lift devices are presented. Problems associated with lateral-control devices, leading-edge air intakes, and interference are briefly discussed. The data indicate that the effects of surface condition on the lift and drag characteristics are at least as large as the effects of the airfoil shape and must be considered in airfoil selection and the prediction of wing characteristics. Airfoils permitting extensive laminar flow, such as the NACA 6-series airfoils, have much lower drag coefficients at high speed and cruising lift coefficients than earlier types of airfoils if, and only if, the wing surfaces are sufficiently smooth and fair. The NACA 6-series airfoils also have favorable critical-speed characteristics and do not appear to present unusual problems associated with the application of high-lift and lateral-control devices.

Author

29. MacDonald, George C.: Interrogation of Prof. Schlichting on Laminar-Flow Wings - Development in Germany, Luftfahrtforschungsanstalt (C.I.O.S., Target No. 25/71). Tech. Intell. Rep. No. I-49, U.S. Strategic Air Forces in Europe, June 30, 1945.

Toward the latter part of 1938, Dr. Lewis of NACA visited in Germany. He gave a "clue" on the subject of laminar-flow wings which was immediately taken up by the Germans. Some of their foremost aerodynamicists worked on the subject. This short document lists the contributions made by some of them during the period 1938-1945.

Availability:
N78-78197

30. Schlichting, H.: Der Umschlag laminar/turbulent und das Widerstandsproblem des Tragflügels. Forschungsbericht Nr. 1410, Deutsche Luftfahrtforschung (Braunschweig), 1941.

Availability:
N78-78046

31. Relf, Ernest F.: Recent Aerodynamic Developments. J. R. Aeronaut. Soc., vol. 50, June 1946, pp. 421-449.

A brief history of the "Laminar-Flow" story includes discussion of Goldstein's family of laminar flow airfoils, the Piercy airfoil, and the early British wind tunnel and flight laminar flow experiments. The early British attempts at using suction began with Dr. A. A. Griffith. This was followed by Dr. Goldstein's work at N.P.L. The nature of the new ideas is indicated and the bearing they may have on the future of aviation is discussed.

32. Von Karman, Theodore: Where We Stand. Headquarters Air Material Command, May 1946, pp. 42-47.

This is a brief review of German development of laminar flow wings and boundary layer control. A comparison is made with the United States progress in laminar flow.

Availability:
N78-78041

33. Tani, Itiro: On the Design of Airfoils in Which the Transition of the Boundary Layer is Delayed. NACA TM 1351, 1952.

A method is presented for designing suitable thickness distributions and mean camber lines for airfoils permitting extensive chordwise laminar flow. Wind tunnel and flight tests confirming the existence of laminar flow; possible maintenance of laminar flow by area suction; and the effects of wind tunnel turbulence and surface roughness on the promotion of premature boundary-layer transition are discussed. In addition, estimates of profile drag and scale effect on maximum lift of the derived airfoils are made.

Author

Availability:
N78-78516

34. Goldstein, Sydney: Low-Drag and Suction Airfoils. J. Aeronaut. Sci., vol. 15, no. 4, Apr. 1948, pp. 189-220.

This is largely the story of the researches carried out in Great Britain arising from an idea due to Dr. A. A. Griffith. This idea is at once very general and very simple. When, at a sufficiently high Reynolds number, a fluid flows along an immersed solid surface, a boundary layer is formed; if the flow in the boundary layer cannot be controlled, harmful results may follow; the boundary layer may be removed by suction in an attempt to avoid these harmful results. Griffith's idea was that if boundary-layer suction is to be applied, the shape of the solid surface should be specially designed. It is the application of this idea to airfoil design which forms the main subject of this lecture and it may be as well to stress that this does not include a discussion of the effects of suction on conventional airfoil shapes, or on any shapes not specially designed for the purpose; such a discussion should really be separate, since the amount of common ground is not large.

A short discussion is included of the principles of the ordinary laminar-flow or low-drag wing, and of the present position with regard to obtaining laminar boundary layers in flight.

The work described in this lecture was all carried out in the Aerodynamics Division of the National Physical Laboratory or at the Royal Aircraft Establishment. Two series of flight tests on laminar flow airfoils carried out at the R.A.E. are described and results discussed. One was on a King Cobra (Bell P.63) and the other on a Hawker Hurricane II.

Author

35. Keeble, T. S.: Development in Australia of a Thick Suction Wing. Third Anglo-American Aeronautical Conference, Joan Bradbrooke and E. C. Pike, eds., R. Aeronaut. Soc., 1952, pp. 45-76J.

At the time of the inaugural meeting of the British Commonwealth Advisory Aeronautical Research Council in 1946, a number of Griffith aerofoils had been designed covering a wide range of cambers, maximum lift coefficients and thickness/chord ratios. Several had been tested in wind tunnels with promising results.

At this meeting it was decided that the time had arrived for a group within the Commonwealth to undertake development to the flight stage of one of these suction aerofoils in order to appreciate the engineering problems involved in building and flying wings of this type, and to see how far the theoretical advantages of the suction aerofoil could be realised in practice. This project was undertaken by the Australian Aeronautical Research Laboratories with the assistance of the Government Aircraft Factory and the Royal Australian Air Force.

This paper describes the wind tunnel development of the aerofoil, the related boundary layer study, the glider and its flight tests. An account is then given of recent wind tunnel research to eliminate the undesirable characteristics found in flight on the GLAS II wing; and finally a preliminary design study has been made of a medium-sized all-wing air liner and a proposal is outlined for a half-scale glider for initial development of this design.

Author

Availability:
N78-78061
N-15966

36. Davies, Handel: Some Aspects of Flight Research. J. R. Aeronaut. Soc., vol. 55, June 1951, pp. 325-361.

An attempt is made to give a representative picture by discussing some typical examples of developments in flight research under three main headings:

1. Work concerned directly with reducing the drag of aircraft.

2. Research on stability and control problems.

3. General aerodynamic research.

In order to cover as wide a field as possible the emphasis will be on the results obtained in this work rather than on detailed descriptions of the experimental techniques involved.

One of the main contributions which flight research can make towards improving the performance of aircraft is to measure the speed and the drag of aircraft in flight, to analyse the sources of this drag and to explore methods of reducing it. Perhaps the best example of this aspect of flight research is provided by the work done at the Royal Aircraft Establishment to investigate boundary layer effects on aircraft and in particular, to determine the conditions under which extensive areas of laminar flow can be achieved in flight. This work will be discussed in some detail. Data from tests on the King Cobra, AW-52, Hurricane, Meteor III, Vampire, and others are included and discussed.

Author

37. Richards, E. J.: A Review of Aerodynamic Cleanness. J. R. Aeronaut. Soc., vol. 54, Mar. 1950, pp. 137-186.

An attempt is made to analyse the overall gains that have been attained in aerodynamic cleanness in the past, to review the overall performance improvement that can be expected in the immediate future from increased cleanness along orthodox lines, and to survey critically certain more advanced concepts aimed at giving still lower drag coefficients and better performance characteristics. It is realised that all these advances can only be achieved by the attainments of the structural designer, and the purpose of the paper will be more than fulfilled if the aerodynamicists among us get a better idea of what is worth urging, and if the structural experts obtain from it a better idea of what they can expect to gain in achieving the improved cleanness urged upon them.

The survey confines itself to large transport aircraft where admittedly the general shape may well be affected by compressibility considerations, but which fly below their critical Mach Numbers and depend for their efficiency on the reduction to a minimum of their normal, sub-critical drag.

Author

38. Pankhurst, R. C.: N.P.L. Aerofoil Catalogue and Bibliography. R. & M. No. 3311, British A.R.C., 1963.

This report catalogs airfoils which have been designed (or substantially modified) at the N.P.L., and which have been the subject of theoretical investigations, aircraft design studies, or wind-tunnel tests. A full bibliography is included.

Author

Availability:
N63-16797

39. Nonweiler, T.: The Design of Wing Sections. Aircr. Eng., vol. XXVIII, no. 329, July 1956, pp. 216-227.

This is a very complete and detailed discussion of the manner in which airfoils have been designed. The emphasis is on NACA and British airfoils.

40. Eppler, R. (Francesca Heffgen, transl.): Laminar Airfoils for Reynolds Numbers Greater Than 4×10^6. B-819-35, Boeing Co., Apr. 1969.

Laminar airfoils, which means airfoils with the highest possible drag gain by laminar boundary layers without suction, have been examined thoroughly in the region of smaller Re numbers. It is time to report on the gains possible in the region above Re = 4×10^6. The NACA airfoils which are now over 20 years old, are considered as a point of departure. We proceed at first purely theoretically, in a way which has already been successful for smaller Re numbers. It could be seen that keeping a boundary layer laminar is not so difficult in the region of smaller Re numbers if one builds precision wings. The most difficult problem lies here in avoiding laminar separations and so-called local separation bubbles. In the Re number region under discussion this problem does practically not play any role at all and any measurements with Re = 4×10^6, where such "bubbles" would have had any effect, are not known to the author had there not been very sudden and very steep pressure increases. These however, are not appropriate for reasons of flight characteristics. The boundary layer transition is here of the utmost importance. A reliable transition criterion is therefore of considerable importance for a theoretical treatment.

Author

Availability:
N69-28178

41. Nonweiler, T. R. F.: A New Series of Low-Drag Aerofoils. R. & M. No. 3618, British A.R.C., 1971.

A series of low drag aerofoils, modelled roughly on the NACA 6-series, is described. It appears to offer theoretical advantages over its progenitor, and allows flexibility in the choice of leading-edge thickness and trailing-edge angle. Aerofoils of this series are specified by five parameters, and the aerodynamic and geometrical characteristics of about 1000 of the sections are listed. The mathematical derivation of their shape (by the Lighthill method) is described in detail, and an ALGOL 60 procedure for the computation of their ordinates is included; care has been taken to construct this procedure so that it may be of general use in other applications of the Lighthill method of design.

Author

Availability:
N71-24498

42. De Lagarde, B.; and De Loof, J. P.: Étude et Essais de Profils Laminaires. L'Aeronautique et L'Astronautique, no. 32, Aug. 1971, pp. 29-39.

Definition of conditions for the utilization of modern gliders, with development of ideal aerodynamic characteristics of the airfoils to be conceived. The study consists of the development of programs making it possible to calculate the pole of a given airfoil so as to determine the profile function of speed distribution, and then to study the distribution of favorable pressures leading to optimized airfoils. Wind tunnel tests on selected models make it possible to complete the family of airfoils to be proposed to constructors.

Availability:
A72-17194

43. Wortmann, F. X.: A Critical Review of the Physical Aspects of Airfoil Design at Low Mach Numbers. Motorless Flight Research, 1972, James L. Nash-Webber, ed., NASA CR-2315, 1973, pp. 179-196.

Airfoil design is always a matter of more or less direct boundary layer control. To accomplish this goal we obviously need airfoil and boundary layer theory, the availability of computers and programs, and, finally, a suitable wind tunnel, as tools.

It has been the purpose of this paper to show that another quality is equally indispensable: imagination which enables one to carve out of the physical aspects of the problem an advanced airfoil. However, the physical aspects are transparent enough to state that we cannot expect a breakthrough. This is especially true for the low-cambered, low angle of attack airfoil. Any advances are slow and hard to achieve as one approaches the physical limits. There exist, however, numerous details in the "airfoil and boundary layer" field where our present knowledge is open to further refinements, and this raises the hope that further advanced airfoil design may also be possible in the future.

The NACA 64_1-012 airfoil is compared with some FX-airfoils.

Author

Availability:
N74-10051

44. Carmichael, B. H.: Application of Sailplane and Low-Drag Underwater Vehicle Technology to the Long-Endurance Drone Problem. AIAA Paper No. 74-1036, Sept. 1974.

Theoretical and experimental contributions to the science of drag reduction through extensive laminar flow are reviewed. Airfoils with high L/D and high L to the 3/2 power/D at a Reynolds number of 1 million are described. The very low drag coefficients of five laminar fuselages are compared with typical turbulent values. A scheme is revealed to eliminate wing-fuselage intersection drag and to avoid turbulent wedges in the intersections. Solutions to practical laminar aircraft problems such as surface roughness, waviness, insect contamination, atmospheric turbulence, noise, and vibration are presented. A drone aircraft of outstanding performance, based on the above accumulated technology, is described.

Author

Availability:
A74-42050

45. Althaus, D.: Stuttgarter Profilkatalog I. Inst. Aerodyn. & Gasdyn., Univ. Stuttgart, 1972.

The "Stuttgarter Profilkatalog I" is a summary of the data for 36 airfoils which are divided in groups:

Cambered airfoils
Airfoils with flaps
Symmetrical airfoils with flaps and special airfoils (airfoils with variable chord)

For each airfoil the coordinates, the shape, the theoretical velocity distribution, and the experimental data for several Reynolds numbers are given.

Some special measurements are also provided:

Measurements on an airfoil with modified flap and high flap deflection
Measurements on two airfoils with various arrangements of airbrakes
Measurements on airfoils with brake-flaps

For comparison with NACA results, measurements on some NACA airfoils are listed too.

The text of the catalog is written in German, but a short introduction in English is included.

Author

Availability:
Copies of this catalog must be ordered directly from the Universität Stuttgart.

46. Wortmann, F. X.: Einige Laminarprofile für Segelflugzeuge. OSTIV Publ. VII, 1963.

Availability:
N78-78474
CN-128,199, 1963

47. Holstein, H.: Experiments on the Influence of Boundary Layers. Rep. & Transl. No. 1005, M.A.P. Völkenrode, Apr. 1, 1948.

The first two parts deal with the means applied to keep the flow laminar along the greatest possible length. These means are the shape of the body and the removal of the boundary layer by suction. The third part discusses the sensitivity of the laminar boundary layer to disturbances on the surface of the body.

Availability:
N78-78473

48. Pankhurst, R. C.: Recent British Work on Methods of Boundary-Layer Control. Boundary Layer Effects in Aerodynamics, Philosophical Library, 1955, pp. 6 P.1 - 6 P.39; Discussion, pp. D.6 P.1 - D.6 P.7.

The state of development of suction aerofoils in 1948 was described by Prof. Goldstein in the Wright Brothers lecture for that year. The present paper gives an account of subsequent British investigations of boundary-layer suction and other methods of boundary-layer control. The purpose of the present paper is to trace how the emphasis has gradually shifted since then, and also to indicate the progress which has been made in other applications of suction and in other forms of boundary-layer control, such as air jets and vortex generators. In order to narrow the field, the discussion will be restricted almost entirely to British work. The material is best sub-divided into

(a) maintenance of laminar flow by suction through slots or porous surfaces;

(b) improvement of stalling behaviour by suction through slots or porous surfaces, or by blowing through slots; and

(c) other methods of boundary-layer control than suction or blowing as usually understood.

Both in Britain and elsewhere a great deal of wind-tunnel data on boundary-layer control by suction and blowing has now been accumulated. Although further flight tests are needed, the stage has been reached at which practical applications to full-scale aircraft should be feasible with a minimum of further wind-tunnel testing, the most pressing problems now being engineering and structural rather than aerodynamic.

The bibliography contains 105 references.

Author

Availability:
N78-78200
N-42403

49. Miles, F. G.: Sucking Away the Boundary Layer. Flight, vol. XXXV, no. 1570, Jan. 26, 1939, pp. 82b-82d.

After experimenting with boundary-layer control and performing the first flight tests with suction, the author of this article comes to the conclusion that suction is superior to blowing. Mr. Miles describes the experiments and results obtained and concludes that boundary-layer control may be worthwhile and suggests that further research be done.

50. Holstein: Ueber Reibungsschichtabsaugung zur Laminarhaltung der Reibungsschicht, Insbesondere an Parallelangestroemten Ebenen Platten. TPA 3/TIB Transl. No. GDC 10/1301 T, British Min. Supply, Dec. 15, 1941.

From the model tests made in the AVA it has been found that by the removal by suction of the friction layer it is possible to produce a rearward displacement of the transition point in the friction layer of a body immersed in a flow. Suction off from the friction layer has thus become a means of reducing friction drag.

It is therefore of interest to obtain further information as to the behaviour of the laminar friction layer when suction is applied, to know the balance between the reduction in drag, and the increase in output required to drive the suction blower in specific cases, to know how this balance varies with variation in the Reynolds Number, and to clarify other similar questions.

Although the fundamental equations required for this purpose have been derived in part in their general form, the examples calculated have been limited to the case of the two dimensional plate exposed to a parallel incident flow, since for this case, due to the absence of any pressure gradient, the calculations are somewhat less complicated.

The variation in the pressure distribution due to sink effect when suction is applied could then always be neglected as being very small.

Author

Availability:
N78-78198

51. Pfenninger, W.: Laminar Flow Airfoils With Boundary Layer Suction. Interavia, vol. II, Mar. 1947, pp. 42-46.

This is a general discussion of work done on 'laminar flow airfoils.' Both theoretical and experimental work is included. Data from several experiments on suction slots for increasing the laminar flow on airfoils are shown and interpreted. It is concluded that the suction wing need not be much heavier than the conventional type.

52. Pfenninger, Werner: Investigations on Reductions of Friction on Wings, in Particular by Means of Boundary-Layer Suction. NACA TM 1181, 1947.

The present report, begun in 1940, deals with the reduction of frictional drag by maintaining a more extended laminar boundary layer, particularly with the aid of boundary-layer suction. The first chapters treat publications in this field, the causes of the boundary-layer transition and a few laminar profiles without boundary-layer suction. Next, tests with laminar suction profiles are described. The behavior of the suction slots for laminar boundary-layer suction was separately examined.

The aim of the tests described here was to keep the boundary layer completely laminar up to the trailing edge of the wing.

Author

Availability:
N78-78517

53. Von Doenhoff, A. E.; and Loftin, L. K., Jr.: Extension of Laminar Boundary Layers by Boundary-Layer Control. NACA Conference on Boundary Layers - A Compilation of the Papers Presented, NASA, 1947, pp. 35-44.

Early NACA work on laminar flow control is briefly summarized. The first tests of laminar airfoils were done in 1938 in the 2-dimensional low-turbulence tunnel. The experimental work on suction slots is described and problems are discussed. It was found that control of the laminar boundary layer by suction slots was effective in delaying transition in a region of adverse pressure gradient, but such conclusive evidence was not reached to show the laminar flow region could be extended under favorable pressure gradient. Power requirements for operation of the suction slots were investigated. Flight tests were made to determine the extent of laminar flow obtainable; and some work on distributed suction was in the planning stage.

Availability:
N78-78047

54. Loftin, Laurence K., Jr.; and Burrows, Dale L.: Investigations Relating to the Extension of Laminar Flow by Means of Boundary-Layer Suction Through Slots. NACA TN 1961, 1949.

Wind-tunnel investigations have been made of suction through slots as a means of increasing the extent of laminar flow on several airfoil sections. The extent of laminar flow was increased in some cases by as much as 52 percent of the chord with a small expenditure of suction power at Reynolds numbers as high as 7.0×10^6. A method is presented for determining an efficient suction slot arrangement for any arbitrary airfoil section operating at a given free-stream Reynolds number.

Author

Availability:
N78-78518

55. Smith, A. M. O.: A Proposed General and Flight Test Investigation of Laminar Boundary Layer Control Using a Perforated Surface. Rep. No. ES 17516, Douglas Aircraft Co., Inc., Mar. 26, 1954.

A three-phase attack on the problems of laminar boundary layer control is proposed. The investigation will be confined to the study and testing of perforated material as a means of boundary layer control. Emphasis in the work will be on the developmental, operational and manufacturing aspects of the problem. Since all past investigations have shown that roughness and dirt are the greatest single source of trouble, major efforts and thought will be applied to find a remedy for the difficulty. The investigation will be divided into three phases as follows: Phase I. General study of the overall problems and economy of laminar boundary layer control. Wind tunnel tests as necessary to supply design data for the perforated material and for exploring means to desensitize the flow to roughness. Phase II. Guided by the information produced by the Phase I study, design, build and flight test, an unswept large chord, practical construction glove wing, for the purpose of learning the performance and problems in actual flight. Phase III. If Phase I and II warrant, design a complete wing for an aircraft to be chosen near the completion of Phase II.

Author

Availability:
N78-78044
N-54686

56. Von Doenhoff, A. E.; and Loftin, L. K., Jr.: Present Status of Research on Boundary-Layer Control. J. Aeronaut. Sci., vol. 16, no. 12, Dec. 1949, pp. 729-740, 760.

The present status of research on boundary-layer control and its possible applications in aeronautics is surveyed. Although the number of possible applications of boundary-layer control is large, only those that have received the most attention recently or show the most promise of producing useful results are considered in the present paper. The possible applications of boundary-layer control considered are:

(1) Reduction of profile drag by the elimination of turbulent separation and by increasing the relative extent of laminar flow.

(2) Increase of the maximum lift coefficient through control of laminar and turbulent separation.

(3) The use of suction and blowing slots near the trailing edge of an airfoil as a means of lateral control.

(4) The use of boundary-layer control as a means of increasing the efficiency of diffusers and bends.

(5) The use of boundary-layer control to influence shock boundary-layer interaction at high speed.

The possible improvements in airplane characteristics resulting from these applications of boundary-layer control are discussed, and the general lines of future research are indicated.

Author

57. Jones, Melvill; and Head, M. R.: The Reduction of Drag by Distributed Suction. Third Anglo-American Aeronautical Conference, Joan Bradbrooke and E. C. Pike, eds., R. Aeronaut. Soc., 1952, pp. 199-230L.

The paper consists of three parts. The first is intended only for those readers who are not familiar with the underlying theory; it contains a brief discussion of the causes of transition to turbulence in the boundary layer both in the absence and in the presence of distributed suction. The second and main part describes and discusses the Cambridge experiments and compares their results with those obtained at Langley Field. The third part contains a tentative estimate of what the equivalent profile drag might be for an ideal aeroplane on which it is supposed that, by distributed suction, laminar flow is maintained over its entire surface.

Author

Availability:
N79-71456
N-15966

58. Lachmann, G. V.: Boundary Layer Control. J. R. Aeronaut. Soc., vol. 59, no. 531, Mar. 1955, pp. 163-198.

Part I is concerned with boundary layer and circulation control through blowing and sucking. A review is given of developments along this line in various countries. General take-off and landing considerations are discussed. Part II gives the history of work on laminarization through boundary layer control. Effects of surface roughness and other factors on laminar boundary layer stability are considered. Methods of propulsion and performance for laminarized aircraft are discussed. A large bibliography is appended.

59. Braslow, Albert L.; Burrows, Dale L.; Tetervin, Neal; and Visconti, Fioravante: Experimental and Theoretical Studies of Area Suction for the Control of the Laminar Boundary Layer on an NACA 64A010 Airfoil. NACA Rep. 1025, 1951. (Supersedes TN 1905 by Burrows, Braslow, and Tetervin and NACA TN 2112 by Braslow and Visconti.)

A low-turbulence wind-tunnel investigation was made of an NACA 64A010 airfoil having a porous surface to determine the reduction in section total-drag coefficient that might be obtained at large Reynolds numbers by the use of suction to produce continuous inflow through the surface of the airfoil (area suction). In addition to the experimental investigation, a related theoretical analysis was made to provide a basis of comparison for the test results.

Full-chord laminar flow was maintained by application of area suction up to a Reynolds number of approximately 20×10^6. At this Reynolds number, combined wake and suction drags of the order of 38 percent of the drag for a smooth and fair NACA 64A010 airfoil without boundary-layer control were obtained. The minimum experimental values of suction-flow coefficient for full-chord laminar flow were of the same order of magnitude as the theoretical values and decreased with an increase in Reynolds number in the same manner as the theoretical values. It seems likely from the results that attainment of full-chord laminar flow by means of continuous suction through a porous surface will not be precluded by a further increase in Reynolds number provided that the airfoil surfaces are maintained sufficiently smooth and fair and provided that outflow of air through the surface is prevented.

Although area suction was able to overcome the destabilizing effects of an adverse pressure gradient such as that which occurs over the rear portion of an airfoil, area suction does not appear to stabilize the boundary layer completely for relatively large disturbances such as those which might be caused by protuberances that have a height comparable to the boundary-layer thickness.

Author

60. Perkins, Courtland D.; and Hazen, David C.: Some Recent Advances in Boundary Layer and Circulation Control. Fourth Anglo-American Aeronautical Conference, Joan Bradbrooke and E. C. Pike, eds., R. Aeronaut. Soc., 1954, pp. 189-224N.

A brief description of boundary layer control systems utilising blowing slots, suction slots or porous material is given. The differences between such systems which are primarily designed to give control over separation and hence low drag, and those systems using blowing or suction over flaps or employing trailing edge suction slots to change the circulation, and hence the lift at a given angle of attack, are pointed out.

A discussion of an experimental investigation conducted by the State College of Mississippi utilising a sailplane to examine the effects of distributed suction on the stabilisation of the laminar boundary layer is presented. It is shown that by tailoring the porosity of the surface, so that just sufficient suction is applied to maintain the laminar boundary layer without excessive thinning, the lowest total drag (aerodynamic plus suction power required) can be obtained.

To demonstrate the difference between boundary layer control and circulation control, the results of an experimental and theoretical programme conducted by Princeton University investigating the possibilities of trailing edge suction slots is reported. The importance of the location of the trailing edge stagnation point is discussed and a theoretical technique for predicting the aerodynamic characteristics of a profile equipped with such a slot is presented and compared with experimental results.

The use of a "snow cornice" type shape, in which it is possible to entrap a vortex either automatically or by means of suction, is reported. Certain applications to wind tunnels and wings which have given promising results are discussed. It is felt that this use of the trapped vortex represents a major advance and that considerable increases of efficiency in all subsonic expansion problems may be possible by utilising this principle.

Author

Availability:
N78-78199
N-34639

61. May, Ralph W., Jr.: NACA Wing Boundary-Layer Control Research. Paper presented at Boundary-Layer Control Symposium (White Oaks, Maryland), June 24, 1953.

The objectives, scope, and significant results of NACA research in the field of boundary-layer control are discussed in general terms, with particular emphasis on the recent and current research. Only those phases of boundary-layer control research concerned with extending laminar flow on wings and improving airplane landing or take-off characteristics are considered.

Author

Availability:
N78-78196
N-24918

62\. Lachmann, G. V.: Laminarisation Through Boundary Layer Control. Proceedings of the Fourth AGARD General Assembly, Netherlands. AG14/P5, AGARD, May 1954, pp. 108-127. (Also available in Aeronaut. Eng. Rev., vol. 13, no. 8, Aug. 1954, pp. 37-51.)

The essential prerequisite for laminarised aircraft is a surface finish which is compatible with the maintenance of a laminar boundary layer thinned down by suction.

Analysis of the effect of isolated roughness on transition which needs experimental corroboration suggests that the height of isolated surface excrescences should be well below 50% of the local displacement thickness of the boundary layer where suction is applied.

Distributed suction is the ideal solution from an aerodynamic point of view since it avoids localized reduction of boundary-layer thickness due to suction, but it is the most difficult method in practice.

Closely spaced rows of spanwise sinks offer the best compromise.

The aerodynamic design should take into account the existence of two critical limits for the boundary-layer thickness with applied suction. The upper limit is best defined by a critical value of R_ϑ for which a conservative value is $R_{\vartheta_{crit}} = 1250$. The ratio of the critical values of momentum thickness (with maximum and minimum suction) ≤ 1 is proportional to a Reynolds Number formed with roughness height as length and a constant.

Care without unduly great practical difficulties in production and maintenance should make possible flight with laminar boundary layer, stabilised by suction, at values of U/ν of the order $1.5 \div 2.5 \times 10^6$.

Cruising in the stratosphere at such values of U/ν makes possible the attainment of high subsonic Mach numbers.

Availability:
N69-80509

63\. Lachmann, G. V.: The Case for Laminarization. Selected Papers on Engineering Mechanics, G. Gabrielli, F. N. Sheubel, and F. L. Wattendorf, eds., Butterworths Sci. Publ. (London), 1955, pp. 142-186.

The essential prerequisite for laminarized aircraft is a surface finish which is compatible with the maintenance of a laminar boundary layer thinned down by suction.

Analysis of the effect of isolated roughness on transition which needs experimental corroboration suggests that the height of isolated surface excrescences should be well below 50 per cent of the local displacement thickness of the boundary layer where suction is applied.

Distributed suction is the ideal solution from an aerodynamic point of view, since it avoids localized reduction of boundary layer thickness due to suction, but it is the most difficult method in practice.

Closely spaced rows of spanwise sinks offer the best compromise.

The aerodynamic design should take into account the existence of two critical limits for the boundary layer thickness with applied suction. The upper limit is best defined by a critical value of momentum thickness $R_{\theta_{crit}}$ and the lower one by a critical ratio of displacement thickness and height of surface excrescences. A conservative value for $R_{\theta_{crit}} = 1250$, and the smallest displacement thickness (where suction is applied) should be more than twice the height of a local excrescence.

Care without unduly great practical difficulties in production and maintenance should make possible flight with laminar boundary layer, stabilized by suction, at values of U/ν of the order of $1.5 - 2.5 \times 10^6$.

Cruising in the stratosphere at such values of U/ν makes possible the attainment of subsonic Mach numbers.

Author

Availability:
CN-142,754

64. Laminar Flow at Radlett. Flight Int., vol. 69, no. 2464, Apr. 13, 1956, pp. 411-412.

A discussion of Handley Page's work in the field of laminar-flow research includes a description of tests made on the D.H.113 ("Vampire Night Fighter") beginning in 1953. The results agreed with the expectations of Mr. Lachmann. It is concluded that boundary layer control will prove most effective for use on future long-range transports.

65. Lachmann, Gustav Victor, ed.: Boundary Layer and Flow Control, Its Principles and Application. Volume 2. Pergamon Press, 1961.

66. Edwards, Brian: Laminar Flow Control - Concepts, Experiences, Speculations. Special Course on Concepts for Drag Reduction, AGARD-R-654, June 1977, pp. 4-1 - 4-41.

The twin concepts of laminar flow control by suction, and of propulsion by restoring the momentum of the sucked mass flow are described. An account is given of the progress of some work relating to laminar flow control. Doubts about the practical application of laminar flow control are aired and the reasons why the work was not continued are briefly discussed. The view is expressed that, despite the recent rapid rise in the price of fuel, future prospects for the application of laminar flow control are still uncertain.

Author

Availability:
N77-32095

67. Head, M. R.; Johnson, D.; and Coxon, M.: Flight Experiments on Boundary-Layer Control for Low Drag. R. & M. No. 3025, British A.R.C., Mar. 1955.

This report describes the first phase of a series of flight experiments on maintaining laminar boundary layers by means of suction. The experiments were performed on a Vampire aircraft to which a suction sleeve had been fitted over part of the upper surface of the wing. The results presented were obtained in the period August, 1953, to March, 1954.

Tests were made with distributed suction applied to a short-span sleeve fitted to the upper surface of the wing. Full-chord laminar flow was maintained up to Reynolds numbers in the region of 29 million and Mach numbers up to 0.70, which was very nearly the critical Mach number of the sleeve section. The suction quantities required were sufficiently small to result in overall reductions in profile drag of between 70 and 80 per cent, account being taken of the power required for suction. Difficulties were experienced due to surface roughness, and although these are believed to have resulted largely from the particular type of porous covering used in the tests, the problem of maintaining a sufficiently smooth and clean surface is evidently of crucial importance to full-scale application.

Author

Availability:
N78-78484
N-38562X

68. Pfenninger, W. (P. B. E. Engler, transl.): On Some Recent Results in the Field of Boundary Layer Aspiration for Retaining Laminar Flow at High Reynolds Numbers. Libr. Transl. No. 1100, British R.A.E., Mar. 1965.

The present techniques for laminar boundary layer control are considered from both the wind tunnel and flight aspects. Various parameters are discussed, including the effects of the number of slits and their fineness, the stability criterion in the boundary layer, the influence of Mach No. and the problems of wing/body junctions. The practical application of the system is evaluated.

Author

Availability:
N65-27224

69. Schlichting, Hermann: Absaugung in der Aerodynamik. Jahrb. 1956 WGL, Fried R. Vieweg & Sohn, c.1956, pp. 19-29.

It is concluded that by using suction the boundary layer on an airfoil can be kept laminar up to very high Reynolds numbers with a corresponding reduction in drag. Continuous distributed suction through the porous surface proved the only effective way to secure this. The possible reduction in frictional drag could be up to 50% or more. The basic theoretical knowledge of this effect came from German work done during World War II.

Availability:
CN-65751

70. Van Nes, W.: Summary of Experimentally Determined Facts Concerning the Behavior of the Boundary Layer and Performance of the Boundary Layer Measurements During Flight. NASA TM-75270, 1978.

The article is a summary report of boundary layer studies carried out by the Engineering Office for Lightweight Construction and Flow Technology, Duisburg, in conjunction with the Institute for Sailing Flight Research, Freiburg im Brsg. Preliminary results of experimental measurements show that: (a) a very thin layer (≃0.4 mm) of the boundary layer seems to be accelerated; (b) the static pressure of the outer flow does not remain exactly constant through the boundary layer; (c) an oncoming boundary layer which already turbulent at the suction point can again become laminar behind this point without being completely sucked off.

Author

Availability:
N78-24083
CN-82469 (Original German, 1957)

71. Smith, A. M. O.: Feasibility Report - Laminar-Boundary-Layer Control. Rep. No. ES 26353 (Contract NOas 54-773c), Douglas Aircraft Co., Inc., July 31, 1956. (Available from DDC as AD 148 307.)

The critical problems of laminar boundary layer control are: pumping, fabrication, and roughness. The outlook for the first two is favorable, but studies concerning the third indicate that the roughness permissible for a laminar boundary layer is extraordinarily small. While the smoothness requirement may ultimately be met, it is so stringent that this contractor believes any consideration of laminar boundary layer control for service aircraft is unwarranted until operational experience is accumulated on a specially instrumented aircraft to learn the difficulties of maintaining natural laminar flow during operation under simulated service conditions. A plastic "veneer" is suggested as a means for attaining the necessary surface smoothness. If these results are favorable, the remaining problems of laminar boundary layer control probably can be solved. Author

Availability:
N78-78471
N-54688
AD 148 307

72. Schmued, Edgar: Progress in Low Drag Boundary-Layer Control. Aeronaut. Eng. Rev., vol. 16, no. 3, Mar. 1957, pp. 34-36.

Review of experiments done in the application of boundary-layer control for drag reduction, and discussion of the resulting gain in performance for long-range airplanes.

73. Braslow, Albert L.; and Muraca, Ralph J.: A Perspective of Laminar-Flow Control. AIAA Paper 78-1528, Aug. 1978.

A historical review of the development of laminar flow control technology is presented with reference to active laminar boundary-layer control through suction, the use of multiple suction slots, wind-tunnel tests, continuous suction, and spanwise contamination. The ACEE laminar flow control program is outlined noting the development of three-dimensional boundary-layer codes, cruise-noise prediction techniques, airfoil development, and leading-edge region cleaning. Attention is given to glove flight tests and the fabrication and testing of wing box designs.

Availability:
A78-46503

74. Northrop's LFC. Flight, vol. 78, no. 2701, Dec. 16, 1960, p. 957. (Illustration in Flight, vol. 79, no. 2726, June 8, 1961, p. 805.)

This article briefly summarizes the results of the past 12 years of Northrop research under W. Pfenninger. Northrop's contribution to low-drag, laminar flow BLC is to be applied to two test aircraft for the USAF. This proposal is briefly discussed. It involves modification of Douglas WB-66Ds. The new suction wing will be considerably larger than the present one, Pratt & Whitney TF33 fans will replace the J71s of the B-66, and a suction power system will be added.

75. Pfenninger, W.: Recent Developments in the Field of Low Drag Boundary Layer Suction Research. AGARD Rep. 262, 1960.

Earlier low-drag suction experiments carried out by the author on laminar suction wings had verified full-chord laminar flow and low-wing profile drags within certain ranges of wing chord Reynolds number and turbulence levels. This Report describes subsequent experiments carried out to determine the behavior of laminar suction wings at a much reduced turbulence level corresponding to flight conditions. These experiments verified that much higher Reynolds numbers can be achieved with full-chord laminar flow if external disturbances such as turbulence, etc., are minimized. Also discussed are various practical suction methods for achieving full-chord, or almost full-chord, laminar flow in flight.

Author

Availability:
N78-78472
N-103,364

76. Pfenninger, W.; and Bacon, J. W., Jr.: About the Development of Swept Laminar Suction Wings With Full Chord Laminar Flow. Boundary Layer and Flow Control, Volume 2, G. V. Lachmann, ed., Pergamon Press, 1961, pp. 1007-1032.

This paper is concerned with the feasibility of full chord laminar flow, achieved by boundary layer suction, on swept wings under crossflow conditions at high wing chord Reynolds numbers. Theoretical and experimental results are compared. Results of tests are evaluated and the necessary chordwise suction distribution was determined from calculations of the development and stability of the laminar boundary layer.

77. Gasich, Welko E.: Laminar Flow Control. Shell Aviation News, no. 282, 1961, pp. 15-19.

A brief description is given of Northrop's LFC program which began in 1949. The object of the program was to increase the cruise performance by the use of LFC to reduce the drag. The test aircraft and tests are described and it is concluded that a turbojet transport with LFC can be made and operated with advantages over conventional type airplanes. Also, operating costs can be decreased by incorporating LFC into future subsonic and supersonic transport design.

78. Schulz, R. W.: Ein voll laminarisierter Absaugeflügel. Luftfahrttechnik Raumfahrttechnik, vol. 9, no. 9, Sept. 1963, pp. 262-264.

Discussion of a wing design which uses a sandwich double outer skin with a spanwise system of slits and holes uniformly distributed over the entire wing surface to provide highly efficient boundary layer control. Each aircraft wing has a separate suction device below the wing, incorporating turbine-driven low- and high-pressure compressors. Structural details of the wing are described and illustrated.

Availability:
A64-11966

79. Plattner, C. M.: X-21 Tests Laminar Flow Control Theory. Aviat. Week & Space Technol., vol. 78, no. 25, June 24, 1963, pp. 52-53, 57, 61-62.

Discussion of the Northrop X-21A research aircraft, the wing-pods of which contain suction compressors by means of which air from the wing surfaces is drawn through slits to smooth turbulent flow over the wing. Tests indicate that application of a laminar flow control (LFC) system to a Norair CX-4 proposed long-range turbojet transport, with a 21-ft-diam. fuselage and Pratt and Whitney JT-3D-8A engines, would result in a reduction in power requirements by about one-fifth. Wind-tunnel tests indicate that the use of LFC will reduce profile drag by a factor of 30.

Availability:
A63-18357

80. WB-66D + LFC = X-21. West. Aerosp., vol. 43, Feb. 1963, pp. 14-15, 17.

Brief description of the Northrop X-21 aircraft, a WB-66D reconnaissance aircraft modified for laminar flow control (LFC) test flights. The boundary-layer suction system eliminates up to 80% of the friction drag attributed to turbulent flow of air over wing surfaces, and is achieved with 23,600 ft of tiny slots in the wing cover skins. The almost invisible slits, extending spanwise along the wing surface from the fuselage to the tip, lead into plenum chambers. A suction compressor siphons the air through the slots into these chambers, then through holes into plastic tributary ducts leading into wing passages. This flow of air is finally expelled rearward by the compressors as augmented thrust (estimated at 500 to 600 lb).

Availability:
A63-12970

81. Antonatos, Philip P.; Nenni, Joseph P.; and Mueller, Roland X.: Summary of Laminar Flow Control Techniques for Aircraft. ASD-TDR-63-689, U.S. Air Force, Sept. 1963. (Available from DDC as AD 434 841.)

From the first aerodynamic investigations that proved the existence of a viscous layer of fluid over a wing surface, it was shown that the penalty in terms of skin friction drag and resulting power requirements for cruise was a high percentage of the total drag of an aircraft. Efficient means were sought for reducing the magnitude of this drag by at least preventing turbulent flow conditions from existing on the wing surfaces. With the advent of the jet engine it became possible to efficiently provide a means of suction to control the boundary layer on the surfaces that would offer practically no weight penalty. Further research showed the feasibility of using fine slots versus a distributed suction technique. As a result, a program to modify the entire wing assembly of a B-66 was initiated to incorporate this new principle and prove the practical feasibility of laminar flow control. Design considerations of this application are reviewed.

Author

Availability:
N64-24072
AD 434 841

82. Kosin, R. E.: Experiences With Laminarization by Suction on a Sweptback Airplane. Northrop paper presented at Wissenschaftliche für Luft-und Raumfahrt and Deutsche Gesellschaft für Raketentechnik und Raumfahrtforschung (Berlin), Sept. 14-18, 1964.

Advances in boundary-layer control theory and practice, including an account of the development of the X-21. As early as 1940, it was recognized that turbulent flow and flow separation of air across an airfoil resulted in major increases in friction drag coefficient. Early attempts to achieve laminarization by modifying airfoil shapes proved to be impracticable, but attempts that employed suction (rather than shape modification) succeeded in reducing drag by 32% in one case and by 70% in another. Work on boundary-layer development on swept laminar suction wings by Gray, Owen, and Randall, by Brown, by Pfenninger, and by Raetz is described. Two X-21 aircraft have been constructed to investigate full-scale effects that are difficult to study on wind-tunnel models. Flight experiences with the X-21 are said to have generally confirmed suction quantity calculations, but a number of problems have been posed such as the existence of turbulence at the attachment line, variations in boundary-layer thickness, and disturbance propagation that is independent of boundary-layer thickness.

Availability:
A65-11645

83. Kosin, Ruediger E.: Laminar Flow Control by Suction as Applied to the X-21A Airplane. J. Aircr., vol. 2, no. 5, Sept.-Oct. 1965, pp. 384-390. (Also available as AIAA Paper 64-284.)

Discussion of the application of laminar flow control on a wing with 30° sweep and about 30×10^6 Reynolds number under cruise condition. The wing, with an area of 1250 ft^2, incorporates narrowly spaced fine laminar flow-control suction slots. The boundary-layer air is removed by suction compressors from the wing surface by about 120 slots on the upper and 120 slots on the lower surface. Slots vary in width from 0.0035 to 0.01 in. and discharge through 48 collector ducts into the suction compressors. The installation of the suction nacelles at about 1/3 half-span permits the collector ducts to be relatively short and the duct velocities low. It also permits separate adjustment of the suction quantities for the inboard and outboard wing. The results of the performance analysis, including wing characteristics, are presented in the form of graphs.

Availability:
A65-34377
A64-20460

84. Recent Developments in Boundary Layer Research - Part IV. AGARDograph 97, May 1965.

Pfenninger, W.: Some Results From the X-21 Program. Part I - Flow Phenomena at the Leading Edge of Swept Wings.

After discussing the discovery of the existence of turbulent flow at the leading edge of the X-21 wing during the early phase of the flight experiments various methods are described which reestablish laminar flow at the front attachment line of swept wings. Boundary layer suction at the wing leading edge for example through vertical nose slots was particularly effective in establishing a laminar attachment line boundary layer at the leading edge of swept wings. In order to establish an undisturbed laminar attachment line boundary layer on swept wings it is essential to minimize disturbances which may cause turbulent bursts at the front attachment line, and to reduce the boundary layer momentum loss Reynolds number R_θ at the front attachment line to sufficiently low values ($R_\theta \leq 150$ for smooth leading edge, $R_\theta \leq 90$ to 100 with large leading edge roughness). R_θ at the front attachment line of swept wings can be reduced to such low values by means of boundary layer suction along the wing leading edge, for example through vertical nose slots, or by reducing the leading edge radius, or a combination of both methods. Wind tunnel experiments on a swept low drag suction wing in low turbulence tunnels as well as on the X-21 in flight have verified extensive laminar flow up to rather high length Reynolds numbers when an undisturbed laminar stagnation line boundary layer had been established by the above described methods.

Author

Fowell, L. R.; and Antonatos, P. P.: Some Results From the X-21A Program. Part 2: Laminar Flow Control Flight Test Results on the X-21A.

Full scale subsonic flight tests have been made since the summer of 1963 with the X-21A laminar flow control research aircraft having swept, slotted suction wings. Results have been obtained concerning the stability, transition and stabilization of the boundary layers over the wings under adverse influences such as sweep effect, high Reynolds numbers, acoustic disturbances, surface roughness, panel vibration, atmospheric particles and meteorological influences. Successful, repeatable laminarization with predetermined suction distributions has been obtained at chord Reynolds numbers of 20×10^6 up to speeds of $M = 0.8$ and altitudes of 40 000 feet. Comparable results at chord Reynolds numbers of 30×10^6 and 40×10^6 are now being sought with investigations centering on spanwise turbulent contamination along the wing leading edge and the possible effects of internal noise from the wing suction ducting and pumping system.

Author

Groth, E. E.; Pate, S. R.; and Nenni, J. P.: Laminar Flow Control at Supersonic Speeds.

Wind tunnel tests were conducted in the 40 inch supersonic wind tunnel at the Arnold Engineering Development Center, Tennessee, for the purpose of maintaining laminar flow at high Reynolds numbers by means of boundary layer suction. Length Reynolds numbers with laminar flow of the order of $20 \cdot 10^6$ were obtained in straight and swept wing models at Mach numbers between 2.0 and 3.5. A 6.5 foot long body of revolution provided a maximum length Reynolds number with full laminar flow of $51 \cdot 10^6$ at $M = 3.0$. The evaluated drag coefficients, which included a term corresponding to the power requirements for suction, were 60 to 80% lower than the friction coefficients of a turbulent flat plate at the same Mach and Reynolds numbers. Laminar flow control had a favorable effect on the interaction with an impinging shock wave in the sense that it delayed the beginning of boundary layer separation and transition to turbulent flow to higher shock intensities.

Author

Availability:
N65-24864

85. Laminar Flow Control Prospects. Astronaut. & Aeronaut., vol. 4, no. 7, July 1966, pp. 30-62.

Goethert, Bernhard: Toward Long-Range Aircraft With Laminar Flow Control.

Von Karman's concept of boundary layer control to increase the performance of aircraft, especially with respect to range and economy of operation, has shown after appropriate exploration that friction drag can be reduced to 1/4 or 1/5 of its normal value.

In the 20 years since the von Karman work Laminar Flow Control (LFC) has emerged with great promise of improvement for subsonic aircraft performance.

The following articles summarize the present (1966) state of the art of LFC research and technology and indicate that ranges in excess of 8000 nautical miles now become feasible.

Antonatos, P. P.: Laminar Flow Control - Concepts and Applications.

Brief discussion of developments which proved the technical feasibility of laminar flow control (LFC). It is noted that to date experimental flight results have shown that LFC is technically feasible, and that it remains to be shown that this principle is operationally feasible for actual flight routes and maintenance procedures as conducted by using agencies. In addition to its use for logistics applications, LFC offers possible aircraft performance benefits in increased endurance, loiter time, and cruise altitude. This makes LFC an attractive consideration for such multipurpose aircraft missions as early warning, airborne communications centers, and airborne defense systems.

Whites, R. C.; Sudderth, R. W.; and Wheldon, W. G.: Laminar Flow Control on the X-21.

Discussion of results from flight-testing the laminar flow control (LFC) system on the X-21 aircraft. It is concluded that (1) the attainment of low drag at length Reynolds numbers to the order of 47 million demonstrates the technical feasibility of laminar flow for aircraft as large as any of the presently planned logistic types, (2) repeated flight demonstrations of predicted performance indicate satisfactory LFC design and analysis techniques, (3) LFC causes no adverse or unusual handling characteristics and requires no new pilot skills, (4) an LFC aircraft can maneuver as normally required for large transports under air traffic control without loss of laminar area, (5) proximity to or entry into clouds or atmospheric turbulence degrades laminar performance, (6) laminar flow tolerates normal variations in chordwise suction distribution, altitude, airspeed, and lift coefficient, and (7) practical manufacturing techniques meet design criteria covering surface irregularities.

Pfenninger, Werner; and Reed, Verlin D.: Laminar-Flow Research and Experiments.

Discussion of the critical parameters and flow characteristics of swept wings with full-chord laminar flow, and examination of special considerations introduced by disturbances imposed on the boundary layer. Significant answers provided by experiments at high Reynolds numbers that are important for large-scale effects are reviewed.

Nenni, Joseph P.; and Gluyas, George L.: Aerodynamic Design and Analysis of an LFC Surface.

Discussion of the possibility of determining empirically permissible degrees of instability to serve as design criteria for maintaining laminar flow, by means of careful comparison between experiment and theory. Other aerodynamic considerations that also lead to design criteria for an LFC aircraft are treated: (1) permissible surface roughness, (2) acoustical environment on the surface, (3) acoustical environment on the wings, and (4) wing smoothness requirements.

Chuprun, John; and Cahill, Jones F.: LFC on Large Logistics Aircraft.

Results are given of design studies on large logistics aircraft which show the potential impact of LFC on aircraft performance. The studies show that the optimum LFC airplane could receive range improvement of 20% to 25% with heavy payloads. Long range medium payload airplanes would show even greater improvement.

86. Wheldon, W. G.; and Whites, R. C.: Flight Testing of the X-21A Laminar Flow Control Airplane. AIAA Paper No. 66-734, Sept. 1966.

Measuring techniques developed and evaluated during the flight testing of laminar flow control on full-scale swept wings are briefly discussed. The tests were conducted utilizing two X-21A airplanes. Measurements fell in two overlapping categories: (1) the determination of laminar and turbulent areas, and (2) the detection and identification of boundary layer disturbances. New or unusual techniques for investigating the boundary layer with common measuring systems include: (1) the use of single total-pressure probes spaced along the wing trailing edge to determine the wing laminar area, (2) determination of wing wake drag from total pressure rakes at the wing trailing edge, (3) evaluation of flow visualization techniques, and (4) investigation of the stability of the boundary layer utilizing pressure transducers, flush and probe microphones, hot film anemometers, hot wire anemometers, and resistance thermometers. In addition, systems have been developed for: sampling ambient particles, measuring surface static pressures with strip-a-tube, control of engine compressor noise with a translating inlet plug, generating and controlling duct noise levels at fixed frequencies or over broad frequency bands; generating and controlling surface skin vibration frequencies and displacements, and measuring very small airflows through fine slots using a mobile ground system without changing the natural slot inflow.

Author

Availability:
A66-40625

87. Pfenninger, W.: Flow Problems of Swept Low-Drag Suction Wings of Practical Construction at High Reynolds Numbers. Ann. N. Y. Acad. Sci., vol. 154, art. 2, Nov. 22, 1968, pp. 672-703.

Summary and evaluation of studies made on swept laminar suction wings, using theoretical analyses and wind-tunnel experiments. Results are reported indicating that, in order to maintain full-chord laminar flow on swept laminar suction wings at further increased wing-chord Reynolds numbers in the presence of acoustic disturbances, amplified boundary-layer oscillations should be minimized by increasing the local suction rates and approaching area suction closely, particularly in the most critical region of the flat pressure distribution. Slotted laminar suction surfaces should be designed at high Reynolds numbers for viscous, steady slot-wakes, achieved either by keeping $Re_s < 100$ with unsophisticated plenum chamber designs, or by using shallow plenum chambers and two rows of holes located at opposite sides of the slot, making considerably higher Re_s possible. Studies of the X-21 wing are discussed.

Availability:
A69-15557

88. Smith, A. M. O.: A Decade of Boundary-Layer Research. Appl. Mech. Rev., vol. 23, no. 1, Jan. 1970, pp. 1-9.

Broad review of research on boundary layers conducted over the entire past decade. It is noted that an interesting phenomenon known as crosshatching was discovered during this decade. Under certain reentry-type conditions, some shapes of missile cones will ablate with a striated pattern. Some of the more important works in the field of laminar flows are mentioned to show the general state of development, together with works describing fundamental advances in the theory of turbulent flow. It is pointed out that, with regard to predicting and understanding transition, progress in the sixties has not been great, but perhaps it has been greater than progress in the basic understanding of turbulent boundary-layer flows. The past decade has seen substantial investigations of two systems that offer real promise of reducing drag. One system, laminar flow control (LFC), is designed to stabilize the boundary layer by means of suction. A second idea that has received much attention in the last decade is that of compliant surfaces. These are damped elastic surfaces, tuned so that transition is delayed or turbulent skin friction reduced, or both.

Availability:
A70-21040

89. Summary of Laminar Boundary Layer Control Research. WADC Tech. Rep. 56-111, U.S. Air Force, Apr. 1957. (Available from DDC as AD 130 759.)

This summary report presents results of the low drag suction investigations which were conducted at the Boundary Layer Control research group at Northrop Aircraft, Inc., Hawthorne, California, under Air Force Contract, Clause 1(b) to Contract No. AF33(616)-205.

The report covers research, investigation, experiments, and tests performed from September 1952 through August 1955. The entire program was conducted and the consequent report was prepared under the direction of the author. Each assistant is recognized as contributing author of the applicable subsection. This document is presented as a series of reports, related to each other though treated separately.

Section I describes the results of basic laminar flow investigations with and without boundary layer control. Various suction methods for the application of low drag boundary layer control are studied and compared. Suction through a large number of fine slots closely approaches continuous suction and appears to be a promising method for low drag suction from the standpoint of aerodynamics, structures, and manufacturing (Bibliography References 1 through 5). With suction through holes, three-dimensional disturbances have been observed, often resulting in premature transition (Bibliography References 6 through 13). For certain applications, suction through holes seems reasonably attractive either with a large number of rows of closely spaced holes, or with a very large number of more or less evenly distributed smaller holes, provided the holes can be kept clean.

Results of the spanwise variation of the suction quantity with suction through fine slots and holes underneath the slots are described in the Bibliography References 14 through 16 and are included in Section I.

Closely connected with the maintenance of 100% laminar flow is the question concerning the highest transition Reynolds number with laminar flow. Results of transition experiments in the inlet length of laminar flow tubes at high Reynolds numbers and low turbulence are presented in the Bibliography References 3 and 17 and in Section I. Transition length Reynolds numbers of 53×10^6 with continuous laminar flow and 70×10^6 to 75×10^6 with intermittent laminar and turbulent flow have been observed during these experiments with accelerated flow.

Section II and the Bibliography References 18 through 20 describe flight low drag suction experiments on the upper surface on an F-94A wing panel with suction through 12 slots and through 69 fine slots. The experience gained from the laminar flow tube experiments with 80 slots (Section I) was used to build the second wing glove as a practical construction panel with 69 fine slots with holes underneath the slots. A laminar flow rate of 100% and very low profile drags were achieved in flight at high wing chord Reynolds numbers and unit length Reynolds numbers with surprisingly little difficulties. Higher wing chord Reynolds numbers with all laminar flow and lower drags were achieved with the 69-slot practical construction panel than with the 12-slot panel.

All laminar flow and very low profile drags have been obtained in flight on a slightly tapered straight wing glove at high Reynolds numbers with two different slot arrangements. Wind tunnel tests concerned with transition measurements on bodies of revolution are described and the first suction experiments in which full laminar flow was obtained on a body of revolution is reported. Basic experiments in a 2-inch and an 8-inch tube with different suction methods, for example, slots and various hole configurations, are described. Basic theoretical work was done on a solution of the boundary layer equations for straight and swept wings of infinite and finite span. Included also, is an analysis of the stability of laminar boundary layers under crossflow conditions by an exact solution of the Orr-Sommerfeld disturbance equations. Thermodynamic cycle studies of propulsion systems for laminar flow airplanes are given and the most promising propulsion systems discussed. General design considerations for laminar flow airplanes are outlined and several hypothetical configurations are discussed.

Author

Availability:
N78-76390
N-53889
AD 130 759

90. Summary of Laminar Boundary Layer Control Research. Volume I. ASD-TDR-63-554, U.S. Air Force, Mar. 1964. (Available from DDC as AD 605 185.)

Raetz, G. S.: Current Status of Resonance Theory of Transition.

Brown, W. Byron: Exact Numerical Solution of the Complete Lees-Lin Equations for the Stability of Compressible Flow.

Brown, W. Byron: Crossflow Stability Calculations on Highly Swept (65° Sweep) Supersonic Low Drag BLC Wing (Mach Number 1.8) With and Without Cooling.

Brown, W. Byron: Incompressible Crossflow Stability Calculations With Various Angles of the Wave Fronts With the Potential Flow Direction.

Gross, L. W.; Bacon, J. W., Jr.; and Tucker, V. L.: Experimental Investigation and Theoretical Analysis of Laminar Boundary Layer Suction on a 30° Swept, 12-Percent-Thick Wing in the NASA Ames 12-Foot Pressure Wind Tunnel.

Gross, L. W.: Experimental Investigation of a 4-Percent Thick Straight Laminar Suction Wing of 17-Foot Chord in the Norair 7- by 10-Foot Wind Tunnel.

Bacon, J. W., Jr.; Pfenninger, W.; and Moore, C. R.: Investigations of a 30° Swept and a 17-Foot Chord Straight Suction Wing in the Presence of Internal Sound, External Sound, and Mechanical Vibrations.

Gross, L. W.: Investigation of a Laminar Suction Modified Sears-Haack Body of Revolution in the Norair 7- by 10-Foot Wind Tunnel.

Bossel, Hartmut H. K.: Analysis of the Boundary Layer Development on a Modified Sears-Haack Suction Body of Revolution.

At subsonic speeds, full length laminar flow and low drags were obtained up to high length Reynolds numbers on a thin straight, on a swept laminar suction wing and on a suction body of revolution. Moderately increased suction rates in the most critical region of a straight and a swept laminar suction wing enabled full chord laminar flow in the presence of external sound. Theoretical investigations are concerned with nonlinear boundary layer oscillations and stability investigations (assuming small disturbances) of a supersonic laminar boundary layer on a flat plate up to high supersonic speeds as well as on a highly swept supersonic low drag suction wing of low wave drag. On a supersonic flat laminar suction plate with and without weak incident shock waves, extensive laminar flow and low equivalent drags were obtained at $M = 3$ up to length Reynolds numbers of $26 \cdot 10^6$. Further supersonic low drag suction experiments on a suction body of revolution, on a 36^o supersonic yawing wing, as well as on a 72^o supersonic yawing wing (swept behind the Mach cone) of low wave drag, are described. The latter wing showed full chord laminar flow with a subsonic type pressure distribution at $M = 2$ and $R_c \cong 9 \cdot 10^6$.

Author

Availability:
N65-25550
AD 605 185

91. Summary of Laminar Boundary Layer Control Research. Volume II. ASD-TDR-63-554, U.S. Air Force, Mar. 1964. (Available from DDC as AD 605 186.)

Groth, E. E.: Investigation of a Laminar Flat Plate With Suction Through Many Fine Slots With and Without Weak Incident Shock Waves, Low Drag Boundary Layer Suction Experiments on a Flat Plate at Mach Numbers 2.5, 3.0, and 3.5.

Groth, E. E.: Boundary Layer Suction Experiments on a Slotted Flat Plate Model With Interfering Shock Waves.

Groth, E. E.: Low Drag Boundary Layer Suction Experiments at Supersonic Speeds on an Ogive Cylinder With 29 Closely Spaced Slots.

Groth, E. E.: Investigations of Swept Wings With Supersonic Leading Edges. Low Drag Boundary Layer Suction Experiments on a 36^o Swept Wing at Mach Numbers 2.5, 3.0, and 3.5.

Groth, E. E.: Boundary Layer Transition Measurements on Swept Wings at Supersonic Speeds.

Goldsmith, J.: Investigation of Laminar Flow Control Airfoils Swept Behind the Mach Angle - Low Drag Boundary Layer Suction Experiments on a 72° Swept Wing Model at Mach Number 2.0 and 2.25.

Goldsmith, J.: Investigation of Laminar Flow Control Airfoils Swept Behind the Mach Angle - Calculation of Compressible Flow Losses Through Swept Suction Slots.

Pfenninger, W.; and Rogers, K. H.: Pressure Drop in Laminar Flow Tubes With Compressible Flow.

Wieder, J.; and Pfenninger, W.: Structural Aspects of Low Drag Suction Airfoils.

Worth, Robert N.: Skin Ducting System Configurations for LFC Aircraft Main Structural Box.

Worth, R. N.: Effect of Weathering on Typical Bonded Boundary Layer Control Structure.

Availability:
N65-25560
AD 605 186

92. Laminar Flow Control Demonstration Airplane System Design Analysis - Summary Report. NOR-61-133 (Contract AF33(600)-42052), Northrop Corp., Aug. 1961. (Available from DDC as AD 489 980.)

Availability:
X67-82271
NOR-61-133
AD 489 980

93. Final Report on LFC Aircraft Design Data Laminar Flow Control Demonstration Program. NOR 67-136 (Contract AF 33(657)-13930), Northrop Corp., June 1967. (Available from DDC as AD 819 317.)

Availability:
X67-22964
NOR 67-136
AD 819 317

94. Stark, W. W.: LFC Summary Flight Test Report - Laminar Flow Control Airplane Demonstration Program. Advanced Technology Program System 659A. NOR-61-134 (Contract AF 33(600)-42052), Northrop Corp., Apr. 1964. (Available from DDC as AD 440 344.)

Drag due to friction of the normal turbulent boundary layer is a considerable portion of the total drag of a wing. Wind tunnel investigations indicated that laminar flow could be maintained on a wing by removing part of the boundary layer over the entire wing surface with essentially the complete elimination of friction drag. Laminar flow application studies indicated a favorable over-all energy balance for the laminar configuration compared to the turbulent which resulted in airplane range-payload performance gains of sufficient magnitude to warrant a full-scale investigation of the feasibility of applying laminar flow control to aircraft. Northrop Norair, a Division of Northrop Corporation, was selected to conduct the X-21A Laminar Flow Control Demonstration Program. This program provided for the design, fabrication, and flight testing of two X-21A experimental test aircraft to demonstrate the feasibility of laminar flow control.

This report presents a summary of the flight test results of this program. In addition to discussions of LFC test data in the Test Results section, the main body of the report includes the Data Analysis Procedures section which details the analysis procedures used. Flight test data required to substantiate the satisfactory completion of secondary test objectives, namely, stability-and-control and safety-of-flight test programs, are included in Appendix A of this report.

Author

Availability:
N64-26978
NOR-61-134
AD 440 344

95. Laminar Boundary Layer Control Investigation. PN-97-7 (Contract No. AF33(616)-205), Northrop Aircraft, Inc., Aug. 1953. (Available from DDC as AD 20 076.)

This report includes the following documents as appendices:

BLC-1	Pfenninger, W.: Design Considerations for Hypothetical Boundary Layer Control Airplane. Part 1 - Design Considerations. May 1951. Bacon, J. W.: Design Considerations for Hypothetical Boundary Layer Control Airplane. Part 2 - Aeroelastic Study. Mar. 1953.
BLC-2	Bacon, J. W., Jr.: An Aeroelastic Study of Configuration II of a Laminar Boundary Layer Control Airplane. May 1953.
BLC-5	Groth, E. E.: Calculation of the Laminar Boundary Layer With Continuous Suction Around a Body of Revolution of Fineness Ratio 8. Aug. 1953.
BLC-6	Groth, E. E.: Low Speed Wind Tunnel Measurements on a Body of Revolution of Fineness Ratio 8. Aug. 1953.
BLC-7	Meyer, W. A.; and Pfenninger, W.: Preliminary Investigations of Laminar Flow in a Tube at High Reynolds Numbers and Low Turbulence With Boundary Layer Suction Through 80 Slots. Aug. 1953.

BLC-8 Design Tests of Y-Stiffened Panels.

Rails, J. A.; and Cole, V. L.: ETR 7980-1 - Design Test of "Y" Stiffened Panels (Specimens 2 and 14). June 1953.

Cole, V. L.: ETR 7980-2 - Design Test of "Y" Stiffened Panels (Specimen 12). Aug. 1953.

BLC-9 Jean, J. E.; and Stoughton, I. R.: Y-Stiffened Panel Evaluation. Aug. 1953. (Revised Dec. 1953. AD-30 321.)

Availability:
SN-24021, Aug. 1953
AD 20 076

96. Laminar Boundary Layer Control Investigation. PN-97-8 (Contract No. AF33(616)-205), Northrop Aircraft, Inc., Sept. 1953. (Available from DDC as AD 25 565.)

BLC-10 Schjelderup, H. C.: Stability of Y-Stiffened Multi-Web Beams. Aug. 1953.

BLC-11 Raetz, G. S.: A Method of Calculating the Incompressible Laminar Boundary Layer on Infinitely-Long Swept Suction Wings, Adaptable to Small-Capacity Automatic Digital Computers. Sept. 1953.

BLC-12 Meyer, W. A.; Goldsmith, John; and Pfenninger, W.: Note on Preliminary Laminar Suction Experiments Through Round Holes at High Reynolds Numbers and Low Turbulence. Sept. 1953.

BLC-13 Rogers, Kenneth H.: Preliminary Investigation of the Pressure Drop in Suction Ducts. Sept. 1953.

BLC-14 Raetz, G. S.: The Incompressible Laminar Boundary Layer on an Infinitely-Long Swept Suction Wing With a Few Different Pressure and Suction Distributions. Sept. 1953.

DYN-19 Peters, F. W.: Exploratory Flutter Analysis of Boundary Layer Airplane Configuration II.

Availability:
SN-24021, Sept. 1953
AD 25 565

97. Laminar Boundary Layer Control Investigation. PN-97-11 (Contract No. AF33(616)-205), Northrop Aircraft, Inc., Dec. 1953. (Available from DDC as AD 30 321.)

BLR-2 Meyer, W. A.: Change of Nozzle Flow Due to an Obstruction. Dec. 1952.

BLC-9 Stoughton, I. R.; and Jean, J. E.: Y-Stiffened Panel Evaluation. Revised Dec. 1953.

BLC-18 Clem, J. R.; and Dedon, W. W.: Compression Test of a 3-Web Y-Stiffened Bonded Panel. Dec. 1953.

BLC-19 Clem, J. R.; and Dedon, W. W.: Compression Tests of Single-Web Y-Stiffened Bonded Panel. Dec. 1953.

BLC-23 Goldsmith, John; and Meyer, W. A.: Preliminary Experiments on Laminar Boundary Layer Suction Through Circular Holes at High Reynolds Numbers and Low Turbulence. Nov. 1953.

BLC-24 Pfenninger, W.; and Meyer, W. A.: Transition Experiments in the Inlet Length of a 1-Inch Tube at High Reynolds Numbers and Low Turbulence. Nov. 1953.

BLC-25 Raetz, G. S.: The Incompressible Laminar Boundary Layer on an Infinitely-Long Swept Wing With Continuous Suction From the 0.37-Chord Line to the Trailing Edge. Dec. 1953.

Availability:
SN-24021, Dec. 1953
AD 30 321

98. Laminar Boundary Layer Control Investigation. NAI-54-99 (Contract No. AF33(616)-205), Northrop Aircraft, Inc., Feb. 1954. (Available from DDC as AD 38 616.)

BLC-17 Clem, J. R.; and Dedon, W. W.: Compression Tests of Angle-Stiffened Panels With Corrugated Wings. Feb. 1954.

BLC-20 Clem, J. R.; and Dedon, W. W.: Compression Tests of Single-Web Y-Stiffened Panels With Bonded Reinforcements. Jan. 1954.

BLC-21 Raetz, G. S.: The Incompressible Laminar Boundary Layer on a Typical Tapered Swept Suction Wing. Feb. 1954.

BLC-28 Goldsmith, John: Additional Experiments on Laminar Boundary Layer Suction Through Circular Holes at High Reynolds Numbers and Low Turbulence. Feb. 1954.

BLC-29 Pfenninger, W.: Some General Considerations of Losses in Boundary Layer Suction Ducting Systems. Feb. 1954.

BLC-30 Rogers, Kenneth H.: A Method of Calculating the Pressure Distribution in Suction Ducts. Feb. 1954.

Availability:
SN-24021, Feb. 1954
NAI-54-99
AD 38 616

99. Laminar Boundary Layer Control Investigation. NAI-54-185 (Contract No. AF33(616)-205), Northrop Aircraft, Inc., Mar. 1954. (Available from DDC as AD 51 763.)

BLC-16 Clem, J. R.; and Dedon, W. W.: Determination of Physical Properties of AG-ZR-MG Alloy for Comparison With ZK60 Alloys. Mar. 1954.

BLC-27 Schjelderup, H. C.: Thickness of Attachment Angle Necessary for Multi-Spar, Thick Skin, Wing Box Construction. Jan. 1954. (Revision 1, dated February 54, and Supplement 1.)

BLC-31 Sipe, O. E.; and Pfenninger, W.: The Minimum Induced Drag in Formation Flight. Mar. 1954.

BLC-32 Clem, J. R.; and Dedon, W. W.: Bending Tests of Honeycomb Spars. Mar. 1954.

BLC-33 Pfenninger, W.; and Sipe, O. E.: Note on the Performance of Ideal Laminar Suction Airplanes Flying in Formation. Mar. 1954.

Availability:
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NAI-54-185
AD 51 763

100. Laminar Boundary Layer Control Investigation. NAI-54-211 (Contract No. AF33(616)-205), Northrop Aircraft, Inc., Apr. 1954. (Available from DDC as AD 52 586.)

BLC-34 Clem, J. R.; and Dedon, W. W.: Compression Test of Two Single-Web Y-Stiffened Panels With Bonded Reinforcements. Apr. 1954.

BLC-35 Clem, J. R.; and Dedon, W. W.: Tensile Test of Slot Connection Panel. Apr. 1954.

BLC-36 Goldsmith, J.: Experiments With Laminar Boundary Layer Suction Through Rows of Closely Spaced Circular Holes at High Reynolds Number and Low Turbulence. Mar. 1954.

BLC-37 Pfenninger, W.: Propellers for Long Range Laminar Suction Airplanes Flying at High Subsonic Speeds. Apr. 1954.

Availability:
SN-24021, Apr. 1954
NAI-54-211
AD 52 586

101. Laminar Boundary Layer Control Investigation. Rep. No. NAI-54-478 (Contract No. AF33(616)-205), Northrop Aircraft, Inc., July 1954. (Available from DDC as AD 54 971.)

NAI-54-483 (BLC-46) Schjelderup, H. C.: Theoretical and Experimental Studies of Deflection Induced Loads Acting in a Continuous Hinge Control Surface. July 1954.

NAI-54-475 (BLC-47) Bacon, J. W., Jr.: Experimental Investigation of Structural Effect of Sweepback on a Strut-Braced Wing. July 1954.

NAI-54-484 (BLC-48) Raetz, G. S.: The Incompressible Laminar Boundary Layer on a Suction Wing Swept 35° and Tapered 10°, With Four Different Pressure and Suction Distributions. July 1954.

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NAI-54-486 (BLC-50) Rogers, K. H.: Investigation of the Pressure Distribution and Boundary Layer in a Suction Duct With Zero-Decelerated Duct Inlet. July 1954.

NAI-54-487 (BLC-51) Groth, E. E.: The Turbine-Compressor System for the F-94 Flight Tests. July 1954.

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NAI-54-488 (BLC-53) Pfenninger, W.; Moness, E.; and Sipe, O. E.: Investigation of Laminar Flow in a Tube at High Reynolds Numbers and Low Turbulence With Boundary Layer Suction Through 80 Slots.

NAI-54-489 (BLC-54) Reilly, R. J.: Influence of Internal Flow Passages on the Spanwise Suction Distribution in a Slot. July 1954.

NAI-54-490 (BLC-55) Worth, R. N.; and Slagg, W. R.: A Method of Manufacture of Suction Slots for a Laminar Suction Airplane. July 1954.

Availability:
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NAI-54-478
AD 54 971

102. Laminar Boundary Layer Control Investigation. NAI-54-802 (Contract No. AF33(616)-205), Northrop Aircraft, Inc., Nov. 1954. (Available from DDC as AD 66 065.)

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NAI-54-799 (BLC-66) Schjelderup, H. C.; and Dedon, W. W.: Additional Theoretical Studies of Deflection Induced Loads Acting on a Continuous Hinge Control Surface. Nov. 1954.

NAI-54-800 (BLC-67) Fiul, A.: A Preliminary Report on a Comparison of Aeroelastic Effects on Cantilevered and Strut-Braced Swept Wings. Nov. 1954.

Availability:
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103. Laminar Boundary Layer Control Investigation. NAI-55-289 (Contract No. AF33(616)-205), Northrop Aircraft, Inc., Mar. 1955. (Available from DDC as AD 74 865.)

NAI-55-286 (BLC-71) Rogers, K. H.: Investigation of the Pressure Distribution Along a Constant Area Suction Duct With 90-Degree Drilled-Hole Inlet. Mar. 1955.

NAI-55-287 (BLC-72) Goldsmith, John: Critical Suction Quantities and Pumping Losses Associated With Laminar Boundary Layer Suction Through Rows of Closely-Spaced Holes. Feb. 1955.

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NAI-55-290 (BLC-75) Meyer, W. A.: Preliminary Report on the Flow Field Due to Low Drag Suction Through Holes. Mar. 1955.

Availability:
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NAI-55-289
AD 74 865

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NAI-55-457 (BLC-76)	Charwat, A.: The Development of a Smoke-Generator for Flow Visualization. Apr. 1955.
NAI-55-458 (BLC-77)	Pfenninger, W.; Groth, E. E.; Carmichael, B. H.; and Whites, R. C.: Low Drag Boundary Layer Suction Experiments in Flight on the Wing Glove of an F-94A Airplane. Phase I - Suction Through Twelve Slots. Apr. 1955. (Including Appendices I, II and III.)

Availability:
SN-24021, Apr. 1955
NAI-55-434
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105. Laminar Boundary Layer Control Investigations. NAI-55-546 (Contract No. AF33(616)-205), Northrop Aircraft, Inc., May 1955. (Available from DDC as AD 79 343.)

NAI-55-547 (BLC-70)	Pfenninger, W.; and Rogers, Kenneth H.: Further Investigations on an Improved Suction Duct. May 1955.
NAI-55-548 (BLC-78)	Brown, W. Byron: Extension of Exact Solution of the Orr-Sommerfeld Stability Equation to Reynolds Numbers of 4,000. May 1955.
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Availability:
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NAI-55-546
AD 79 343

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NAI-55-624 (BLC-80)	Newton, J. S.: A Preliminary Study of Altitude Limitations on Aircraft Gas-Turbine Combustion Chambers at Subsonic Flight Speed. June 1955.
NAI-55-458 (BLC-77)	Slagg, W. R.; and Riley, V. F.: Appendix I - Problems Connected With the Design of a Boundary Layer Control Flight Test Panel. Apr. 1955. Atkinson, J. M.: Appendix II - Flight Test Instrumentation for Boundary Layer Control Investigations on F-94A Airplane. Apr. 1955.

Groth, E. E.: Appendix III - The Suction Compressor Turbine System for the F-94A Flight Tests. May 1955.

Availability:
SN-24021, June 1955
NAI-55-626
AD 89 588

107. Research and Reports on Laminar Flow Boundary Layer Control Systems. NAI-55-857 (Contract No. AF33(616)-3168), Northrop Aircraft, Inc., Oct. 1955. (Available from DDC as AD 89 596.)

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NAI-55-946 (BLC-82) Sipe, O. E., Jr.: Note on the Turbulence Level of the Northrop Wind Tunnel. Oct. 1955.

Availability:
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NAI-55-857
AD 89 596

108. Research and Reports on Laminar Flow Boundary Layer Control Systems. NAI-55-1027, Northrop Aircraft, Inc., Nov. 1955.

Availability:
SN-24021, Nov. 1955
NAI-55-1027

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Availability:
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AD 89 594

110. Research and Reports on Laminar Flow Boundary Layer Control Systems. NAI-56-227 (Contract No. AF33(616)-3168), Northrop Aircraft, Inc., Feb. 1956. (Available from DDC as AD 92 135.)

NAI-56-188 (BLC-84) Pfenninger, W.: Experimental Investigation of an Airfoil With High Lift to Drag Ratios at Low Reynolds Numbers. Feb. 1956.

Availability:
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NAI-56-227
AD 92 135

111. Research and Reports on Laminar Flow Boundary Layer Control Systems. NAI-56-304 (Contract No. AF33(616)-3168), Northrop Aircraft, Inc., Mar. 1956. (Available from DDC as AD 92 134.)

NAI-56-293 (BLC-86) Goldsmith, J.: Investigation of the Flow in a Tube With Laminar Suction Through 80 Rows of Closely-Spaced Holes. Mar. 1956.

Availability:
SN-24021, Mar. 1956
NAI-56-304
AD 92 134

112. Research and Reports on Laminar Flow Boundary Layer Control Systems. NAI-56-306 (Contract No. AF33(616)-3168), Northrop Aircraft, Inc., May 1956. (Available from DDC as AD 105 926.)

NAI-56-428 (BLC-88) Goldsmith, John: Influence of Single Roughness Elements on Transition at High Reynolds Numbers. Apr. 1956.

Availability:
SN-24021, May 1956
NAI-56-306
AD 105 926

113. Research and Reports on Laminar Flow Boundary Layer Control Systems. NAI-56-308 (Contract No. AF33(616)-3168), Northrop Aircraft, Inc., July 1956. (Available from DDC as AD 106 068.)

NAI-56-614 (BLC-89) Rogers, K. H.: Experimental and Analytical Investigation of a Vee Inlet Suction Duct. July 1956.

NAI-56-615 (BLC-90) Pfenninger, W.; and Bacon, John W., Jr.: General Design Investigations of Long Range Laminar Suction Airplanes. Aug. 1956.

Availability:
N78-75289
SN-24021, July 1956
NAI-56-308
AD 106 068

114. Research and Reports on Laminar Flow Boundary Layer Control Systems. NAI-56-317 (Contract No. AF33(616)-3168), Northrop Aircraft, Inc., Apr. 1957. (Available from DDC as AD 140 589.)

NAI-57-659 (BLC-96) Pfenninger, W.: Further Basic Investigations on the Critical Wing Wake Reynolds Number for Laminar Flow on a Fuselage Downstream of a Wing Fuselage Juncture. May 1957.

NAI-57-676 (BLC-97) Groth, E. E.: Wind Tunnel Experiments on a 5%-Thick Biconvex Airfoil Section at M = 2.23 and 2.77. May 1957.

Availability:
SN-24021, Apr. 1957
NAI-56-317
AD 140 589

115. Research and Reports on Laminar Flow Boundary Layer Control Systems. NAI-56-318 (Contract No. AF33(616)-3168), Northrop Aircraft, Inc., May 1957. (Available from DDC as AD 140 586.)

NAI-57-710 (BLC-98) Pfenninger, W.: Note on Long Range Photoreconnaissance Airplane With Low Drag Cruising at Very High Altitudes. May 1957.

Availability:
SN-24021, May 1957
NAI-56-318
AD 140 586

116. Research and Reports on Laminar Flow Boundary Layer Control Systems. NAI-56-319 (Contract No. AF33(616)-3168), Northrop Aircraft, Inc., June 1957. (Available from DDC as AD 140 583.)

NAI-57-826 (BLC-99) Bacon, John W., Jr.; Fiul, A.; and Pfenninger, W.: WADC 10-Ft Transonic Wind Tunnel Tests on Strut-Braced Boundary Layer Airplane. June 1957.

2644-1-P Kuethe, A. M.; and Deitrick, R. A.: Hot-Wire Measurements on a Boundary-Layer Control Body of Revolution. Univ. of Michigan, Eng. Res. Inst., Progress Rep. No. 1, June 1957.

Availability:
SN-24021, June 1957
NAI-56-319
AD 140 583

117. Research and Reports on Laminar Flow Boundary Layer Control Systems. NAI-57-1090 (Contract No. AF33(616)-3168), Northrop Aircraft, Inc., Aug. 1957. (Available from DDC as AD 150 529.)

NAI-57-1025 (BLC-102) Carmichael, Bruce; Whites, R. C.; and Wisma, R. E.: Low Drag Boundary Layer Suction Experiments in Flight on the Wing Glove of an F-94A Airplane. Phase IV - Suction Through 81 Slots Between 8% and 95% Chord. Aug. 1957.

Availability:
N78-74849
SN-24021, Aug. 1957
NAI-57-1090
AD 150 529

118. Research on Laminar Flow Boundary Layer Control Systems. NAI-58-24 (Contract No. AF33(616)-3168), Northrop Aircraft, Inc., Dec. 1957. (Available from DDC as AD 152 319.)

NAI-58-19 (BLC-104) Rogers, K. H.: Experimental and Theoretical Investigations of the Pressure Drop Through Holes and Slots in Incompressible Viscous Flow. Jan. 1958.

Availability:
SN-24021, Dec. 1957
NAI-58-24
AD 152 319

119. Research on Laminar Flow Boundary Layer Control Systems. NAI-58-266 (Contract No. AF33(616)-3168), Northrop Aircraft, Inc., Mar. 1958. (Available from DDC as AD 162 060.)

NAI-58-195 (BLC-105) Groth, E. E.: Low Drag Boundary Layer Suction Experiments on a 5% Thick Biconvex Airfoil Section at $M = 2.23$ and 2.77. Mar. 1958.

NAI-58-249 (BLC-106) Goldsmith, John: Preliminary Experiments on the Maintenance of Laminar Flow by Means of Suction in the Region of a Wing Leading Edge and Fuselage Juncture. Apr. 1958.

Availability:
N78-75633
SN-24021, Mar. 1958
NAI-58-266
AD 162 060

120. Research on Laminar Flow Boundary Layer Control Systems. NAI-58-616 (Contract No. AF33(616)-3168), Northrop Aircraft, Inc., July 1958.

NAI-58-589 Carmichael, B. H.: Critical Reynolds Numbers for Multiple Three-
(BLC-112) Dimensional Roughness Elements. July 1958.

Availability:
N66-80685
SN-24021, July 1958
NAI-58-616

121. Research on Laminar Flow Boundary Layer Control Systems. NAI-59-28 (Contract No. AF33(616)-3168), Northrop Aircraft, Inc., Dec. 1958.

NAI-59-4 Groth, E. E.: Investigation of the Flow Field Around a Suction
(BLC-116) Slot at Supersonic Speeds. Jan. 1959.

Availability:
N78-78477
SN-24021, Dec. 1958
NAI-59-28

122. Wells, Jack D.: Laminar Flow Control and the X-21. Proceedings of the 1963 "Report to the Aerospace Profession," Soc. Exp. Test Pilots, Sept. 1963, pp. 112-134.

Discussion of problems and methods of laminar flow control, and description of the X-21A aircraft, developed from the B-66 aircraft, which was selected to be modified to the laminar control configuration because of its ability to simulate in size and speed the operating Reynolds number range of transport type aircraft. A figure shows the X-21A wing, which has 30 degrees of sweep, and wing area increased from 780 to 1,250 sq ft. The wing has been contoured so as to establish favorable chordwise and spanwise pressure distribution to minimize crossflow velocities while providing a maximum amount of lift without local shock effects. Considered are fuselage contouring, wing structural design, typical performance comparison, multi-purpose aircraft studies, supersonic studies, flight tests, operational evaluation, in-flight acoustic environment, current flight status, degree of laminarization, and performance. It is noted that the design and fabrication of the wing are practical, and that smoothness requirements can be met at reasonable costs. The knowledge gained on the X-21 to date is stated to be directly applicable to a production wing.

Availability:
A64-12896

123. Carlson, J. C.: Results of a Low Speed Wind Tunnel Test to Investigate the Influence of Leading Edge Radius and Angle of Attack on the Spanwise Spread of Turbulence Along the Leading Edge of a Swept-Back Wing. NOR-64-30, Northrop Corp., Mar. 1964.

Leading edge transition studies were conducted for three leading edge radii on a two-dimensional 33 degree swept, symmetrical section wing in the Northrop

7 × 10 foot low speed wind tunnel at several angles of attack. Results of the studies showed that disturbances in the stagnation region of a swept back wing could cause complete spanwise contamination outboard of the disturbance once a certain combination of free stream velocity and angle of attack was attained for a given sweep angle and leading edge radius. It was found that all cases of spanwise contamination could be related to a small range of stagnation line boundary layer Reynolds numbers based on the stagnation line momentum thickness and the spanwise component of the potential flow velocity.

There appeared to be no distinct speed at which spanwise contamination occurred. Once a turbulent wedge due to a disturbance on the stagnation line developed, small increases in speed would move the outboard limit of contamination until finally the complete model outboard of the disturbance had turbulent flow in the stagnation region.

Turbulent boundary layers feeding onto the wing leading edge from the tunnel floor were found to be sufficiently strong to cause spanwise contamination; therefore tests were conducted which showed that a short chordwise fence with a single suction slot at the fence-wing leading edge intersection was sufficient to provide a clean leading edge and move the transition line back to the position as predicted by swept wing stability theory.

The similarity between the shape of the swept wing stagnation line velocity profile and the flat plate Blasius profile suggests a possible critical Reynolds number for Tollmien-Schlichting type disturbances which could cause transition at or very near the stagnation line of a swept back wing even though other disturbances are not present.

Author

Availability:
NOR-64-30
N79-75673

124. Shenstone, B. S.: Sucking Off the Boundary Layer. Aeroplane, vol. 52, no. 1340, Jan. 27, 1937, pp. 98-100. (Comments in vol. 54, no. 1402, Apr. 6, 1938, p. 425.)

This is a discussion of how boundary layer suction may be used to reduce drag, and the effect this suction has on airplane performance.

125. Tye, W.: The Effect of Smooth Wings on Weight and Performance. Rep. No. S.M.E.3234, British R.A.E., Oct. 1942.

Attention has been focussed recently on the structural problems involved in providing smooth wing surfaces. As a preliminary step it is useful to consider to what extent additional structure weight can be accepted for the sake of reduced drag. This note attempts to establish the order of the values involved.

Author

Availability:
N78-78059

126. Douglas, G. P.; and Pugsley, A. G.: The Field of Usefulness of Specially Smooth Wings. Rep. No. S.M.E.3232, British R.A.E., Oct. 1942.

The main purpose of this short report is to indicate the classes of aeroplane whose performance would especially benefit by the provision of wing surfaces sufficiently smooth and firm to secure laminar boundary layers over the forward 60% of the wing chord outside the slipstream. It is emphasised that the increase in performance which can be obtained by the general improvement of finish of existing types, though considerable when the finish is poor, is not included in the estimates given.

Author

Availability:
N78-78055

127. Smith, A. M. O.: Further Studies of the Problems of Drag Reduction by Boundary Layer Removal. Rep. No. ES 20941, Douglas Aircraft Co., Inc., Oct. 8, 1947.

This is a detailed study of the range of a jet airplane using boundary layer control and an investigation of suction slot spacing.

Author

Availability:
N78-78042

128. Roy, Maurice: Réduction de la Résistance et Aspiration Continue de Couche-Limite. Rech. Aéronaut., no. 25, Jan.-Feb. 1952, pp. 3-8.

At the Brighton Conference (September 1951), Sir Melville Jones and M. R. Head gave calculations that showed a saving of propulsive power of up to 50% for an airfoil when the boundary layer was removed by suction from a large part of the surface (assumed porous). Roy shows that this saving is probably much overestimated, as it does not take into consideration the power required to effect the suction. The ejection of the air from the boundary layer through a slot in the trailing edge is discussed, as is also the use of this ejected air as part of the propulsive system. The effect of the size of the slot on the efficiency of the system is also considered. As the calculations of Jones and Head and also those of Roy are based on parameters that have yet to be determined experimentally, the quantitative drag reduction due to the boundary layer suction is still a matter of controversy. Only the case of an ideal wing of infinite span with no body interaction effects is considered. Although the fluid is assumed to have negligible compressibility, the calculations could easily be extended to include compressibility effects.

Abstract courtesy APPLIED MECHANICS REVIEWS

129. Courtney, A. L.: The Use of Boundary Layer Suction in High-Speed Civil Airliners of Conventional Layout. Tech. Memo. No. Aero 327, British R.A.E., Feb. 1953.

Starting with an existing design study for a 550 mph airliner carrying 100 passengers 5000 miles this note discusses the effect on the passenger load of reducing the profile drag, allowing arbitrary amounts for the weight of suction apparatus. It is estimated that a typical high-speed suction aircraft achieving 80% smaller C_{D_0} than the aircraft (entailing suction on the body as well as the wing) for a weight penalty of $7\frac{1}{2}$% AUW would carry a 70% greater passenger load for the same range, speed and AUW. The extra passengers could be accommodated with the same standard of comfort in a slightly larger aircraft with relatively larger body size but of quite normal appearance. The cost per passenger-trip for the suction aircraft would be about half that for the datum aircraft and only slightly greater than that of the thick all-wing suction design of 150 mph lower cruising speed discussed in ref. 1. It is concluded that subject to the assumptions made being of the right order the high-speed thin wing suction design with fuselage is a better proposition than the low speed thick all-wing design and merits further study, particularly as regards the detail design and engineering aspects of the problem.

Author

Availability:
N78-78057
N-53306

130. Darby, R. A.: An Aircraft Manufacturer Looks at Boundary Layer Control. Eng. Rep. No. RR-1, Fairchild Aircraft, Apr. 1, 1954. (Available from DDC as AD 82 204.)

The objectives of boundary layer control are examined. The nature of the boundary layer is described, and transition and separation explained. The basic methods of controlling separation and transition are briefly described, and the simplest and most used boundary layer parameters defined. A rather lengthy series of separation control installations that have been flight tested are presented, with the most important results, where available. Two applications of transition control, with numerical results, conclude the main body of the report.

Author

Availability:
N78-78058
N-44770
AD 82 204

131. Pfenninger, W.; and Bacon, John W., Jr.: Design Studies of Long Range Laminar Suction Airplanes at High Subsonic Speeds. Summary of Laminar Boundary Layer Control Research, WADC Tech. Rep. 56-111, U.S. Air Force, Apr. 1957, pp. 294-328. (Available from DDC as AD 130 759.)

The design of long range laminar suction airplanes is strongly affected by the requirements for extensive laminar flow, by the induced drag and the parasite drag of the fuselage. With the low friction drag possible with very extensive laminar flow, the induced drag becomes increasingly important, requiring wings with a larger span, higher aspect ratio, and span to maximum wing thickness ratio than nonsuction wings. Strut-braced high aspect ratio wings appear promising for long range laminar suction airplanes. Laminar suction airplanes with maximum range should be designed with larger wing areas (wing span and wing chord) than nonsuction airplanes, since the increased wing chords do not appreciably increase the friction drag. Swept all laminar suction wings which are desirable from the standpoint of gust loads and high subsonic cruising speeds, seem to be theoretically feasible at moderately large wing chord Reynolds numbers. Completely laminar flow and very low profile drags have been observed on wings in flight at high Reynolds numbers, and 100% laminar flow has been maintained on a body of revolution by means of boundary layer suction. Extensive laminarization of an airplane as a result of low drag boundary layer control will increase the lift to drag ratio of long range airplanes considerably and, in addition, will reduce the engine specific fuel consumption. The question then arises as to how low drag boundary layer suction can best be applied to long range airplanes, particularly for extreme ranges. The purpose of this study is to show the range potential of laminar suction airplanes and to present some of the specific design problems of such airplanes and possible solutions.

Author

Availability:
N78-76390
N-53889
AD 130 759

132. Pfenninger, W.: Note About the Range Performance of High Altitude Long Range Photoreconnaissance Airplanes With Low Drag Boundary Layer Suction. Rep. No. NAI-56-264 (Rep. No. BLC-85), Northrop Aircraft, Inc., Mar. 1956. (Available from DDC as AD 105 924.) (Also available in Summary of Laminar Boundary Layer Control Research, WADC Tech. Rep. 56-111, U.S. Air Force, Apr. 1957, pp. 329-338. (Available from DDC as AD 130 759.))

Completely laminar flow and very low profile drags have been achieved on wings in flight at high Reynolds numbers by means of boundary layer suction. Extensive laminarization of an airplane as a result of low drag boundary layer suction will increase the airplane lift to drag ratio considerably and, in addition, will slightly reduce the specific fuel consumption. These results will enable increased ranges at all altitudes above approximately 20,000 feet. The question then arises as to how low drag boundary layer control can best be applied to airplanes with extreme ranges.

The purpose of the present study is to show the possible range-altitude performances of high altitude long range photoreconnaissance airplanes with laminar suction.

Author

Availability:
N78-75294
N78-76390
CN-56124
N-53889
NAI-56-264 (BLC-85)
AD 105 924
AD 130 759

133. Pfenninger, W.: Note on Long Range Photoreconnaissance Airplanes With Low Drag BLC Cruising at Very High Altitudes, NAI-57-710, Rep. No. BLC-98 (Contract AF33(616)-3168), Northrop Aircraft, Inc., May 1957. (Available from DDC as AD 140 586.)

As a result of the small length and unit length Reynolds numbers of a subsonic photoreconnaissance airplane cruising at very high altitudes, it appears feasible to maintain extensive and, very likely, completely laminar flow over the whole airplane, by means of low drag boundary layer suction, even in the rear part of the fuselage downstream of a wing fuselage juncture.

Author

Availability:
SN-24021, May 1957
NAI-57-710
BLC-98
AD 140 586

134. Pfenninger, W.: Design Considerations of Large Subsonic Long Range Transport Airplanes With Low Drag Boundary Layer Suction. Rep. No. NAI-58-529 (BLC-111), Northrop Corp., July 1958. (Available from DDC as AD 821 759.)

The design of a large long range subsonic transport airplane with low drag boundary layer suction is influenced by many different and often contradicting factors. The designer has to balance them in such a manner as to obtain the best possible range-payload performance. At the same time, in view of the high length Reynolds numbers with laminar flow on a large transport airplane, he has to compromise the design in such a manner as to maintain extensive laminar flow with a high probability of success without excessive difficulties and complications. These latter considerations will influence the design of large laminar suction airplanes to a much higher degree than one might suspect at a first look. The designer will be forced to carefully balance all the aerodynamic, structural, aeroelastic, propulsion, and manufacturing problems of a laminar suction airplane against each other, in order to obtain a good performance without encountering extreme difficulties in the design of the various components of a large long range laminar suction airplane.

Author

Availability:
N63-82435
SN-24021, Oct. 1958
NAI-58-529 (BLC-111)
AD 821 759

135. Lachmann, G. V.: Aspects of Design, Engineering and Operational Economy of Low Drag Aircraft. Boundary Layer and Flow Control, Volume 2, G. V. Lachmann, ed., Pergamon Press, 1961, pp. 1123-1166.

It has been demonstrated both in the United Kingdom and in the United States that laminar flow over the full chord can be achieved in flight. Jet fighter aircraft fitted with gloves to the wing to which suction was applied were used in both countries for these experiments which represented the culmination of many year's work on boundary layer control. The state of the art which has been reached is summarized.

To bridge the gap between the present state of the laminar flow technique and successful operational transport aircraft three important questions have to be answered:

(i) Can practical engineering solutions achieve the design and construction of aircraft skin and suction systems which are light, simple and robust and low enough in cost to satisfy the operator?

(ii) Can surface contamination by flies and dust be overcome in a practical way in all likely operational conditions without undue penalties in operating costs?

(iii) Can the laminarized aircraft be designed directly competitive with its conventional rival in speed, range, payload and airfield requirements and at the same time, based on the most careful comparative project studies, show a marked economic advantage?

An attempt is made in the following to give an answer to these questions with respect to potential subsonic low drag aircraft. An outlook is also given in regard to a second-stage application of the laminar flow technique to future supersonic aircraft.

It has to be emphasized that the practical basis of all deductions consists today in a limited amount of flight experience with small partially laminarized aircraft, design studies and technological investigations of different types of suction surfaces, ducts, suction pumps, etc.

It goes without saying that operators will only be convinced of the potential benefits resulting from the laminar flow technique after a representative aeroplane has been designed and built and has plainly demonstrated the economic advantages by operating successfully in realistic conditions.

Author

136. Laminar Report - Handley Page Progress in the Field of Boundary-Layer Control. Flight Int., vol. 82, no. 2783, July 12, 1962, pp. 64-66.

Describes briefly the role of Handley Page Ltd. under the direction of Dr. G. V. Lachmann in the field of laminar boundary layer control. Much interest in the U.K. and U.S. was lost after W. E. Gray of the R.A.E. found that huge suction was necessary to keep the flow over a swept wing laminar. However, Handley Page and M. R. Head were encouraged by a group from Northrop (headed by Pfenninger) and they found that they could drastically reduce the suction required on a swept wing. Northrop under U.S.A.F. Contracts began the modifications on the two B-66s that were to become the X-21's. Britain did some flight testing of test wings and by 1962 had done some preliminary work by flying slender delta wings at $\pm M = 2$.

137. Laminar Flow Control Program, NB 61-371, Northrop Corp., Dec. 1961.

This brochure is a reprint of presentations made at the Scientific Advisory Board Aerospace Vehicles Panel Meeting on Laminar Flow Control held at the Northrop Norair Engineering Center on 9 November 1961.

Groth, Eric E.: Low Drag Boundary Layer Suction Experiments at Supersonic Speeds. pp. 3-11.

Pfenninger, W.: Influence of Acoustical Disturbances on the Behavior of a Swept Laminar Suction Wing. pp. 13-32.

Kuska, M.: LFC Demonstration Airplane Program Status. pp. 33-41.

Warner, D. D.: Wing Geometry and Suction Distribution of LFC Demonstration Airplane. pp. 43-63.

Brown, S. H.: Laminar Flow Control Design Application Studies. pp. 65-109.

Availability:
X63-80002

138. Gasich, Welko E.: Application of Laminar Flow Control to Transport Aircraft. Aerosp. Eng., vol. 20, no. 10, Oct. 1961, pp. 22-23, 44, 46-48, 50-52.

This paper summarizes the research work conducted by Northrop Corporation in the field of Laminar Flow Control and relates this research to application studies for transport-type aircraft. It discusses some of the areas which have received relatively little emphasis, and which are now commanding greater attention among aircraft designers and airline operators. In order to determine the applicability of Laminar Flow Control to transport aircraft, one must compare the operating costs of normal aircraft having turbulent boundary layers with aircraft employing Laminar Flow Control on wings and empennage. This consideration leads to the determination of manufacturing costs, maintenance costs, and operational considerations. It is the intent of this paper to discuss these facets of the problem and to relate them to design studies for transport aircraft employing Laminar Flow Control.

A brief description of the two demonstration airplane configurations and the program objectives are discussed.

Author

Availability:
N78-78056
N-99923

139. Pfenninger, W.; and Bacon, John W., Jr.: General Design Investigations of Long Range Laminar Suction Airplanes. NAI-56-615, Rep. No. BLC-90 (Contract AF-33(616)-3168), Northrop Aircraft, Inc., Aug. 1956. (Available from DDC as AD 106 068(b).)

Completely laminar flow and very low profile drags have been observed on wings in flight at high Reynolds numbers and 100% laminar flow has been maintained on a body of revolution by means of boundary layer suction. Extensive laminarization of an airplane as a result of low drag boundary layer control will increase the lift to drag ratio of long range airplanes considerably and, in addition, will reduce the engine specific fuel consumption. The question then arises as to how low drag boundary layer suction can best be applied to long range airplanes, particularly for extreme ranges. The purpose of this study is to show the range potential of laminar suction airplanes and to present some of the specific design problems of such airplanes and possible solutions.

Author

Availability:
SN-24021, July 1956
NAI-56-615
BLC-90
AD 106 068(b)

140. Amsler, R. C.: A Generalized Design and Cost Study of Laminar Flow Control Application to Cargo Aircraft. NOR-62-28, Northrop Corp., Feb. 1962.

This report is the result of a study conducted at Norair to determine the potential improvements, in performance and direct operating cost, which can be obtained by the application of Laminar Flow Control to turbofan-powered transports designed specifically for economical air transportation of cargo at high subsonic speeds, in both military and commercial operations.

This study is primarily concerned with determining the effects of take-off gross weight, payload, cruise Mach number, and extent of application of Laminar Flow Control on performance, acquisition cost, and direct operating cost. In order to determine the effects of cruise Mach number, turbulent aircraft and aircraft with LFC applied to the wing and tail, both with a design payload of 50,000 pounds and a design range of 4,000 nautical miles, were studied for cruise Mach numbers of .70, .75, .80, and .85. The effects of take-off gross weight were studied by varying take-off gross weight from 150,000 to 500,000 pounds for the .70 and .80 cruise Mach number aircraft. In order to determine the effects of the extent of application of LFC, the .80 cruise Mach number aircraft were studied with LFC on the wing only, as well as with LFC on the wing and tail. Finally, in order to determine the effects of payload, design payloads were varied from 50,000 to 125,000 pounds for the .80 cruise Mach number aircraft, both turbulent and LFC wing and tail.

In order to be capable of world-wide operation from established airfields, all aircraft considered in this study are designed for operation at design take-off gross weight from 8,000 foot runways according to FAA rules.

Author

Availability:
NOR-62-28

141. Amsler, R. C.; and Newton, J. S.: Multipurpose Long Endurance Aircraft (MPLE) Airplane Design Analysis. Rep. NOR 63-109, Northrop Corp., June 1963.

The major aspects of configuration, propulsion and LFC systems, structural design, weight analysis, aerodynamics, and aircraft performance were considered in the development of this study. Variables which could be eliminated at the beginning of the study by logical reasoning were so eliminated and the reasoning involved therein is explained in this report, while variables which could not be so eliminated were analyzed in sufficient detail to establish their effect on aircraft selection.

The results of the study are presented in the form of tables, graphs, and conclusions illustrating the characteristics of the various aircraft configurations analyzed and the effects of the primary variables of airplane gross weight, design payload, cruise altitude, design cruise speed, and propulsion cycle on endurance and range for both turbulent and LFC aircraft.

Conclusions are reached regarding operational flexibility and areas of sufficient interest to warrant further study.

Author

Availability:
NOR-63-109

142. Ladin, E.; Madson, S. L.; and Ralles, H. A.: Multipurpose Long Endurance Aircraft (MPLE) System Evaluation and Cost Analysis. Rep. NOR 63-111 (Contract AF18(600)-2174), Northrop Corp., June 1963.

Included herein are various components of the systems cost and the total systems cost over a 7-year period for the Offensive Armed Mission, Defensive Armed Mission (AEW&C), and the Command and Surveillance Mission (Extended Range Ballistic Missile Detection). In addition, operating costs are shown for the Logistic Mission.

A description of the cost model and a typical example is given in the Appendix.

Therefore, it is concluded that either the 450,000 lb. gross weight, 108,500 lb. payload or the 300,000 lb. gross weight, 73,000 lb. payload would be a good selection. Investigation of the probable threat should more clearly define the desirable payload.

Study of speed and altitude effects on system cost, Figures 19 and 20 show that the optimum LFC aircraft with regenerative turboprop engines for the AEW&C mission is one designed for Mach 0.5 at 25,000 feet or Mach 0.6 at 35,000 feet. The turbulent aircraft optimum is shown on Figures 21 and 22 to be Mach 0.5 at 25,000 feet.

The total systems costs of aircraft with regenerative high-bypass turbofan engines having speeds of 0.6 - 0.7 Mach at 35,000 ft. (Figure 18) are about 3% lower than the regenerative turboprop aircraft at 0.5 Mach and 25,000 ft. altitude.

It is noted that the installation of Laminar Flow Control on the aircraft surfaces, regardless of size or propulsion method, reduces total system costs by 15 to 20 percent.

Author

Availability:
NOR 63-111

143. The Laminar Flow Control Presentation for the Aeronautical Systems Division, May 3-4, 1962. NB 62-105, Norair Div., Northrop Corp., Aug. 1962.

Primary subject areas of presentation:

I LOW DRAG BOUNDARY LAYER SUCTION RESEARCH

Recent Developments in the Field of Low Drag Boundary Layer Suction 1

Low Drag Boundary Layer Suction Experiments at Supersonic Speeds 23

Influence of Acoustical Disturbances on the Behavior of a Swept Laminar Suction Wing 33

Theoretical Investigation of Laminar Boundary Layer at Supersonic Speeds 45

II THE TECHNOLOGICAL DEMONSTRATION AIRPLANE PROGRAM STATUS

Development of a Wing Configuration for Laminar Flow Control . . . 53

Laminar Flow Control Suction Distribution on Swept Wings 63

The Suction System 69

Wing Structural Design 81

Availability:
N64-81625

144. Amsler, R. C.: Aircraft Performance Studies for the CX-HLS-Type Heavy Logistic Aircraft. NOR 64-110, Northrop Corp., May 1964.

Summarizes a rather brief study of the effects of various configuration and propulsion parameters on the performance of aircraft designed to satisfy the heavy logistic aircraft designated the CX-HLS. The results of the study on this type of aircraft indicate that the optimum turbofan bypass ratio is approximately 10, providing approximately a 15 to 20% greater range than a bypass ratio of 2; that engine regeneration yields a further range increase of 10% or more; and that LFC on the wing and empennage increases range by approximately 30 to 40%. The combination can result in range increases of 65 or 80%.

Availability:
NOR 64-110

145. Newton, J. S.: Propulsion and LFC Systems Studies for Heavy Logistic Aircraft. NOR 64-109, Northrop Corp., June 1964.

The relationship between primary propulsion engines and the main components of LFC systems is discussed and preliminary performance and weight estimates for LFC systems are included. Graphs and sketches illustrate the characteristics of the systems studied. Suggestions for possible improvements are made.

Availability:
NOR 64-109

146. Cargo Aircraft Efficiency With LFC. 65-6474YZ, Norair Div., Northrop Corp., [1965].

The increased range possibilities, or the increased load-carrying capabilities, at the same range with LFC are shown in charts as LFC technology is applied to a C-5 type aircraft.

Availability:
N79-73467

147. Skavdahl, Howard: Endurance Capabilities of Current State-of-the-Art Airplanes With and Without Boundary-Layer Control. U.S. Air Force Proj. RAND Res. Memo. RM-2459, RAND Corp., Feb. 16, 1960. (Available from DDC as AD 316 692.)

This research memorandum presents the methods and results of a design study concerning the endurance-payload capability of conventional airplane designs based on present state-of-the-art technologies. A later publication will present the system costs for the airplanes described in this memorandum.

Two general types of airplanes are considered here. One type makes use of boundary-layer control (BLC) on the wing and empennage surfaces for the purpose of reducing drag during cruise. The other airplane type does not use BLC. All other aspects of the technical design of the two types of airplanes are the same. The design and operational parameters investigated, and their variations, are shown below.

	Parameter range
Gross weight, lb	300,000 - 600,000
Payload, lb	25,000 - 150,000
Design altitude, ft	25,000 - 40,000
Design velocity, kn	175 - 265

Performance results indicate that the optimum wing aspect ratio is approximately 12 for both types of airplanes, whereas the optimum wing thickness ratio for the BLC and non-BLC designs is 0.20 and 0.16, respectively. The endurance calculations show that a 500,000-lb BLC airplane can remain airborne 5 days with a payload of 50,000 lb, or 3 days with a payload of 100,000 lb. The airplanes designed with BLC have 55 to 75 per cent greater endurance capability than the airplanes designed without BLC. An additional advantage of these airplanes is their large capacity, permitting abundant space for crew relaxation and flexibility in payload.

Author

Availability:
N79-70661
N-82373
AD 316 692

148. Higman, Terry: A Comparison of Laminar Flow Control and Turbulent Airplane Designs. Doc. No. D6-24211 TN, Boeing Co., 1969.

A parametric study has been conducted to evaluate the merits of applying laminar flow control (LFC) to a commercial airplane. The study encompasses a comparison of LFC and turbulent configurations with a fixed payload (200 passengers) at design ranges of 3000 and 5700 nautical miles, and a comparison of LFC and turbulent configurations with a fixed engine size (T_{SLS} = 25,000 lb) for a design range of 5700 nautical miles. For the laminar airplanes at the long range, sensitivity studies are included to show the influence of the LFC

weight penalty, wing aspect ratio, and leading edge devices. Economic data showing cost considerations of the selected configurations are presented.
Author

Availability:
N78-78054

149. Baranov, A. A.; Budzinauskas, M. P.; Yenenkov, V. G.; Klyachkin, A. L.; Maksay, A. V.; Milen'kin, Yu. D.; Mogilevskiy, G. D.; Smirnov, A. G.; Dantsyg, A. Ya.; and Lebendik, V. P.: Issledovaniye dal'nykh passazhirskikh samoletov s usovershenstvovannoy aerodinamikoy i perspektivnymi dvigatelyami. Riga, 1971.

The book contains the results of research on long-distance passenger planes (l=8000 and 15,000 kilometers) with improved aerodynamic features (due to the introduction of laminar flow-around control systems) and with prospective power plants (third generation ducted-fan turbine engine). The effect of the lamination of the wing and the tail fins with regard to corresponding technical costs (the introduction of special suction engines or devices, complication and weighting of the construction of the supporting surfaces) on the aerodynamic quality, take-off weight and the thrust-weight ratio of the airplane and on the total cost of transports is shown. A comparative technical and economic study of the effect of calculated Mo Numbers and flight altitudes on the technical and economic characteristics of long-distance planes with standard (turbulent) and laminar flow-around is conducted. The expediency of using suction engines for the suction method of boundary layer control on jet flaps with the purpose of improving take-off and landing characteristics of airplanes is examined.

The study was completed by the authors in 1969 and is for specialists in the area of airplane and engine construction; it may be used for the degree design in aviation VUZs of the Soviet Union.

Availability:
STIF (In cataloging process)

150. Ryzhenko, A. I.; and Iasinskii, F. G.: Postanovka zadachi proektirovaniia i analiza variantov seriinykh konstruktsii sistem otsosa pogranichnogo sloia. Samoletostr. Tekh. Vozdushn. Flota, no. 40, 1976, pp. 73-74.

The paper deals with the need to work out a set of design solutions for boundary layer suction (BLS) systems to minimize drag on airframes, and to pose the problem of selecting the best variants of such BLS systems for mass production, on the basis of optimization studies. Soviet and foreign work on optimization of thin-walled aviation structural elements and applicable optimization techniques are reviewed briefly. Boundary-layer laminarization, airframe skin fabrication variants, and tradeoffs in the design of BLS surface are discussed.

Availability:
A77-32713

151. Kulfan, Robert M.; and Howard, Weston M.: Application of Advanced Aerodynamic Concepts to Large Subsonic Transport Airplanes. AFFDL-TR-75-112, U.S. Air Force, Nov. 1975. (Available from DDC as AD A019 956.)

A preliminary design study has been made to identify the performance advantages obtained when advanced aerodynamic technology aircraft are used to perform subsonic military air missions requiring long range (10 000 nmi) or high endurance (24 hr) with heavy payloads (250 000 lb and 400 000 lb, respectively). The study consisted of two phases; the first included evaluating the performance benefits by individually applying various advanced aerodynamic concepts and recommending areas where additional research and development work are necessary to develop, apply, and further identify the potential of the most promising concepts. The second phase included configuring integrated advanced technology aircraft (long-range airplane, and high endurance airplane) that incorporated the most promising compatible aerodynamic concepts. Comparisons were made with corresponding conventional aerodynamic technology configurations designed for similar missions.

The results indicated that laminar flow control offers the greatest single performance benefit for large military transport aircraft. With 60% of the wing and tail wetted areas laminarized, fuel savings of 29% and gross weight reductions of 17% were identified. Advanced high-speed airfoils that offer a high probability of success were established as the best supporting concept to be utilized in combination with other advanced concepts.

Application of a compatible set of advanced aerodynamic concepts considered feasible for the 1985 time period resulted in fuel savings of 63% and weight reduction of 42% for the long-range airplane. The fuel savings and weight reduction for the high endurance airplane were 54% and 28%, respectively. The concepts combined to attain these improvements were: wingtip fins, high-speed airfoils, body boundary layer control or compliant skin, laminar flow control, aft center of gravity, wing-body contouring, and integration of these into a configuration using a high aspect ratio wing.

Recommendations are given for additional system studies and more detailed design and development work to establish more fully the potential of the various aerodynamic concepts.

Author

Availability:
N76-25159
AD A019 956

152. Lee, Godfrey H.: Unassailable Aerodynamic Logic. Aerospace, vol. 3, no. 9, Nov. 1976, pp. 14-28.

The LFC airplane is discussed in general; the emphasis being on the work of Handley Page after World War II. This work was carried out under the leadership of Dr. Lachmann and is briefly described.

Availability:
CN-150,091

153. Sturgeon, R. F.; and Bennett, J. A.: Design Considerations for Laminar-Flow-Control Aircraft. Advances in Engineering Science - Volume 4, NASA CP-2001, 1976, pp. 1539-1548.

A study was conducted to investigate major design considerations involved in the application of laminar flow control to the wings and empennage of long range subsonic transport aircraft compatible with initial operation in 1985. For commercial transports with a design mission range of 10,186 km (5500 n mil) and a payload of 200 passengers, parametric configuration analyses were conducted to evaluate the effect of aircraft performance, operational, and geometric parameters on fuel efficiency. Study results indicate that major design goals for aircraft optimization include maximization of aspect ratio and wing loading and minimization of wing sweep consistent with wing volume and airport performance requirements.

Author

Availability:
N77-10366

154. Sturgeon, R. F.; Bennett, J. A.; Etchberger, F. R.; Ferrill, R. S.; and Meade, L. E.: Study of the Application of Advanced Technologies to Laminar-Flow Control Systems for Subsonic Transports. Volume I: Summary. NASA CR-144975, 1976.

A study was conducted to evaluate the technical and economic feasibility of applying laminar flow control to the wings and empennage of long-range subsonic transport aircraft compatible with initial operation in 1985. For a design mission range of 10,186 km (5500 n mi), advanced technology laminar-flow-control (LFC) and turbulent-flow (TF) aircraft were developed for both 200- and 400-passenger payloads, and compared on the basis of production costs, direct operating costs, and fuel efficiency.

As part of the study, parametric analyses were conducted to establish the optimum geometry for LFC and TF aircraft, advanced LFC system concepts and arrangements were evaluated, and configuration variations maximizing the effectiveness of LFC were developed. For the final LFC aircraft, analyses were conducted to define maintenance costs and procedures, manufacturing costs and procedures, and operational considerations peculiar to LFC aircraft.

Compared to the corresponding advanced technology TF transports, the 200- and 400-passenger LFC aircraft realized reductions in fuel consumption up to 28.2%, reductions in direct operating costs up to 8.4%, and improvements in fuel efficiency, in ssm/lb of fuel, up to 39.4%. Compared to current commercial transports at the design range, the LFC study aircraft demonstrate improvements in fuel efficiency up to 131%.

Research and technology requirements requisite to the development of LFC transport aircraft were identified.

Author

Availability:
N76-24144

155. Sturgeon, R. F.; Bennett, J. A.; Etchberger, F. R.; Ferrill, R. S.; and Meade, L. E.: Study of the Application of Advanced Technologies to Laminar-Flow Control Systems for Subsonic Transports. Volume II: Analyses. NASA CR-144949, 1976.

(This document supersedes preliminary issue dated Jan. 15, 1976.)

Availability:
N76-24145

156. Sturgeon, R. F.: The Development and Evaluation of Advanced Technology Laminar-Flow-Control Subsonic Transport Aircraft. AIAA paper 78-96, Jan. 1978.

A study was conducted to evaluate the technical and economic feasibility of applying laminar flow control (LFC) to the wings and empennage of long-range subsonic transport aircraft for initial operation in 1985. For a design mission range of 5500 n mi, advanced technology LFC and turbulent-flow aircraft were developed for a 200-passenger payload, and compared on the basis of production costs, direct operating costs, and fuel efficiency. Parametric analyses were conducted to establish optimum geometry, advanced system concepts were evaluated, and configuration variations maximizing the effectiveness of LFC were developed. The final comparisons include consideration of maintenance costs and procedures, manufacturing costs and procedures, and operational considerations peculiar to LFC aircraft.

Author

Availability:
A78-52626

157. Lovell, W. A.; Price, J. E.; Quartero, C. B.; Turriziani, R. V.; and Washburn, G. F.: Design of a Large Span-Distributed Load Flying-Wing Cargo Airplane With Laminar Flow Control. NASA CR-145376, 1978.

A design study was conducted to add laminar flow control to a previously design span-distributed load airplane while maintaining constant range and payload. With laminar flow control applied to 100 percent of the wing and vertical tail chords, the empty weight increased by 4.2 percent, the drag decreased by 27.4 percent, the required engine thrust decreased by 14.8 percent, and the fuel consumption decreased by 21.8 percent. When laminar flow control was applied to a lesser extent of the chord (approximately 80 percent), the empty weight increased by 3.4 percent, the drag decreased by 20.0 percent, the required engine thrust decreased by 13.0 percent, and the fuel consumption decreased by 16.2 percent. In both cases the required take-off gross weight of the aircraft was less than the original turbulent aircraft.

Author

Availability:
N78-30045

158. Jernell, Lloyd S.: Effects of Laminar Flow Control on the Performance of a Large Span-Distributed-Load Flying-Wing Cargo Airplane Concept. NASA TM 78715, 1978.

A study was conducted to determine the effects of laminar flow control on the performance of a large span-distributed-load flying-wing cargo airplane concept having a design payload of 2.669 MN (600 000 lbf) and range of 5.93 Mm (3 200 n.mi.). Two configurations were considered. One employed laminarized flow over the entire surfaces of the wing and vertical tails, with the exception of the estimated areas of interference due to the fuselage and engines. The other case differed only in that laminar flow was not applied to the flaps, elevons, spoilers, or rudders. The two cases are referred to as the 100 percent and 80 percent laminar configurations, respectively.

The utilization of laminar flow control results in reductions in the standard day, sea level installed maximum static thrust per engine from 240 kN (54 000 lbf) for the non-LFC configuration to 205 kN (46 000 lbf) for the 100 percent laminar configuration and 209 kN (47 000 lbf) for the 80 percent case. Weight increases due to the LFC systems cause increases in the operating empty weights of approximately 3 to 4 percent. The design takeoff gross weights decrease approximately 3 to 5 percent. The FAR-25 takeoff field distances for the LFC configurations are greater by about 6 to 7 percent. Block times are virtually unaffected by the utilization of LFC. As compared to the non-LFC configuration, block fuel weights are reduced 24 percent for the 100 laminar configuration and 18 percent for the 80 percent case. Fuel efficiencies for the respective configurations are increased 33 percent and 23 percent.

Author

Availability:
N78-17851

159. Turriziani, R. V.; Lovell, W. A.; Price, J. E.; Quartero, C. B.; and Washburn, G. F.: Preliminary Design Characteristics of a Subsonic Business-Jet Concept Employing Laminar Flow Control. NASA CR-158958, 1978.

Aircraft configurations were developed with laminar flow control (LFC) and without LFC. The LFC configuration had approximately eleven percent less parasite drag and a seven percent increase in the maximum lift-to-drag ratio. Although these aerodynamic advantages were partially offset by the additional weight of the LFC system, the LFC aircraft burned from six to eight percent less fuel for comparable missions. For the trans-atlantic design mission with the gross weight fixed, the LFC configuration would carry a greater payload for ten percent fuel per passenger mile.

Availability:
N78-33087

160. Kulfan, Robert M.; and Vachal, John D.: Application of Laminar Flow Control to Large Subsonic Military Transport Airplanes. AFFDL-TR-77-65, U.S. Air Force, July 1977. (Available from DDC as AD A052 422.)

A preliminary design study has been made to investigate the impact of the application of laminar flow control on the performance, weight, fuel consumption, and economics of a large transport airplane designed to carry a heavy payload (350,000 lb) for a long range (10,000 nmi). The study was conducted in three phases. In the first phase, conceptual design investigations were conducted to identify the features of an LFC airplane optimized to accomplish the mission objectives. A reference turbulent airplane also was developed in this phase. Design and analysis studies were made to develop the final LFC configuration. This configuration was sized to determine the gross weight, engine size, wing area, and fuel requirements necessary to achieve the design mission. Various performance trade and sensitivity studies were conducted for the turbulent and LFC airplanes in the third phase. Life-cycle and operating cost evaluations were also made. A valid assessment of an LFC airplane must be preceded by an extensive design, development, and flight test program. Consequently, this study focused on identifying the relative benefits from applying LFC, and on the sensitivities of these relative benefits to the current major LFC uncertainty items.

Author

Availability:
N78-24098
AD A052 422

161. Laminar Flow Control Airplane Demonstration Program: LFC Airplane Operational & Cost Analysis. NOR-61-143 (Contract AF 33(600)-42052), Northrop Corp., Apr. 1964. (Available from DDC as AD 601 735.)

This report presents operational and cost analyses of service-type aircraft incorporating Northrop Norair's Laminar Flow Control System. This is one of a series of three reports presenting final results of the X-21A Laminar Flow Control Airplane Demonstration Program conducted under USAF Contract AF 33(600)-42052. Other reports in the series are; "LFC Airplane Design Data," Report NOR-61-141, and "LFC Airplane Manufacturing Techniques," Report NOR-61-142.

The operational analysis indicates the primary operational requirements of LFC systems are those related to smoothness and cleanliness of the surfaces and to the operation and control of the suction system. Present indications are that surface smoothness and cleanliness can be assured by a combination of appropriate inspection and cleaning procedures during preflight operations, and the use of suitable in-flight procedures during adverse weather conditions. Procedures and techniques related to operation of the suction system are simple, and requirements for system adjustments during flight are minimal; hence, these functions can be integrated with existing duties of the flight engineer.

Other operational characteristics considered in this analysis are effects of the loss of laminar flow on mission performance and flying qualities. Results of this analysis indicate no major operational problems will be encountered with service-type LFC airplanes.

The first part of the cost analysis is concerned with procurement costs and the second in estimating direct operating costs. Costs are compared with turbulent and laminar aircraft. DOC savings could be 8-16%.

Author

Availability:
N75-77407
NOR-61-143
AD 601 735

162. Jobe, C. E.; Kulfan, R. M.; and Vachal, J. D.: Application of Laminar Flow Control to Large Subsonic Military Transport Airplanes. AIAA Paper 78-95, Jan. 1978.

A study of performance increase that could result from applying advanced aerodynamic concepts to large, long-range military transport aircraft showed that laminar flow control (LFC) offered the largest potential. A more in-depth design study then investigated the impact of LFC on the performance, weight, fuel consumption, and economics of a military transport designed to carry 350,000 lb 10,000 nmi. The design study identifies the optimum wing planform and cruise speed, the relative performance increases from different amounts of LFC, and sensitivities to the major LFC uncertainty items; i.e., increased systems weight, complexity, and maintenance, which can only be quantified by design, development, and flight test.

Author

Availability:
A78-22571

163. Eckard, Glenn J.; Hatley, James P.; and Hoefs, Kenneth N.: Laminar Flow Control Airplane Performance Methods. Doc. No. D6-6619, Boeing Co., Jan. 1964.

The analysis of a laminar flow airplane as compared to a turbulent airplane is unique in that there is an interaction of the thrust and drag forces, whereas in a turbulent airplane design, they are essentially independent. This report presents a method of analysis (aerodynamic and propulsive) for an airplane employing laminar flow control (LFC) for drag reduction. The thrust and drag terms originating from the application of LFC are consistently applied to both the thrust calculation and the airplane drag calculation. A brief description of the primary considerations in establishing thrust, drag and fuel flow of a subsonic airplane to which LFC has been applied is given.

Author

Availability:
CN-150,143

164. Pfenninger, W.; Raetz, G. S.; and Brown, W. B.: Note on Design Problems of Swept Laminar Suction Wings. Rep. No. NAI-55-549, BLC-79, Northrop Aircraft, Inc., May 1955. (Available from DDC as AD 79 343.) (Also available in Summary of Laminar Boundary Layer Control Research, WADC Tech. Rep. 56-111, Apr. 1957, pp. 146-175. (Available from DDC as AD 130 759.))

The minimum suction quantity required to maintain 100% laminar flow on a swept wing at moderately high Reynolds numbers was estimated. For a 6%-thick 40°-swept wing at a flight Mach number of 0.9, a flight Reynolds number of 10^7, and a lift coefficient of 0.3, the suction quantity on the upper wing surface has to be increased by 40%, as compared with a straight wing with the same resultant incremental velocities. However, the range of a laminar suction airplane propelled by gas turbines (fed with ram air) driving separate suction compressors is practically unaffected by the increased suction quantities required by wing sweep.

Author

Availability:
N76-77660
SN-24021, May 1955
NAI-55-549
BLC-79
AD 79 343
N78-76390
N-53889
AD 130 759

165. Bonner, Tom F., Jr.; Pride, Joseph D., Jr.; and Fernald, William W.: Aircraft Energy Efficiency Laminar Flow Control Wing Design Study. NASA TM 78634, 1977.

An engineering design study was made of a commercial-passenger-type long range aircraft with laminar flow control (LFC) applied to its wings. The objective of this engineering design study was to perform the necessary design and analyses to configure an integrated LFC wing, including all of the subsystem interfaces associated with a typical wing design plus those special requirements related to the LFC systems.

The LFC-aircraft configuration selected for this design study was sized for a range of 10,192.5 km (5500 n. mi.) with 200 tourist class passengers in 7 abreast seating, plus 4,535.9 kg (10,000 lbm.) cargo and a F.A.R. take-off field length not to exceed 3,200 m (10,500 ft.).

The design mission was for cruise at M = .8 at a ceiling of 11,582 m (38,000 ft.). The airplane achieved a cruise L/D ratio of 25.2; approximately 25% better in performance than with LFC system inoperative. The total fuel required for the 10,192.5 km (5500 n. mi.) mission was 56,698.7 kg (125,000 lbm.).

Structural integration of the LFC system slots, i.e., ducting and plenum compartment, was evaluated. Two structural materials, aluminum and titanium, were evaluated and compared. The results of this design study indicates that LFC can be effectively integrated into the wing structure using both standard aluminum and advanced titanium technology and the titanium technology can be expected to yield a lighter weight design.

Author

Availability:
N78-13042

166. CTOL Transport Technology - 1978. NASA CP-2036, Pt. I, 1978.

The proceedings of the NASA CTOL Transport Technology Conference held at Langley Research Center February 28 - March 3, 1978, are presented in this compilation. New technology generated by NASA in-house and contract efforts, including the ongoing Aircraft Energy Efficiency (ACEE) program, in the various disciplinary areas specifically associated with advanced conventional take-off and landing (CTOL) transport aircraft are presented. The conference was divided into six sessions:

1. A session on propulsion addressed jet engine performance deterioration and improvement; energy efficient engine design and integration; advanced turboprops, engine materials, noise, and emissions; and broad specification fuels.

2. A session on structures and materials addressed structural sizing methodology; environmental effects of composites; and applications of advanced composite materials.

3. A session on laminar flow control addressed insect contamination and alleviation; suction prediction techniques; porous materials; and laminar flow applications.

4. A session on advanced aerodynamics and active controls technology addressed advanced wings, winglets, and nacelles; aerodynamic flow calculation techniques; fault-tolerant computers; and active control applications.

5. A session on operations and safety addressed safety research; wake vortex phenomena; advanced landing-gear research; noise prediction; improved terminal area operations; airline operating costs; and a method for cost/benefit analysis for aeronautical research and technology.

6. A session on advanced systems addressed developments in short-haul and supersonic transport research; coal-derived fuels and aircraft systems; and advanced transport concepts.

Kramer, James J.: Overview of NASA CTOL Program.

Technology generated by NASA and specifically oriented toward advanced commercial air transport is reviewed. Results of the Aircraft Energy Efficiency program and of related disciplinary areas are reported. The CTOL research efforts are put into perspective relative to the total NASA aeronautics program.

Muraca, Ralph J.: Laminar Flow Control Overview.

Application of laminar flow control technology to future CTOL long range transport aircraft was considered. Topics covered include: (1) airfoil development and test; (2) development and improvement of design methods; (3) evaluation of leading edge contamination; and (4) laminar flow control system definition and concept evaluation.

Peterson, John B., Jr.; and Fisher, David F.: Flight Investigation of Insect Contamination and Its Alleviation.

An investigation of leading edge contamination by insects was conducted with a JetStar airplane instrumented to detect transition on the outboard leading edge flap and equipped with a system to spray the leading edge in flight.

The results of airline type flights with the JetStar indicated that insects can contaminate the leading edge during takeoff and climbout. The results also showed that the insects collected on the leading edges at 180 knots did not erode at cruise conditions for a laminar flow control airplane and caused premature transition of the laminar boundary layer. None of the superslick and hydrophobic surfaces tested showed any significant advantages in alleviating the insect contamination problem. While there may be other solutions to the insect contamination problem, the results of these tests with a spray system showed that a continuous water spray while encountering the insects is effective in preventing insect contamination of the leading edges.

Srokowski, Andrew J.: Development of Advanced Stability Theory Suction Prediction Techniques for Laminar Flow Control.

The problem of obtaining accurate estimates of suction requirements on swept laminar flow control wings was discussed. A fast accurate computer code developed to predict suction requirements by integrating disturbance amplification rates was described. Assumptions and approximations used in the present computer code are examined in light of flow conditions on the swept wing which may limit their validity.

Allison, Dennis O.; and Dagenhart, John R.: Design of a Laminar-Flow-Control Supercritical Airfoil for a Swept Wing.

An airfoil was analytically designed and analyzed for a combination of supercritical flow and laminar flow control (LFC) by boundary layer suction. A shockless inverse method was used to design an airfoil and an analysis method was used in lower surface redesign work. The laminar flow pressure distributions were computed without a boundary layer under the assumption that the laminar boundary layer would be kept thin by suction. Inviscid calculations showed that this 13.5 percent thick airfoil has shockless flows for conditions at and below the design normal Mach number of 0.73 and the design section lift coefficient of 0.60, and that the maximum local normal Mach number is 1.12 at the design point. The laminar boundary layer instabilities can be controlled with suction but the undercut leading edge of the airfoil provides a low velocity, constant pressure coefficients region which is conducive to laminar flow without suction. The airfoil was designed to be capable of lift recovery with no suction by the deflection of a small trailing edge flap.

Gratzer, L. B.; and George-Falvy, D.: Application of Laminar Flow Control Technology to Long-Range Transport Design.

The impact of laminar flow control (LFC) technology on aircraft structural design concepts and systems was discussed and the corresponding benefits were shown in terms of performance and fuel economy. Specific topics discussed include: (1) recent advances in laminar boundary layer development and stability analysis techniques in terms of suction requirements and wing suction surface design; (2) validation of theory and realistic simulation of disturbances and off-design conditions by wind tunnel testing; (3) compatibility of aerodynamic design of airfoils and wings with LFC requirements; (4) structural alternatives involving advanced alloys or composites in combinations made possible by advanced materials processing and manufacturing techniques; (5) addition of suction compressor and drive units and their location on the aircraft; and (6) problems associated with operation of LFC aircraft, including accumulation of insects at low altitudes and environmental considerations.

Sturgeon, R. F.: Toward a Laminar-Flow-Control Transport.

Analyses were conducted to define a practical design for an advanced technology laminar flow control (LFC) transport for initial passenger operation in the early 1990's. Mission requirements, appropriate design criteria, and level of technology for the study aircraft were defined. The characteristics of the selected configuration were established, aircraft and LFC subsystems compatible with the mission requirements were defined, and the aircraft was evaluated in terms of fuel efficiency. A wing design integrating the LFC ducting and metering system into advanced composite wing structure was developed, manufacturing procedures for the surface panel design were established, and environmental and structural testing of surface panel components were conducted. Test results revealed a requirement for relatively minor changes in the manufacturing procedures employed, but have shown the general compatibility of both the selected design and the use of composite materials with the requirements of LFC wing surface panels.

Pearce, Wilfred E.: Application of Porous Materials for Laminar Flow Control.

Fairly smooth porous materials were elected for study Doweave; Fibermetal; Dynapore; and perforated titanium sheet. Factors examined include: surface smoothness; suction characteristics; porosity; surface impact resistance; and strain compatibility. A laminar flow control suction glove arrangement was identified with material combinations compatible with thermal expansion and structural strain.

Availability:
N78-27046

167. Pfenninger, W.; and Bacon, John W., Jr.: Note About the Range Performance of Future Long Range Low Drag Suction Airplanes With Partially Supersonic Range. Summary of Laminar Boundary Layer Control Research, WADC Tech. Rep. 56-111, Apr. 1957, pp. 339-351. (Available from DDC as AD 130 759.)

Completely laminar flow and very low profile drags have been achieved on wings in flight at high Reynolds numbers by means of boundary layer suction (References 1 through 4). Extensive laminarization of an airplane as a result of low drag boundary layer suction will increase the airplane lift to drag ratio considerably and, in addition, will slightly reduce the specific fuel consumption (References 6 and 7). These results will enable increased ranges at all altitudes above approximately 20,000 feet. The question then arises as to how low drag boundary layer control can best be applied to airplanes with extreme ranges.

The purpose of the present study is to show the possible range performance of a future subsonic-supersonic long range bomber-type airplane with low drag boundary layer control. Technical improvements (propulsion, fuel, aerodynamics, structures, materials) which might be feasible in the future have been taken into account in the general design consideration.

Author

Availability:
N78-75293
CN-56122
N78-76390
N-53889
AD 130 759

168. Craven, A. H.; and Hopkins, H. L.: On the Application of Boundary Layer Control to a Slender Wing Supersonic Airliner Cruising at M = 2.2. Rep. No. 157, Coll. of Aeronaut., Cranfield (England), Apr. 1962.

The use of suction or injection to reduce the drag of a supersonic airliner is considered. It is shown that injection gives no reduction in operating costs. With suction applied to an M = 2.2 aircraft on the London-New York route, the basic operating cost of 13.30d per short ton statute mile is expected to be reduced by 0.5d for the same payload, assuming no change in configuration. If the theoretical maximum skin friction reduction could be obtained, the payload could be increased by 4750 lb., and the direct operating cost could be reduced to 10.63d per short ton statute mile.

Author

Availability:
N62-17292

169. Seiff, Alvin: The Prospects for Laminar Flow on Hypersonic Airplanes. NACA RM A58D25, 1958.

The factors which affect the extent of laminar flow on airplanes for hypersonic flight are discussed on the basis of the available data. Factors considered include flight Reynolds number, surface roughness, angle of attack, angle of leading-edge sweepback, and aerodynamic interference. Test data are presented for one complete configuration.

Author

170. Study of the Feasibility of Delaying Transition on Hypersonic Cones by Suction. Rep. No. NOR 67-101 (Contract AF 04(694)-381), Northrop Corp., May 1967. (Available from DDC as AD 381 327.)

Availability:
X73-73640
NOR 67-101
AD 381 327

171. Smith, Maurice H.: Bibliography on Boundary Layer Control. Lit. Search No. 6, James Forrestal Res. Cent., Princeton Univ., Jan. 14, 1955.

Emphasis was placed upon 1950 - late 1954, though some earlier papers are included. Most of the items pertain to boundary layer control by mechanical means. Corollary material on flow visualization, the electric analogy, and injection pumps is included in separate sections. Some papers on geometric control are included.

Except for the special subject categories, the material has been listed by the country of origin. Abstracts have been provided for about two-thirds of the papers listed. Subject and author indexes have been included.

Availability:
N79-70012
N-40374

172. Blue, D. D.; and Satin, A.: Preliminary "Boundary Layer Control Application to Aircraft." ONR, Air Branch, 1950.

The status of BLC as applied to aircraft in 1950 is first discussed with emphasis on the German work during 1940-1945. Navy research, both experimental and theoretical, is proposed under titles such as:

Turbojet Engines for BLC
Possible Boundary Layer and Flow Control
Unconventional New Developments
BLC Application to Dornier Do-24
Boundary Layer Effects at Supersonic Speeds
Future BLC Program (in which it is suggested to invite German Aeronautical scientists to take part)

A bibliography of 312 items is included.

Availability:
N79-70013
N-12366

173. Lang, Thomas G.; and Brooks, John D.: Control of Torpedo Boundary Layers by Suction. NAVORD Rep. 6536, U.S. Navy, Apr. 30, 1959. (Available from DDC as AD 239 083.)

The available information on boundary-layer control and permeable materials is summarized and applied to a torpedo configuration. The torpedo could be propelled by sucking water through a porous shell and expelling it at the tail in the form of a jet. An analysis of the available data indicates that the drag of such a torpedo would be reduced by a factor of four. Various porous materials were investigated and a porous fiberglass was selected for preliminary testing. After discussion of several possible torpedo configurations a preliminary design of a free-running test vehicle is presented. The theory and the experimental determination of permeability as well as a bibliography of boundary-layer control are included as Appendixes.

Author

Availability:
N78-78542
CN-84315
AD 239 083

174. Jobe, Charles E.: A Bibliography of AFFDL/FXM Reports on Laminar Flow Control. AFFDL-TM-76-26-FXM, U.S. Air Force, Mar. 1976.

AFFDL/FXM was the Air Force office responsible for technically monitoring the X-21A Laminar Flow Control Flight Demonstration Program and the many associated research contracts. Approximately 165 reports and technical notes remain from the LFC research; due to the critical shortage of file cabinets and many "file Field days."

The bibliography is arranged alphabetically by personal author and date. The corporate author was used when the personal author was unknown. The many progress reports are listed as such, by contract number. A cross-reference list by NORTHROP BLC- ( ) number is contained on page 22.

Author

Availability:
N79-70034

175. Kopkin, T. J.; and Rife, C. D.: Laminar Flow Control Bibliography. Rep. No. LG 77ER0018, Lockheed-Georgia Co., Jan. 17, 1977. (Available from DDC as AD B026 321L.)

Availability:
X78-75877
AD B026 321L

176. Smith, A. M. O.; and Clutter, Darwin: A Proposal to Assess the Dependability of Laminar Flow and the Practical Problems of Maintaining It on an Airplane in Service Use. Rep. No. ES 26666, Douglas Aircraft Co., Inc., Aug. 2, 1957.

It is the purpose of this proposal to assess the reliability, and operational problems of maintaining extensive laminar flow under service conditions. Because roughness and other effects are at last adequately understood, the time is ripe for serious efforts in this area, first for the purpose of realizing the drag reduction potential, and second for evaluating the problems concomitant to the successful realization. A condensed statement of the program follows. Succeeding pages explain and elaborate the various items. A Lockheed TV-2 Trainer has been selected as the test airplane for the reason that it is inexpensive and has an unswept wing using an NACA low-drag airfoil section (NACA 65-123) favorable to laminar flow.

Author

Availability:
N79-70011
N-76505

177. Chapman, Gary T.: Transition of the Laminar Boundary Layer on a Delta Wing With 74° Sweep in Free Flight at Mach Numbers From 2.8 to 5.3. NASA TN D-1066, 1961.

The tests were conducted at Mach numbers from 2.8 to 5.3, with model surface temperatures small compared to boundary-layer recovery temperature. The effects of Mach number, unit Reynolds number, leading-edge diameter, temperature ratio, and angle of attack were investigated in an exploratory fashion. The results were compared to results of wind-tunnel tests of swept wings and to results of free-flight tests for unswept leading edges.

Author

Availability:
N62-71640

178. Rumsey, Charles B.; Piland, Robert O.; and Hopko, Russell N.: Aerodynamic-Heating Data Obtained From Free-Flight Tests Between Mach Numbers of 1 and 5. NASA TN D-216, 1960.

Aerodynamic-heating data were obtained from temperature measurements made at a single station on each of two models. The first model provided data on a parabolic nose between Mach numbers of 2.3 and 5.0, corresponding to Reynolds numbers of 11×10^6 and 19×10^6, respectively. The corresponding ratio of skin temperature to local static temperature varied from 1.1 to 2.6. The second model provided data on a conical nose between Mach numbers of 1.1 and 4.0, corresponding to Reynolds numbers of 14×10^6 and 28×10^6, respectively, with the ratio of skin temperature to local static temperature varying from 1.0 to 2.3. The measurements are compared with the theory of Van Driest for turbulent flow.

Author

Availability:
N78-78522

179. Rumsey, Charles B.; and Lee, Dorothy B.: Measurements of Aerodynamic Heat Transfer and Boundary-Layer Transition on a 10° Cone in Free Flight at Supersonic Mach Numbers Up to 5.9. NASA TN D-745, 1961. (Supersedes NACA RM L56B07.)

Data are presented for a range of local Mach number just outside the boundary layer on the cone from 1.57 to 5.50, and a range of local Reynolds number from 6.6×10^6 to 55.2×10^6 based on length from the nose tip.

At Mach numbers up to 4, measurements of laminar, transitional, and turbulent heat-transfer coefficients were obtained. In general, the measured laminar heat-transfer coefficients expressed as Stanton number agree well with theory for laminar heat transfer on a cone. The measured turbulent heat-transfer coefficients expressed as Stanton number agree reasonably well with turbulent theory for heat transfer on a cone with Reynolds number based either on length from the nose tip or length from the transition point.

During the last part of the flight test when the Mach number was above approximately 4, the measured heat-transfer coefficients were consistently about midway between the theoretical laminar and turbulent heat-transfer values all along the nose.

Experimental transition Reynolds numbers varied from less than 8.5×10^6 to 19.4×10^6. At a relatively constant ratio of wall temperature to local static temperature near 1.2, the transition Reynolds number increased from 9.2×10^6 to 19.4×10^6 as Mach number increased from 1.57 to 3.38. At a relatively constant Mach number near 3.7, the transition Reynolds number decreased about 30 percent as the ratio of wall temperature minus adiabatic wall temperature to stagnation temperature changed from -0.35 to -0.25.

During the flight, local Mach number and the ratio of wall temperature to local static temperature simultaneously reached values well within the region for infinite laminar stability predicted by two-dimensional disturbance theory. The transition Reynolds number increased to a maximum value of 19.4×10^6 as the test conditions probed into the theoretical stability region.

Author

Availability:
N62-71319

180. Rumsey, Charles B.; and Lee, Dorothy B.: Measurements of Aerodynamic Heat Transfer on a 15° Cone-Cylinder-Flare Configuration in Free Flight at Mach Numbers Up to 4.7. NASA TN D-824, 1961. (Supersedes NACA RM L57J10.)

Measurements of aerodynamic heat transfer have been made at a number of stations along a cone-cylinder-flare model having a 15° total-angle conical nose and a 10° half-angle flare skirt. The maximum Mach number was 4.7, and local Reynolds numbers based on body length to a measurement station varied from 2×10^6 to 138×10^6.

Local Stanton numbers measured on the nose cone and flare showed fair agreement with laminar and turbulent theories, while the measurements on the cylinder were generally somewhat lower than theory.

Experimental recovery factors, determined twice during the test, were unaccountably lower than theoretical values.

Local transition Reynolds numbers, based on length from the nose tip, varied from 3×10^6 to 18×10^6 and were much lower than values previously obtained on the smoother nose of a similar model.

At an angle of attack of about 9°, the heat transfer on the flare increased to more than twice the theoretical turbulent value for zero angle of attack.

Author

Availability:
N62-71396

181. Rumsey, Charles B.; and Lee, Dorothy B.: Measurements of Aerodynamic Heat Transfer and Boundary-Layer Transition on a 15° Cone in Free Flight at Supersonic Mach Numbers Up to 5.2. NASA TN D-888, 1961. (Supersedes NACA RM L56F26.)

Data are presented for a range of local Mach number just outside the boundary layer from 1.40 to 4.65 and a range of local Reynolds number from 3.8×10^6 to 46.5×10^6, based on length from the nose tip to a measurement station.

Laminar, transitional, and turbulent heat-transfer coefficients were measured. The laminar data were in agreement with laminar theory for cones, and the turbulent data agreed well with turbulent theory for cones using Reynolds number based on length from the nose tip.

At a nearly constant ratio of wall to local static temperature of 1.2, the Reynolds number of transition increased from 14×10^6 to 30×10^6 as Mach number increased from 1.4 to 2.9 and then decreased to 17×10^6 as Mach number increased to 3.7.

At Mach numbers near 3.5, transition Reynolds numbers appeared to be independent of skin temperature at skin temperatures very cold with respect to adiabatic wall temperature.

The transition Reynolds number was 17.7×10^6 at a condition of Mach number and ratio of wall to local static temperature near that for which three-dimensional disturbance theory has been evaluated and has predicted laminar boundary-layer stability to very high Reynolds numbers ($\sim 10^{12}$).

Author

Availability:
N62-71462

182. Merlet, Charles F.; and Rumsey, Charles B.: Supersonic Free-Flight Measurement of Heat Transfer and Transition on a 10° Cone Having a Low Temperature Ratio. NASA TN D-951, 1961. (Supersedes NACA RM L56L10.)

Heat-transfer coefficients in the form of Stanton number and boundary-layer transition data were obtained from a free-flight test of a 100-inch-long 10° total-angle cone with a 1/16-inch tip radius which penetrated deep into the region of infinite stability of laminar boundary layer over a range of wall-to-local-stream temperature ratios and for local Mach numbers from 1.8 to 3.5. Experimental heat-transfer coefficients, obtained at Reynolds numbers up to 160×10^6, were in general somewhat higher than theoretical values. A maximum Reynolds number of transition of only 33×10^6 was obtained. Contrary to theoretical and some other experimental investigations, the transition Reynolds number initially increased while the wall temperature ratio increased at relatively constant Mach number. Further increases in wall temperature ratio were accompanied by a decrease in transition Reynolds number. Increasing transition Reynolds number with increasing Mach number was also indicated at a relatively constant wall temperature ratio.

Author

Availability:
N62-71525

183. Young, A. D.; Serby, J. E.; and Morris, D. E.: Flight Tests on the Effect of Surface Finish on Wing Drag. R. & M. No. 2258, British A.R.C., 1939.

The "cleaning up" of aeroplanes both in shape and surface finish that has taken place during recent years has resulted in a considerable decrease in parasitic drag and a corresponding improvement in performance. Further improvements in the surface finish of modern aeroplanes are still possible, but in general they involve increased production and upkeep difficulties; it is important, therefore, that information should be available to designers whereby they can estimate what such improvements are worth.

A series of flight tests have been made at the Royal Aircraft Establishment to investigate the major problems connected with the effect of surface finish on drag. The tests were designed so that the information derived from them should as far as possible be capable of general application.

Profile drag measurements were made by the momentum method of metal skins fitted over parts of the wings of a Battle. On these skins were tested camouflage paint, snap rivets, flush rivets, lap joints and leading edge slats. Tests were also made of the normal wing covering of the aeroplane including the effect of the bomb doors. The range of Reynolds number of the tests was from about 12×10^6 to 18×10^6 and the chord length in the plane of measurement was 10 ft. Simple formulae have been derived for estimating the drag of rivets and lap joints.

Author

Availability:
N78-78486

184. Zalovcik, John A.: A Profile-Drag Investigation in Flight on an Experimental Fighter-Type Airplane - The North American XP-51 (Air Corps Serial No. 41-38). NACA ACR, Nov. 1942.

This aircraft was equipped with wings that incorporated airfoil sections much like the NACA low-drag airfoil sections. Wake-survey measurements were made behind a right-wing section and profile drag tests were made with various surface conditions. The profile-drag coefficient varied with surface conditions from 0.0070 to 0.0053. The low figure was realized with the final smoothed and faired surface and this at a RN of 16×10^6 and a lift coefficient of about 0.10.

Availability:
N79-73465

185. Allen, H. Julian: Notes on the Effect of Surface Distortions on the Drag and Critical Mach Number of Airfoils. NACA ACR 3129, 1943.

The effect of two-dimensional bumps and surface waviness on the pressure distribution over airfoils is considered. It is shown that the results of the analysis may be useful in evaluating the effects of accidental or intended surface distortions on the drag and critical Mach number of airfoils.

Author

Availability:
N79-74312

186. Fage, A.: The Smallest Size of a Spanwise Surface Corrugation Which Affects Boundary-Layer Transition on an Aerofoil. R. & M. No. 2120, British A.R.C., 1943.

The effect of a spanwise surface corrugation on the position of transition from laminar to turbulent flow in the boundary layer of an aerofoil depends on the local disturbances caused by the corrugation and on the stability of flow in the laminar boundary layer beyond. The report describes wind-tunnel experiments made for bulge, hollow and ridge corrugations on an aerofoil and on a flat plate to obtain data needed to allow empirical relations to be derived which would give a rough estimate for the minimum height of a spanwise surface corrugation which affects the position of boundary-layer transition, and so the drag, of a laminar-flow aerofoil. The conditions under which the experiments were made were such that the results obtained are not likely to be affected by turbulence in the wind-tunnel stream nor by surface roughness due to small excresences. The effect of velocity gradient in the direction of flow along the surface is considered. The conditions of flow on and near smooth bulge and hollow corrugations are deduced from surface pressure measurements. The experiments on the flat plate were made by W. S. Walker and J. R. Greening and those on the aerofoil by W. S. Walker and R. J. Cox. Results obtained by Dr. G. S. Hislop from experiments made at Cambridge for narrow spanwise surface ridge corrugations on a flat plate are included for analysis.

Author

Availability:
N78-78487

187. Braslow, Albert L.: Investigation of Effects of Various Camouflage Paints and Painting Procedures on the Drag Characteristics of an NACA $65_{(421)}$-420, a = 1.0 Airfoil Section. NACA WR L-141, 1944. (Formerly NACA CB L4G17.)

The effects of various camouflage paints and painting procedures on the drag characteristics of a 60-inch-chord low-drag airfoil have been investigated in the NACA two-dimensional low-turbulence pressure tunnel. A typical field application of camouflage paint increased the section drag coefficient of the aerodynamically smooth airfoil at a Reynolds number of 44 $\times 10^6$ from 0.0046 to 0.0079 at a section lift coefficient of 0.3 and from 0.0053 to 0.0086 at a section lift coefficient of 0.7. In order to approach the drag characteristics of the aerodynamically smooth airfoil section at high-speed and cruising lift coefficients and flight Reynolds numbers, it was necessary to sand the airfoil surfaces lightly after painting.

Author

Availability:
N78-78523

188. Loftin, Laurence K., Jr.: Effects of Specific Types of Surface Roughness on Boundary-Layer Transition. NACA WR L-48, 1946. (Formerly NACA ACR L5J29a.)

Tests were conducted with two typical low-drag airfoils of 90-inch chord to determine the effects of surface projections, grooves, and sanding scratches on boundary-layer transition. The Reynolds number at which a spanwise row of cylindrical projections would cause premature transition was determined for a range of Reynolds number from approximately 3×10^6 to 10×10^6. Data were obtained for projections of various sizes and chordwise locations on both low-drag airfoils. The tests of surface grooves and sanding scratches indicated that, for the range of Reynolds number investigated, the laminar boundary layer was much less sensitive to surface grooves and sanding scratches than to projections above the surface.

Author

Availability:
N78-78524

189. Coles, R. B.: Measurements of the Degree of Smoothness Attained in a Laminar-Flow Wing Specimen (Short Bros.). R. & M. No. 2253, British A.R.C., 1949.

This report describes tests made to determine the degree of surface smoothness attained in a 6-ft. chord wing specimen having two spars and a thin skin stiffened between spars by ribs and channel section chordwise members. The specimen was designed and made by Short Bros. of Rochester.

The tests included measurements of the initial surface smoothness, distortion under load, proof and ultimate tests and compression tests on two short lengths of the upper front spar flange. These tests show that in order to reduce the amplitude of the skin distortions to the required limits the rigidity of the channel section stiffeners should be increased and possibly additional local stiffening near the front spar added. No permanent distortions of the wing beyond the allowed limits are likely to occur under service conditions.

The compressive stress in the spar flanges at failure was 37,500 lb./sq. in. Strut tests on 6-in. and 12-in. lengths of the upper front spar flange gave failing stresses of 59,000 lb./sq. in. and 48,000 lb./sq. in. respectively.

Author

Availability:
N78-78488

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190. Stüper, J.: The Influence of Surface Irregularities on Transition With Various Pressure Gradients. Rep. A.59, Dep. Supply and Develop., Div. Aeronaut. (Melbourne), May 1949.

The effect of surface irregularities on the boundary layer and transition has been examined on a flat glass plate 66 in. long. By suitably fairing the roof of the working section of a closed wind tunnel, a pressure gradient was obtained along the flat plate similar to that on the upper surface of a GLAS II aerofoil at $C_L = 0$. For comparison, tests were also made on the plate with zero pressure gradient. The surface irregularities were piano wires of diameters ranging from 0.0120 in. to 0.0480 in. fixed to the surface at 7 in. or at 24 in. from the leading edge. The range of Reynolds number ($U_0 l/\nu$) covered in the tests was from 0.5×10^6 to 3.3×10^6. The transition region was found by means of a hot-wire anemometer. The momentum thickness of the boundary layer at the trailing edge was determined. The sensitivity of the laminar boundary layer to irregularities on an otherwise smooth surface was not greatly altered by a favourable pressure gradient for the range of Reynolds number covered by the experiments and with the amount of turbulence present in the tunnel.

Author

Availability:
N79-70010
N-3614

191. Williams, D. H.: Comment on Stüper's "The Influence of Surface Irregularities on Transition With Various Pressure Gradients." Aerodyn. Tech. Memo. 77, Aeronaut. Res. Labs., Dep. Supply and Develop. (Melbourne), Dec. 1949.

Stüper found, from experiments on a flat plate with a pressure gradient, that laminar flow would not be maintained up to the slot on the wing of a Glas II glider at any reasonable flying speed. Further experiments suggest that the low values he found for the Reynolds number of transition may be appreciably less than flight values, partly due to tunnel turbulence but more due to disturbances starting at the rather sharp leading edge of the plate. If the stagnation point is located aft of the leading edge, the extent of the laminar region on the plate is considerably greater than if the stagnation point is on the leading edge.

Author

Availability:
N79-70009
N-3614A

192. Keeble, T. S.; and Atkins, P. B.: The Effect of Excrescences on Transition; Some Observations in the Boundary Layer on Williams GLAS II Profile. Aerodyn. Note 101, Aeronaut. Res. Labs., Dep. Supply (Melbourne), May 1951.

An account is given of measurements of boundary layer thickness and velocity profiles on a 3 foot chord model of GLAS II at a wind speed of 88 f.p.s. ($R_c = 1.7 \times 10^6$). With a clean wing the layer is laminar in nature right up to the slot at 70%C.

Critical positions for transition were determined by a visual technique (with napthalene) for three types of surface excrescence; pins, spherical bumps and ridges. Greater heights of bump were required to cause transition than might have been expected from early work and ridges about three times the height of a bump could be tolerated. Larger bumps and ridges could be attached to the surface without causing transition as the front stagnation point was approached. The results of the visual method have been checked by taking boundary layer traverses behind the ridges.

A comparison of these results with those of Gregory and Walker at N.P.L. has been made. Agreement at Reynolds Numbers above 2×10^6 (based on distance from the leading edge) has been obtained for bumps but near the front of the aerofoil the results differ greatly; a different relation would be required for ridges. A physical explanation of the "universal" curve of Gregory and Walker has been advanced and further tests suggested to check its correctness.

Author

Availability:
N79-70008
N-11617

193. Wijker, H.: Experiments on Disturbed Regions in the Laminar Boundary Layer Behind Isolated Surface Excrescences for Two- and Three-Dimensional Flow. Rep. A.1267, Nat. Luchtvaartlab. (Amsterdam), Oct. 31, 1951.

The report contains a number of photos of the disturbed regions behind protuberances in laminar boundary layers of two- and three-dimensional flow. Velocity profiles in these regions are measured for two-dimensional flow. The construction of stream lines along the surface from measured pressure distributions in three-dimensional potential flow is given in an appendix.

Author

Availability:
N79-70007
N-14664

194. Schwartzberg, Milton A.; and Braslow, Albert L.: Experimental Study of the Effects of Finite Surface Disturbances and Angle of Attack on the Laminar Boundary Layer of an NACA 64A010 Airfoil With Area Suction. NACA TN 2796, 1952.

A Langley low-turbulence wind-tunnel investigation was made of an NACA 64A010 airfoil section with continuous suction (area suction) through its porous surfaces to determine its ability to maintain extensive laminar flow behind finite surface disturbances and at angles of attack other than 0°.

Although full-chord laminar flow can be obtained at large values of the Reynolds number through the use of area suction, application of area suction permitted only a small increase in the size of a finite disturbance required to cause premature boundary-layer transition as compared with the nonsuction airfoil. The results indicated that the stability theory for the incompressible laminar boundary layer, which is derived for vanishingly small, two-dimensional, aerodynamically possible disturbances in the boundary layer, is of little practical significance in determining the sensitivity of the laminar boundary layer to surface projections. Combined wake and suction-drag coefficients lower than the drag coefficient of the plain airfoil were obtained through a range of low lift coefficient by the use of area suction.

Author

Availability:
N78-78525

195. Gray, W. E.; and Davies, H.: Note on the Maintenance of Laminar-Flow Wings. R. & M. No. 2485, British A.R.C., 1952.

The maintenance of laminar-flow wings involves two problems:

(1) The prevention of deterioration in the surface itself (e.g. cracking of the paint or filler, increase in roughness or waviness, etc., whether due to weathering, stresses in flight, or accidental damage).

(2) The prevention of contamination of the surface with flies, etc.

This Note gives an account of experience gained at the Royal Aircraft Establishment in dealing with these problems during flight tests on the characteristics of low-drag wings. (Tests made on the King Cobra and the Hurricane.)

Author

Availability:
N78-78469
N-21586

196. Dryden, Hugh L.: Review of Published Data on the Effect of Roughness on Transition From Laminar to Turbulent Flow. J. Aeronaut. Sci., vol. 20, no. 7, July 1953, pp. 477-482.

A review is presented of the published data on the effect of roughness, especially single roughness elements, on transition from laminar to turbulent flow, in which an attempt is made to reanalyze and correlate the available information. The reanalysis shows that the transition Reynolds Number of a flat plate with zero pressure gradient is a function of the ratio of the height of the roughness element to the displacement thickness of the boundary layer at the element, this functional relation being a better representation of the data than a constant critical Reynolds Number of the roughness element. Other data show that the effects of roughness are similar in streams of different initial turbulence and that a plot of the ratio of transition Reynolds Number of the rough plate to that for the smooth plate against the ratio of the height of the roughness element to displacement thickness of the boundary layer at the element gives good correlation of all the data for a given shape of roughness element when transition occurs downstream from the roughness element. At a certain value of the height-thickness ratio dependent on the stream speed, location of roughness element, and air-stream turbulence, the transition position reaches the element and remains there as the height or the stream speed is further increased.

The paper also discusses available data on the effect of distributed roughness on transition on a flat plate, as well as some of the published data on roughness effects on transition on airfoils.

Author

197. Dryden, Hugh L.: Effects of Roughness and Suction on Transition From Laminar to Turbulent Flow. Publ. Sci. & Tech. Minist. Air (Paris), [1954].

In recent years attention has turned to stabilizing the laminar boundary layer by removing some of the boundary layer air through a porous boundary by applying suction. Some test results indicate a large unfavorable effect of small roughness, although apparently a considerable degree of stabilization by suction was obtained. Other experiments have also indicated the same stabilizing effect of suction, but the results seem to me to be disappointing in the light of the results to be inferred from the Tollmien-Schlichting theory of the stability of a laminar boundary layer. The adverse element again seems to be unavoidable surface roughness. I believe that the main features of transition are suggested by the data at hand. This brief note is an attempted assessment of the effect of roughness in reducing the gains attainable through the use of suction.

Author

Availability:
N79-70659
N-25,500A

198. Cowled, E. H.: Experimental Determination of the Critical Heights of Surface Irregularities. Aerodyn. Note 138, Aeronaut. Res. Labs., Dep. Supply (Melbourne), Nov. 1954.

Results of transition experiments with five types of surface irregularity are presented. The tests are concerned primarily with the influence of shape on the critical heights of isolated disturbances; some experiments were also carried out to determine the effect of several irregularities arranged in a chordwise row.

The problem of correlating data obtained by different experimental methods is discussed.

Author

Availability:
N79-70005
N-36676

199. Spence, D. A.; and Randall, D. G.: The Influence of Surface Waves on the Stability of a Laminar Boundary Layer With Uniform Suction. C.P. No. 161, British A.R.C., 1954.

In order to estimate the destabilising effect of the waves likely to be encountered on wing surfaces which will be used with boundary layer suction, calculations have been made of the effect of small sinusoidal surface waves on the stability of the asymptotic suction profile. Curves are presented of the percentage increases in local suction flow $\frac{v_s}{U}$ necessary to maintain the stability of the boundary layer at the same level as on a completely flat surface, for various values of the variables $\frac{v_s}{U}$, height:wavelength ratio $\frac{h}{L}$, and Reynolds number based on wavelength, $\frac{UL}{\nu}$. These should provide quantitative estimates for more general cases. It is found, as might have been expected, that the lower $\frac{v_s}{U}$ or the larger $\frac{h}{L}$, the larger the necessary percentage increase in $\frac{v_s}{U}$, especially for low $\frac{UL}{\nu}$. 10 per cent is a typical magnitude for the necessary increase at a high Reynolds number.

Author

Availability:
N-32442
N78-78792

200. R. & M. No. 2779, British A.R.C., 1956.
Gregory, N.; and Walker, W. S.: Part I - The Effect on Transition of Isolated Surface Excrescences in the Boundary Layer.
Johnson, D.: Part II - Brief Flight Tests on a Vampire I Aircraft To Determine the Effect of Isolated Surface Pimples on Transition.

The effect of isolated surface excrescences in a laminar boundary layer in producing disturbances which may lead to turbulent flow has been examined experimentally by several methods. Photographs of some of the flow patterns visualised by smoke and china-clay techniques are given.

The critical heights of pimple which just give rise to spreading wedges of turbulent flow have been measured on a flat plate and on two aerofoils at several angles of incidence. The results are analysed and are presented in a form which enables approximate estimates to be made of the protuberances permissible on laminar-flow surfaces at full-scale flight Reynolds numbers. The estimates suggest that at an altitude of 30,000 ft the critical pimple height is 0.004 in. for a speed of 350 m.p.h., while 0.002 in. may be permissible at all subsonic speeds. At sea-level, however, the tolerances are approximately halved. To provide information at flight Reynolds numbers, two flights have been made on a Vampire aircraft indicating the effect of tiny paint pimples on the laminar boundary layer at a Reynolds number, based on wing chord, of 25×10^6 near sea-level.

It was found that the critical pimple height at 0.03-chord was 0.001 in. increasing to 0.003 in. at 0.20-chord, values which are within experimental error of those estimated by the method due to Fage. Although the pimples were of no specific shape, e.g., cylindrical or conical, it is suggested that, in view of the close agreement between estimated and observed results, no further flight tests are necessary.

Author

Availability:
N78-78557
N-48741

201. Smith, A. M. O.; and Clutter, D. W.: The Smallest Height of Roughness Capable of Affecting Boundary-Layer Transition in Low-Speed Flow. Rep. No. ES 26803 (Contract No. NOa(s) 54-773c), Douglas Aircraft Co., Inc., Aug. 31, 1957.

An investigation has been made to determine the smallest size of isolated roughness that will affect transition in a laminar boundary layer. The investigation was made in the Douglas El Segundo wind tunnel on a 108-inch-chord test surface designed to give large extents of laminar flow; the x-Reynolds number of transition $U_T x_T/\nu$ ranged from 2.0×10^6 to 7.4×10^6. Critical heights were found for three types of roughness over a range of variables larger than that covered by previous experiments. The types of roughness were:

(a) Two-dimensional, in the form of spanwise wires having various diameters.

(b) Three-dimensional, in the form of 1/16-inch-diameter discs of various thicknesses.

(c) Sandpaper type.

In addition to the types of roughness, the tests covered a considerable range of Reynolds numbers, locations of roughness on the test surface, and pressure distributions. Supplementary tests were performed to compare four methods of locating transition, namely, china clay, the stethoscope, the total-head tube, and the hot wire. Brief tests were made to find the effect of tunnel turbulence on critical roughness height.

Author

Availability:
N79-70006
N-57041

202. Jack, John R.; Wisniewski, Richard J.; and Diaconis, Nick S.: Effect of Extreme Surface Cooling on Boundary-Layer Transition. NACA TN 4094, 1957.

An investigation was made to determine the combined effects of surface cooling, pressure gradients, nose blunting, and surface finish on boundary-layer transition. Data were obtained for various body shapes at a Mach number of 3.12 and Reynolds numbers per foot as high as 15×10^6.

Previous transition studies, with moderate cooling, have shown agreement with the predictions of stability theory. For surface roughnesses ranging from 4 to 1250 microinches the location of transition was unaffected with moderate cooling. With extreme cooling, an adverse effect was observed for each of the parameters investigated. In general, the transition Reynolds number decreased with decreasing surface temperature. In particular, the beneficial effects of a favorable pressure gradient obtained with moderate cooling disappear with extreme cooling, and a transition Reynolds number lower than that observed on a cone is obtained. Further, an increase in the nose bluntness decreased the transition Reynolds number under conditions of extreme cooling.

Author

Availability:
N78-78526

203. Goldsmith, John: Influence of Single Roughness Elements on Transition at High Reynolds Numbers. Rep. No. NAI-56-428 (Rep. No. BLC-88), Northrop Aircraft, Inc., Apr. 1956. (Available from DDC as AD 105 926(a).)

Transition experiments have been conducted in a 2-inch diameter tube in order to determine the influence of single small cylindrical obstacles. The transition length Reynolds number of the tube in the smooth condition was about 15×10^6. Results of the present measurements in the low Reynolds number range do not differ greatly from similar measurements made on flat plates and laminar airfoils. The measured value of the Reynolds number of the roughness element (based on roughness height and the local velocity at this height) is nearly constant and equal to about 600.

Author

Availability:
SN-24021, May 1956
NAI-56-428 (BLC-88)
AD 105 926(a)

204. Braslow, Albert L.; and Horton, Elmer A.: Effects of Surface Roughness on Transition. NACA Conference on High-Speed Aerodynamics - A Compilation of the Papers Presented, NASA, Mar. 1958, pp. 439-450.

It is known, at least qualitatively, how such factors as pressure gradients and leading-edge sweep influence the ability to maintain laminar flow over smooth configurations. If, after a study of such effects, laminar flow still appears possible, the next hurdle to be overcome is the adverse effect of surface roughness on transition. This paper will review recent results obtained at supersonic speeds as well as subsonic on the size of roughness required to promote premature transition.

Author

Availability:
N71-75285
N-59840

205. Braslow, Albert L.; and Knox, Eugene C.: Simplified Method for Determination of Critical Height of Distributed Roughness Particles for Boundary-Layer Transition at Mach Numbers From 0 to 5. NACA TN 4363, 1958.

A simplified method has been devised for determination of the critical height of three-dimensional roughness particles required to promote premature transition of a laminar boundary layer on models of airplanes or airplane components in a wind tunnel with zero heat transfer. A single equation is derived which relates the roughness height to a Reynolds number based on the roughness height and on local flow conditions at the height of the roughness, and charts are presented from which the critical roughness height can be easily obtained for Mach numbers from 0 to 5. A discussion of the use of these charts is presented with consideration of various model configurations.

The method has been applied to various types of configurations in several wind-tunnel investigations conducted by the National Advisory Committee for Aeronautics at Mach numbers up to 4, and in all cases the calculated roughness height caused premature boundary-layer transition for the range of test conditions.

Author

Availability:
N78-78527

206. Von Doenhoff, Albert E.; and Horton, Elmer A.: A Low-Speed Experimental Investigation of the Effect of a Sandpaper Type of Roughness on Boundary-Layer Transition. NACA Rep. 1349, 1958. (Supersedes NACA TN 3858.)

An investigation was made in the Langley low-turbulence pressure tunnel to determine the effect of size and location of a sandpaper type of roughness on the Reynolds number for transition. Transition was observed by means of a hot-wire anemometer located at various chordwise stations for each position of the roughness. These observations indicated that when the roughness is sufficiently submerged in the boundary layer to provide a substantially linear variation of boundary-layer velocity with distance from the surface up to the top of the roughness, turbulent "spots" begin to appear immediately behind the roughness when the Reynolds number based on the velocity at the top of the roughness and the roughness height exceeds a value of approximately 600.

At Reynolds numbers even slightly below the critical value (value for transition), the sandpaper type of roughness introduced no measurable disturbances into the laminar layer downstream of the roughness. The extent of the roughened area does not appear to have an important effect on the critical value of the roughness Reynolds number.

Author

Availability:
N78-78528

207. Wortmann, F. X.: Drag Reduction for Gliders (continued). NASA TM-75293, 1978.

Continuation of a discussion of the various factors that can contribute to a decrease in drag of glider aircraft. The possibility of reducing drag by proper selection of the wing planform and warping of the wing has been discussed in Part 1. A discussion is now given of the various aspects associated with drag decrease by proper selection of the wing profile, laminarization of the flow (boundary-layer control), and proper design of trailing-edge flaps, landing flaps, fuselage, and tail assembly.

Availability:
N78-24116

208. Carmichael, B. H.: Critical Reynolds Numbers for Multiple Three Dimensional Roughness Elements. Rep. No. NAI-58-589 (BLC-112), Northrop Aircraft, Inc., July 31, 1958.

Roughness size sufficient to trip the laminar boundary layer is extended in this study to multiple 3-dimensional roughness elements. Effects of diameter, height, spacing, number of elements, number of rows, dissimilar diameter, and dissimilar height are treated in detail.

Author

Availability:
N66-80685
SN-24021, July 1958
NAI-58-589 (BLC-112)

209. Rabb, Leonard; and Krasnican, Milan J.: Effects of Surface Roughness and Extreme Cooling on Boundary-Layer Transition for 15° Cone-Cylinder in Free Flight at Mach Numbers to 7.6. NACA RM E57K19, 1958.

Three cone-cylinder bodies were flown to obtain boundary-layer-transition data at very low ratios of wall to local stream temperature. Surface finishes were nominally 2-, 20-, and 50-microinch average roughness height. The smooth-body (2-microin. surface) transition data were in excellent agreement with previous smooth-body results. Laminar boundary layers were maintained to a local temperature ratio of 0.35 for this body. On the two rough models, transition occurred under conditions generally believed to be favorable for maintaining laminar flow; that is, the local Reynolds numbers were either decreasing or constant and the local temperature ratios were decreasing. This "transition reversal" phenomenon was originally described by Jack, Wisniewski, and Diaconis for smooth bodies and bodies with uniformly distributed roughness. The transition data of the two rough models qualitatively confirm their results. Turbulent heat-transfer data were in good agreement with theoretical turbulent Stanton numbers when heat-transfer reduction due to tip blunting was considered.

The maximum free-stream Mach number for these flights was 7.6, and the maximum Reynolds number (uncorrected for blunt-tip effects) at which laminar flow was observed was 46.3×10^6.

Author

Availability:
N78-78529

210. Cambridge University Aeronautical Laboratory: Experiments on Distributed Suction Through a Rough Porous Surface. R. & M. No. 3118, British A.R.C., 1959.

Flight tests in which suction was applied through a slightly rough porous surface to maintain laminar flow in the boundary layer have shown that when the pressure on the surface was uniform there was an upper limit to the airspeed outside the layer above which no reasonable suction would prevent transition in turbulence. Comparison between these and similar tests on a smoother surface suggest that there will be, associated with every porous surface, two limiting speeds, one above which no reasonable suction will maintain laminar flow and one below which the surface can be regarded as aerodynamically smooth. Consideration is given to the way in which these speeds will vary with the kinematic viscosity of the air, in conditions which lead to dynamical similarity. (Anson aircraft.)

Author

Availability:
N78-78489
N-16787X

211. Carmichael, B. H.: Surface Waviness Criteria for Swept and Unswept Laminar Suction Wings. Rep. No. NOR-59-438 (BLC-123) (Contract AF33(616)-3168), Northrop Aircraft, Inc., Aug. 1959.

This report summarizes the available experimental data concerning the critical size of surface waviness on swept and unswept laminar suction wings. A short discussion of all pertinent variables is included. The design charts apply to sinusoidal waves on swept and unswept wings in regions having a close approach to distributed suction (e.g., multislot construction). They also apply to unswept wings when the wave is in a nonsuction region but where strong flow acceleration exists. A design chart enables computation of the critical wave ratio over a wide range of the variables.

Author

Availability:
NOR-59-438 (BLC-123)

212. Braslow, Albert L.; Knox, Eugene C.; and Horton, Elmer A.: Effect of Distributed Three-Dimensional Roughness and Surface Cooling on Boundary-Layer Transition and Lateral Spread of Turbulence at Supersonic Speeds. NASA TN D-53, 1959. (Supersedes NACA RM L58A17.)

An investigation was made in the Langley 4- by 4-foot supersonic pressure tunnel at Mach numbers of 1.61 and 2.01 to determine (1) the effect of distributed roughness on boundary-layer transition with the model surface at adiabatic wall temperature and cooled and (2) the effect of surface cooling on the lateral spread of turbulence. Both distributed granular-type and single spherical roughness particles were used, and transition of the boundary layer was determined by hot-wire anemometers. The transition-triggering mechanism of the three-dimensional roughness at supersonic speeds appeared to be the same as that previously observed at subsonic speeds. In fact, the critical value of the roughness Reynolds number parameter $\sqrt{R_{k,t}}$ (that is, the value at which turbulent spots are initiated by the roughness) was found to be approximately the same at supersonic and subsonic speeds when complete local conditions at the top of the roughness, including density and viscosity, were considered in the formulation of the roughness Reynolds number. For three-dimensional roughness at a Reynolds number less than its critical value, the roughness introduced no disturbances of sufficient magnitude to influence transition. Surface cooling, although providing a theoretical increase in stability to small disturbances, did not increase to any important extent the value of the critical roughness Reynolds number for three-dimensional roughness particles. Cooling, therefore, because of its effect on the boundary-layer thickness, density, and viscosity actually promoted transition due to existing three-dimensional surface roughness for given Mach and Reynolds numbers. The measured lateral spread of turbulence in the boundary layer appeared to be unaffected by the increased laminar stability derived from the surface cooling.

Author

213. Coleman, W. S.: The Effect on Profile Drag of Randomly Distributed, Low-Intensity Roughness. Blackburn Aircraft Ltd., Jan. 1960.

The effect of random, or accidental, roughness on the behaviour of the boundary layer is discussed in terms of the turbulent spots generated by the excrescences. Functions defining the probability distribution of laminar and turbulent flow at any cross-section of the boundary layer are obtained from (a) the kinematic properties of spots, and (b) the transition theory of Emmons. The two approaches are found to lead to substantially the same result. Finally, the influence of the roughness on wing profile drag is considered. It is shown that an appreciable increase of drag may be expected to develop when the mean spacing of the critical excrescences near the leading edge falls below about 0.5 of the chord.

Author

Availability:
N78-78561
N-83696

214. Bidwell, Jerold M.: Roughness Effect on Boundary-Layer Transition With a Cold Wall. R-60-6, The Martin Co., Apr. 1960.

This report presents a review of the current state of the art and a further study of the effects of a cold wall on the laminar boundary layer.

The critical roughness Reynolds number was used with the Chapman-Rubesin flat-plate laminar-boundary-layer equations to extend the insulated-wall critical-roughness charts of Braslow and Knox to cases of large heat transfer to the wall. Curves of laminar-boundary-layer properties for wall-to-free-stream-temperature ratios from 0.08 to 1.5 and Mach numbers from 1 to 5 are presented. The mechanism of the roughness effect on boundary-layer transition is briefly reviewed. A bibliography of some important papers concerning the roughness effect on boundary-layer transition is also included.

Author

Availability:
N64-85479
N-82032

215. Braslow, Albert L.: Review of the Effect of Distributed Surface Roughness on Boundary-Layer Transition. Presented to meeting of AGARD Wind Tunnel and Model Testing Panel (London, England), Apr. 25-29, 1960.

Presented is a discussion of the transition phenomena associated with distributed roughness, a correlation of three-dimensional roughness effects at both subsonic and supersonic speeds, and the effect of laminar boundary-layer stability as influenced by heat transfer, pressure gradients, and boundary-layer control on the sensitivity of laminar flow to distributed roughness. The results presented indicate that the transition-triggering mechanism of three-dimensional-type surface roughness appears to be the same at supersonic and subsonic speeds. In either case, a Reynolds number based on the height of the roughness and the local flow conditions at the top of the roughness can be used to predict with reasonable accuracy the height of three-dimensional roughness required to cause premature transition. Neither the three-dimensional roughness Reynolds number nor the lateral spread of turbulence behind the roughness is changed to any important extent by increasing the laminar boundary-layer stability to theoretically small disturbances. Therefore, for a given stream Mach number and Reynolds number, surface cooling, boundary-layer suction, or a favorable pressure gradient will, in the presence of three-dimensional roughness, promote rather than delay transition.

Author

Availability:
N79-70004
N-81061

216. Von Doenhoff, Albert E.; and Braslow, Albert L.: The Effect of Distributed Roughness on Laminar Flow. Boundary Layer and Flow Control, Volume 2, G. V. Lachmann, ed., Pergamon Press, 1961, pp. 657-681.

In a previous section of this volume, a review was presented of the manner in which flow in a boundary layer becomes turbulent. Present knowledge indicates that regardless of the type of initial disturbance present, turbulence always starts from point-like turbulent spots which grow in size with downstream movement and finally merge to form a continuously turbulent region. The most upstream location of continuously turbulent flow, however, does depend upon the type and magnitude of the initial disturbance such as stream turbulence level or surface protuberances. A discussion of transition resulting from two-dimensional type surface irregularities was contained in a previous section. The present discussion will deal with three-dimensional type protuberances.

Author

217. Gerhardt, H. A.: Attaining Surface Smoothness in LFC Wings. NOR-64-63 (Contract AF33(600)-42052), Northrop Corp., Jan. 1964.

The structural design and manufacturing approaches for attainment of surface smoothness on wings with laminar flow control as developed by the Northrop Corporation are presented. In particular, experience gained during the manufacturing procedures of the X-21A aircraft is treated. A survey is given of the tolerances on surface waves, gaps, and steps, and the techniques of waviness measurement are pointed out. Surface finishing processes such as filling and sanding, and a repair technique, are outlined.

Author

Availability:
NOR-64-63

218. Head, M. R.: Transition Due to Roughness. J. R. Aeronaut. Soc., vol. 69, no. 653, May 1965, pp. 344-345.

Consideration of the common statement in the literature on laminar flow control that the important parameter controlling the height of tolerable roughness is the Reynolds number per foot, or unit Reynolds number, U/ν; provided this parameter is the same in any two cases (which are closely similar geometrically), then it is assumed that the tolerable roughness height will also be similar. It is pointed out that this is true only in very restricted circumstances, and it is shown that, in general, the actual physical scale is also of considerable importance.

Availability:
A65-26127

219. Gaster, M.: A Simple Device for Preventing Turbulent Contamination on Swept Leading Edges. J. R. Aeronaut. Soc., vol. 69, no. 659, Nov. 1965, pp. 788-789.

Description of simple means for preventing the turbulent contamination of the laminar flow on highly swept wings. This turbulence arises at the root of the wing and sweeps along the attachment line. It is suggested that by "attaching" a bump on the leading edge, so shaped that a fresh stagnation point is created, it is possible to maintain a new boundary layer which forms outboard in a laminar state on the attachment line. The results of wind-tunnel and flight tests with this concept are reviewed.

Availability:
A66-15998

220. Carmichael, B. H.: Prediction of Critical Reynolds Numbers for Single Three-Dimensional Roughness Elements. Rep. No. NAI-58-412 (BLC-109) (Contract AF33(616)-3168), Northrop Aircraft, Inc., May 1958.

An improved method for the prediction of roughness size just sufficient to trip the laminar boundary layer to the turbulent state has been experimentally obtained. Results are restricted to single three dimensional cylindrical elements with flat top in an incompressible boundary layer without suction. The results are applicable to cylinders of any height (not exceeding the total boundary layer thickness) and any diameter, located anywhere on the surface with a wide variety of allowable pressure distributions.

The critical Schiller number $R_k = u_k \cdot k/\nu_k$ is found to be a function of a single parameter $k^2/\theta_k d$ which is the product of the roughness fineness ratio k/d and the roughness relative height k/θ_k. This correlation was found to be independent of location on the surface and velocity distribution.

An equally accurate correlation was found when the critical diameter Reynolds number $\frac{U \cdot d}{\nu_k}$ was plotted against $k^2/\theta d$.

Author

Availability:
N66-81570
SN-24021, May 1958
NAI-58-412 (BLC-109)

221. Anderson, G. F.; Sutera, S. P.; and Murthy, V. S.: Laminar Boundary Layer Control by Combined Blowing and Suction in the Presence of Roughness. WT-51, Brown Univ., Oct. 1967. (Available from DDC as AD 666 569.) (Shortened versions of this document are available in J. Hydronaut., vol. 3, no. 3, July 1969, pp. 145-151, and as AIAA Paper No. 68-642.)

The feasibility of maintaining a fully laminar boundary layer on a given two-dimensional body by means of combined blowing and suction and the effectiveness of blowing for increasing the boundary layers tolerance to roughness are investigated theoretically. The potential flow past the body is determined by using a suitably selected source distribution and then refining the body obtained from this selection by means of slender body techniques. The boundary-layer calculations are then made for various blowing rates at the stagnation point. The calculations indicate that the combination of suction, applied to maintain a laminar boundary layer, and blowing near the stagnation point, to improve the tolerance of the laminar boundary to roughness, can substantially reduce the skin friction of bodies operating at high Reynolds numbers.

Author

Availability:
N68-21253
AD 666 569
A69-34015
A68-33825

222. Gibbings, J. C.; and Hall, D. J.: Criterion for Tolerable Roughness in a Laminar Boundary Layer. J. Aircr., vol. 6, no. 2, Mar.-Apr. 1969, pp. 171-173.

Discussion of the degree of surface roughness that an incompressible laminar boundary layer can tolerate without transition being affected. It is important first to define what is meant by "tolerable" roughness and second, to distinguish between the effects of two-dimensional and three-dimensional roughness shapes. Various criteria for tolerable roughness are considered and evaluated.

Availability:
A69-26774

223. Hahn, Mansop; and Pfenninger, W.: Prevention of Transition Over a Backward Step by Suction. J. Aircr., vol. 10, no. 10, Oct. 1973, pp. 618-622.

A study was made on prevention of transition of the flow downstream of a backward facing step by means of suction. Distributed suction was approached through closely spaced slots in the region downstream of the step. The optimum location and rate of suction to maintain laminar flow downstream of the step were determined. The effects of step height Reynolds number on transition of the boundary layer with and without suction were investigated. Suction in the region slightly upstream of reattachment shortened the reattachment length by about 20% and was very effective in preventing transition. The minimum suction rate required for laminarization of the flow downstream of the step was equivalent to 15-20% removal of the boundary-layer displacement thickness upstream of the step. The transition Reynolds number based on step height was increased from 1100 without suction to 2200 with suction.

Author

Availability:
A74-11339

224. Kachanov, Ju. S.; Kozlov, V. V.; Kotjolkin, Ju. D.; Levchenko, V. Ja.; and Rudnitsky, A. L.: Laminar Boundary Layer on a Wavy Wall. Acta Astronaut., vol. 2, no. 5/6, May/June 1975, pp. 557-559.

The results of the measurements of velocity profiles in the boundary layer on a wavy wall are proved to be in good accord with Görtler's theoretical model developed to describe such flows. Precise measurements of the mean velocity profiles in an air flow have been performed with the use of a laser-anemometer system.

Author

Availability:
A75-41886

225. Merkle, Charles L.; Tzou, Kent T. S.; and Kubota, Toshi: An Analytical Study of the Effect of Surface Roughness on Boundary-Layer Stability. DT-7606-4 (Contract N00014-77-C-0005), Dynamics Technol., Inc., Oct. 1977. (Available from DDC as AD A004 786.)

An analytical model has been developed to describe the manner in which distributed surface roughness affects transition. The model pictures the roughness as having two distinct effects: one, it introduces higher disturbance levels in the boundary layer; and two, it alters the mean velocity profile and, hence, the growth rate of the disturbances. The alteration of the mean velocity profile is described by means of a turbulent sublayer, which visualizes an enhanced momentum transfer in a narrow layer next to the surface. The corresponding change in the amplification of disturbances is then determined by means of linear stability theory, and is related to transition by an empirical transition criterion.

Availability:
N75-25886
AD A004 786

226. Beasley, William D.; and McGhee, Robert J.: An Exploratory Investigation of the Effects of a Thin Plastic Film Cover on the Profile Drag of an Aircraft Wing Panel. NASA TM-74073, 1977.

An exploratory low-speed wind tunnel test has been conducted in the Langley low-turbulence pressure tunnel to evaluate the concept of applying a thin plastic coating on an aircraft wing panel as one method of reducing drag due to surface roughnesses or excrescences such as steps, gaps, improperly seated fasteners, leaks, etc. The test was conducted at a Mach number of 0.15 and an angle-of-attack of 0°. The chord Reynolds number was varied from about 7×10^6 to 63×10^6.

The results at the lowest Reynolds number indicate that coating the wing-panel decreased the profile drag coefficient to approximately that for an aerodynamically smooth NACA 6-series laminar flow airfoil. At Reynolds numbers sufficiently high to insure essentially full chord turbulent boundary layers a reduction of about 12-percent was measured. Other types of wing sections and construction methods should be investigated to establish the useful range of profile drag reduction by film coatings.

Author

Availability:
N78-10023

227. Atkins, P. B.: Wing Leading Edge Contamination by Insects. Flight Note 17, Aeronaut. Res. Labs. (Melbourne), Oct. 1951.

An investigation to determine the area of contamination on leading edges of various aircraft showed that, on the conventional aerofoils tested, up to 14% chord of the upper surface may be affected. At Laverton, Vic. the problem was found to be quite serious even in Winter - 167 flies being caught on the leading edges of Vampire wings in one flight.

The results of insect distribution varying with atmospheric conditions and height are shown against results obtained in Louisiana. Corresponding latitudes indicate that similar distribution might be found in Australia, although types and species of insect would differ.

Since it is impractical to prevent insects from hitting the leading edges of aircraft wings, it is considered that efforts should be made to prevent them from interfering seriously with the flow over the wing either by developing means of removing them or of dealing with the turbulence they cause.

Author

Availability:
N79-70042
N-11837

228. Coleman, Walter S.: The Characteristics of Roughness From Insects as Observed for Two-Dimensional, Incompressible Flow Past Airfoils. J. Aero/Space Sci., vol. 26, no. 3, May 1959, pp. 264-280.

Advances in the practical development of boundary-layer control for the maintenance of extensive laminar flow have drawn attention to the problem of surface roughness, due not only to artificial irregularities such as rivet heads, lap joints, window panels, etc., but also to the kind generated in flight from impact with insects. This natural form of roughening, the effects of which have been noted, though not investigated previously, is the subject of the present paper.

The phenomenon may be divided into two parts - namely, (1) the manner of distribution and magnitude of the roughness, and (2) its effect upon the stability of the laminar boundary layer. Wind-tunnel experiments with the fruit fly, Drosophila, and the common housefly for the investigation of both (1) and (2) in the case of two-dimensional, incompressible flow past airfoils are fully described. The former problem has also been treated mathematically in a separate paper, not yet published, agreement between theory and experiment being satisfactory in all essentials.

The characteristics of the roughness profile consist principally of a pronounced peak near the leading edge, followed by an extensive area of surface over which there is a much reduced and gradually diminishing value of the excrescence height. Further, it is shown that, if the severe leading-edge roughness, or its effect upon the boundary layer, can be eliminated, then the downstream roughness causes no disturbance to the passage of a laminar layer - i.e., the surface, though roughened, is aerodynamically smooth. Moreover, it appears that the conditions defining the upstream boundary to this region of insignificant roughness are fundamentally the same as those which determine the critical state for transition at an artificial disturbance of a three-dimensional character.

Author

229. Lachmann, G. V.: Aspects of Insect Contamination in Relation to Laminar Flow Aircraft. C.P. No. 484, British A.R.C., 1960. (Available from DDC as AD B029 106.)

After considerable discussion it is concluded that there is a distinct possibility that when the cruising altitude and speed of laminarised aircraft are high enough fly accretions will be eroded to such an extent that the roughness Reynolds number will be subcritical.

Alternatively, two promising methods remain:

(a) Protective films or adhesive fibrous mats applied to the leading edge prior to take-off and ripped off after reaching cruising altitude would seem to be the most practical form of protection

(b) Spraying the leading edge with water mixed with a detergent appears to be the most promising form of removing fly deposits in flight.

Flight trials on a laminarised aircraft will help to decide whether fly contamination can be ignored altogether or, alternatively, which of the two methods deserves preference in operational service.

Author

Availability:
N-85326
AD B029 106
N78-78793

230. Coleman, W. S.: A Theoretical Approach to the Aerodynamically Significant Properties of Roughness From Insects. Aeronaut. Q., vol. XI, pt. 2, May 1960, pp. 171-194.

In previous work the author draws attention to the difficulties of measuring the streamwise extent of the roughness from insects. The present paper deals with the problem theoretically for an aerofoil in two-dimensional, incompressible flow. A tentative approach to the determination of effective excrescence height downstream of the leading-edge zone is also advanced. The application of these investigations, in conjunction with the previous analysis regarding the critical conditions for premature transition, leads to estimates of the amount of significant roughness which are in good agreement with flight observation.

Author

231. Peterson, John B., Jr.; and Horton, Elmer A.: An Investigation of the Effect of a Highly Favorable Pressure Gradient on Boundary-Layer Transition as Caused by Various Types of Roughness on a 10-Foot-Diameter Hemisphere at Subsonic Speeds. NASA Memo 2-8-59L, 1959.

Tests were conducted at a Reynolds number up to 10×10^6 and at a maximum Mach number of about 0.1 which show that the occurrence of transition behind three-dimensional particle types of roughness could be correlated with the roughness Reynolds number.

Results of tests with two-dimensional types of roughness are presented which show the effects of wire and scratch types of roughness on transition. Also included in the investigation were studies of the spread of turbulence behind a single roughness particle and the effects of holes such as pressure orifices on boundary-layer transition.

232. Braslow, Albert L.; Hicks, Raymond M.; and Harris, Roy V., Jr.: Use of Grit-Type Boundary-Layer-Transition Trips on Wind-Tunnel Models. NASA TN D-3579, 1966.

Some general guidelines that are applicable to grit-type boundary-layer-transition trips located near the leading edges of model components are presented. Conditions that permit transition to be fixed at the roughness at subsonic and supersonic speeds without a resultant grit drag are reviewed. In certain cases in which grit drag is unavoidable, two methods - the choice of which depends upon the characteristics of the wind tunnel used - for correcting such drag are discussed. At hypersonic speeds, the problem of fixing boundary layer transition without distorting the turbulent boundary layer velocity profile has not been solved.

Author

Availability:
N66-36119

233. Coleman, W. S.: Roughness Due to Insects. Boundary Layer and Flow Control, Volume 2, G. V. Lachmann, ed., Pergamon Press, 1961, pp. 682-747.

The problem of roughness due to insects and what to do about it is discussed in this comprehensive paper. The author considers, with thoroughness, the factors which determine the formation of this roughness. These factors are aeronautical, meteorological and entomological. The geometrical characteristics of the roughness due to insects (height and distribution of the excrescences) is also discussed. Experiments done are described. The effect of roughness on the stability of the boundary layer is discussed in one section. Avoidance of early transition by the use of scrapers, deflectors, covers of paper or fabric or some type of film, liquids discharged over the surface, etc., are various devices considered in the light of results from laboratory and flight tests.

234. Wortmann, F. X.: A Method for Avoiding Insect Roughness on Aircraft. NASA TT F-15,454, 1974. (Also available as Eine Möglichkeit zur Vermeidung der Insektenrauhigkeit an Flugzeugen, Luftahrttechnik Raumfahrttechnik, vol. 9, no. 9, Sept. 1963, pp. 272-274 and in OSTIV Publ. VII, 1963.)

Insect-induced roughness on aircraft can be avoided by highly elastic rubber coverings on wing and control surface leading edges. Film photographs have shown that such elastic surfaces can elastically reflect impacting insects or viscous liquid drops. This prevents the formation of insect roughness and the endangered fuselage and wing leading edges remain smooth.

Author

Availability:
N74-21646

235. Fisher, David F.; and Peterson, John B., Jr.: Flight Experience on the Need and Use of Inflight Leading Edge Washing for a Laminar Flow Airfoil. AIAA Paper 78-1512, Aug. 1978.

An investigation of leading-edge contamination by insects was conducted at the NASA Dryden Flight Research Center with a JetStar airplane instrumented to detect transition on the outboard leading-edge flap and equipped with a system to wash the leading edge in flight. The results of airline-type flights with the JetStar indicated that insects can contaminate the leading edge during takeoff and climbout at large jet airports in the United States. The results also showed that the insects collected on the leading edges at 180 knots did not erode at cruise conditions for a laminar flow control airplane and caused premature transition of the laminar boundary layer. None of the superslick and hydrophobic surfaces tested showed any significant advantages in alleviating the insect contamination problem. While there may be other solutions to the insect contamination problem, the results of these tests with a washer system showed that a continuous water spray while encountering the insects is effective in preventing insect contamination of the leading edges.

Author

Availability:
A78-47947

236. Hardy, A. C.; and Milne, P. S.: Studies in the Distribution of Insects by Aerial Currents - Experiments in Aerial Tow-Netting From Kites. J. Anim. Ecol., vol. 7, no. 2, Nov. 1938, pp. 199-229.

The insects carried by convection currents and wind, the aerial plankton, are investigated between the heights of 150 and 2000 ft. by collecting nets carried up by kites. The nets are sent up closed, opened automatically at the desired height, and closed again at the end of the sampling period before being hauled down.

The equipment and methods of working are fully described.

Eighty-two samples were taken yielding a collection of 839 insects during a total flying time of 124.5 hr.

The aerial plankton is made up essentially of small or light-bodied insects with weak powers of flight but with relatively large wing surface compared with body mass.

The composition of the aerial plankton at different heights is determined and the height distribution of the different families compared. A list of species identified is appended.

The influence of weather conditions is examined. Different insect groups are shown to be affected somewhat differently, but high temperature and low humidity are found for all to be more favourable to aerial drift than the reverse conditions.

The average density of the drifting population is estimated for different height ranges up to 2000 ft.

The economic significance of insect drift is discussed.

Author

237. Johnson, C. G.: The Distribution of Insects in the Air and the Empirical Relation of Density to Height. J. Anim. Ecol., vol. 26, 1957, pp. 479-494.

Many insect species, perhaps the majority of those flying in rather exposed situations, become dispersed into the upper air above about 100-200 ft. The population in the upper air is not distinct from that flying in the lower layers, since in general, from zero height to some thousands of feet there is a continuous distribution, density diminishing with height in a well-defined profile.

This profile may be interpreted in terms of particle diffusion wherein all individuals are subject to upward and downward diffusion by flight, gravity and turbulence. Such a gradient can be expressed accurately by the formula

$$f(z) = C(z + z_e)^{-\lambda}$$

where $f(z)$ is density at height z,

C is a scale factor depending on population size,

λ is an index of the diffusion process and of the profile,

z_e is a parameter whose significance probably depends on the rate of exchange of insects between air and ground.

This expression may not hold good when the profile is decaying or building up.

The empirical derivation of the expression is described and most relevant published data on vertical distribution up to 5000 ft have been satisfactorily fitted to the above expression.

This expression for the profile can be integrated to give an estimate of the total numbers of insects in a given zone of air or, within practical limits in the whole atmosphere. λ expresses in a single parameter the relative numbers at different heights; thus the more insects there are in the lower compared with the upper layers of the air, the higher the value of λ will be.

The expression is the first step in an analysis of the vertical dispersal process which will be discussed in a later paper in relation to mathematical and physical theories of diffusion.

Author

238. Johnson, C. G.: The Study of Wind-Borne Insect Populations in Relation to Terrestrial Ecology, Flight Periodicity and the Estimation of Aerial Populations. Sci. Prog., vol. 39, 1951, pp. 41-62.

Many studies on general insect aerial populations have suffered from a tendency to treat the aerial population as a whole and, by disregarding the population ecology and behaviour of closely related groups, to fail to distinguish important factors controlling the supply of insects to the upper air; and by a preoccupation with the idea of passive drift to minimise the importance of behaviour in the dispersal of insects by wind.

The study of aphids shows that there is a diurnal periodicity of flight and a nocturnal quiescence at crop level: and that the supply of insects to the upper air depends on the extent to which this diurnal supply coincides with convection and turbulence. This diurnal-nocturnal rhythm is reflected up to heights of at least 2000 ft. above ground.

The question of population density is considered, and the density or state of crowding in a space is distinguished from the factors of activity or drift into the space which may or may not contribute to it. Defects in past methods of density estimation are discussed and the inefficiency of aerial tow-nets in still air and the impracticability of weighting the catch correctly demonstrated. A new technique, the suction trap, has been developed which, sampling air at a constant rate, catches efficiently in still air, and gives a more direct reading of density without the necessity to make a correction for wind-speed.

Author

239. Johnson, D.: Brief Measurements of Insect Contamination on Aircraft Wings. Tech. Note No. Aero. 2164, British R.A.E., May 1952.

The character and distribution of insect contamination has been investigated on the wings of three aircraft (Armstrong Whitworth E.9/44 (A.W.52), a Comet airliner, and a Meteor fighter) and additional information obtained on a number of other aircraft of various types. The results suggest that the contamination, which might cause transition from laminar to turbulent flow, extends to 5% chord on the upper surface and 12% chord on the lower surface of a wing. These limits agree very well with the results of a similar investigation made in Australia on different aircraft.

The contamination which occurs beyond these limits is only a very small percentage of the total and consists of smears on the surface. It is not likely to cause transition but might be of importance in connection with porous suction wings.

Author

Availability:
N-53305

240. Gregory, N.: Research on Suction Surfaces for Laminar Flow. Boundary Layer and Flow Control, Volume 2, G. V. Lachmann, ed., Pergamon Press, 1961, pp. 924-960.

This chapter is a critical review of present-day (1961) achievements in the design of practical suction surfaces for laminar flow. Experimental work is described and problems remaining to be solved are discussed.

241. Gerber, Alfred: Investigation on Removal of the Boundary Layer by Suction. Transl. No. 353, Materiel Div., U.S. Army Air Corps, Sept. 26, 1941. (Available from DDC as ATI-68359.)

A theoretical discussion pertaining to the stabilizing of boundary layer through the use of suction slots, together with the results of wind tunnel tests. The tests included an airfoil with slots and Fowler flaps for which a maximum lift coefficient of 4.192 was obtained at $\alpha = 10^{\circ}$.

Abstract courtesy APPLIED MECHANICS REVIEWS

Availability:
N79-70002
ATI-68359

242. Holstein, Horst; and Doneis, A. (Hermann Schoenen, transl.): Experiments on the Pressure Recovery of Slots Designed for Suction of the Laminar Friction Layer. ZWB FB 1773, A 35-27, Feb. 15, 1947. (Available from DDC as ATI 26471.)

Experiments were conducted to determine the pressure recovery of slots designed for suction of the laminar friction layer. The shape of the slot, as well as the width of the slot, was changed during the time of the tests and the possibility of altering the shape of the slot was increased by applying a plain diffuser with a variable opening angle. Results show that at a given suction volume it is possible, with proper selection of the shape and width of the slot, to maintain the pressure in the suction vessel at least equal to the outside flow, for as long as the suction volume remains equal to or less than the magnitude of the boundary layer.

Availability:
ATI-26471
N79-73668

243. Fage, A.; and Sargent, R. F.: Design of Suction Slots. R. & M. No. 2127, British A.R.C., 1944.

Part I describes visual observations of flow that were made to determine the optimum entry shape of two-dimensional slots to be used for boundary layer suction. The observations were made in a low-speed wind tunnel for three values of the ratio of the rate of air sucked into the slot to the rate of flow in the boundary layer, and for slot angles of 15°, 30°, 45°, 90° and 135°. Part II describes experiments made at higher speeds of laminar flow for slots on the wall of a straight circular pipe. This was done as a check on conclusions drawn from part I.

Author

Availability:
N78-78490

244. Tests of a Griffith Aerofoil in the 13 ft. × 9 ft. Wind Tunnel. R. & M. No. 2148, British A.R.C., 1944.
Richards, E. J.: Part I - Wind-Tunnel Technique and Interim Note.
Richards, E. J.; Walker, W. S.; and Greening, J. R.: Part II - Effect of Concavity on Drag.
Richards, E. J.; and Walker, W. S.: Part III - The Effects of Wide Slots and of Premature Transition to Turbulence.
Richards, E. J.; and Walker, W. S.: Part IV - Lift, Drag, Pitching Moments and Velocity Distributions.

Part I describes the technique used in the experiments, and the method of interpretation of the results to include in the drag a term to account for the power used to develop the necessary suction. The experiments show that separation of the flow on the surface can be fully prevented on this type of aerofoil by sucking less than half the air in the laminar boundary layer at the design position of the slot. If the flow is turbulent from the wing leading edge, the amount of air that must be sucked away is very little greater than that if the flow is laminar to the slot.

In earlier experiments it was found that the flow to the rear of the suction slot remained laminar to the trailing edge of the aerofoil. In the present experiments this was not found to be so, transition to turbulence occurring some distance rear of the slot. Part II of this report describes an investigation of this effect and shows that this instability results from the dynamic instability of the boundary layer along a concave surface, and that it is impossible to design any practicable aerofoil shape over which this instability can be prevented at the Reynolds numbers of flight.

Part III of the report extends the investigation of slot design to greater slot widths and less extreme shapes and includes the effect on suction mass flow of premature transition to turbulence forward.

In Part IV aerofoil characteristics are discussed both with and without suction, including the velocity distribution over the aerofoil, lift coefficient, pitching moments and hinge moment variation with incidence. The effective drag coefficient variation is examined and extrapolation to full-scale Reynolds numbers carried out. It is shown that even with turbulent flow aft of the suction slot, a low-drag coefficient may be anticipated at the Reynolds numbers of flight. The effect of nacelles on suction wings is also examined.

Author

Availability:
N78-78491

245. Maillart, Guy: Aspiration de la Couche Limite. B.S.T. No. 106, Publ. Sci. & Tech., Minist. Air (Paris), 1946.

The history of the use of suction of the boundary layer is given. A discussion of the effects of slot form, placement, and size is included. Early experiments by Schrenck and Bamber and Ackeret and Margoulis are described. Suction of the boundary layer on flat plates, airfoils, diffusers, etc. is discussed.

Availability:
N79-71086

246. Pierpont, P. Kenneth: Investigation of Suction-Slot Shapes for Controlling a Turbulent Boundary Layer. NACA TN 1292, 1947.

Tests of three types of boundary-layer-control suction slots have been made in a two-dimensional diffuser to investigate design criterions and to evaluate the practical minimum total-pressure losses. The tests were conducted at a velocity of about 100 feet per second with a boundary layer which had a displacement thickness of 0.85 inch and a shape parameter of about 1.8.

The shape of the boundary layer behind the slot was found to depend only on the quantity of air removed provided that the slot inlet had rounded edges. Near maximum effectiveness was obtained when the quantity rate of air flow through the slot was equal to that which would pass at free-stream velocity through an area equal to the displacement thickness per unit span.

The total-pressure losses through the slot were found to be appreciably reduced by rounding the inlet edges, inclining the slot, slightly diverging the slot walls, and, especially, providing adequate width. The optimum inlet-velocity ratio for a diffuser slot is of the order of 0.60 to 0.65. For the foregoing rate of air flow and with a round-edge diffuser slot inclined at 30° to the air stream, the total-pressure drop was 48 percent less than the value for a normal-opening sharp-edge slot. For this configuration only 55 percent of the measured total-pressure drop could be accounted for by the total-pressure deficiency in the part of the boundary layer removed.

Author

Availability:
N78-78530

247. Reilly, Richard J.: Influence of Internal Flow Passages on the Spanwise Suction Distribution in a Slot. Rep. No. BLC-54, Rep. No. NAI-54-489 (Contract AF33(616)-3168), Northrop Aircraft, Inc., July 1954. (Available from DDC as AD 54 971.)

In order to determine the effect of internal flow passages on the spanwise suction distribution in a slot, a series of spanwise static pressure surveys were conducted in the entrance of a suction slot. The air was sucked from the atmosphere through the slot, into a small chamber and then through a row of holes. A flow measuring tube, installed between the holes and the suction pump, was used to measure the total airflow quantity.

The effect of varying the distance between the slot exit and the row of holes (plenum chamber depth) was measured for four different hole configurations at three Reynolds numbers.

From the static pressure at the slot inlet the spanwise suction distribution was evaluated and presented in Figures 3 - 6 in the form of $u/\bar{U}$.

Results: The spanwise variation of the suction quantity is generally small provided the plenum chamber depth is equal to or larger than the slot width. With an increased number of correspondingly smaller holes the spanwise variation of the suction quantity can be considerably reduced. For otherwise identical configurations larger diameter holes will improve the spanwise suction distribution.

For the range of Reynolds numbers investigated, there appears to be little variation in suction distribution with Reynolds number.

Author

Availability:
SN-24021, July 1954
BLC-54
NAI-54-489
AD 54 971

248. Reilly, Richard J.: Influence of Chordwise Separation Between a Slot and Its Suction Holes on the Spanwise Suction Distribution in a Slot. Rep. No. BLC-59, Rept. No. NAI-54-567 (Contract AF33(616)-3168), Northrop Aircraft, Inc., Aug. 1954.

Experiments were conducted in order to determine the spanwise variation in suction quantity along a slot when the slot was displaced in a chordwise direction from a row of suction holes below the slot. The experimental method was similar to that employed for BLC-54.

For the configurations investigated, the maximum variation in suction distribution occurs with the slot centered over the row of holes. When the slot is displaced a distance equal to the radius of the suction holes, this maximum variation was reduced by approximately one-half. Further displacement of the slot reduces the variation until a uniform distribution is reached at a displacement of from one and one-half to four times the radius of the suction holes, depending on the individual configuration.

Author

Availability:
BLC-59
NAI-54-567

249. Reilly, Richard J.: The Influence of Slot Width on the Spanwise Suction Distribution in a Slot. Rep. No. NAI-54-717 (BLC-62) (Contract AF33(616)-3168), Northrop Aircraft, Inc., Oct. 1954.

Experiments were performed in order to determine the effect of slot width on the spanwise suction distribution in a slot. The configurations tested and the experimental method were similar to those employed for BLC-54 and BLC-59 with the exception that the slot width was enlarged to 0.020 inch; twice the previous value.

For the configuration tested, the wider slot resulted in greater spanwise suction variation, for the same Reynolds number based on the flow through the slot and the holes. Chordwise displacement of the slot relative to the holes, again produced a more uniform suction distribution.

Author

Availability:
NAI-54-717 (BLC-62)

250. Dunlap, Roger; and Amick, James L.: Preliminary Tests of Boundary Layer Suction Through a Single Slot on a Body of Revolution in Supersonic Flow. WTM-262 (Contract AF33(616)-3168), Eng. Res. Inst., Univ. of Michigan, Sept. 1958.

This is a report on measurements of boundary layer suction and its effects on the flow about a single slotted body of revolution. The tests were conducted in the Mach number 2.84 nozzle of the University of Michigan 8 × 13 inch supersonic wind tunnel. The purpose of these tests was to study the application of boundary layer suction through one slot of the cylindrical part of an ogive-cylinder body of revolution. The two main variables involved were mass flow removal rate and slot width. The measurements to be made consisted of various static pressures and temperatures as well as total pressure surveys through the boundary layer and along the edge of the boundary layer in the vicinity of the slot, for several slot widths and mass flow removal rates. In addition, suction quantities were measured at reduced tunnel static pressures with the tunnel not in operation.

Author

Availability:
N78-78477
SN-24021, Dec. 1958

251. Groth, E. E.: Investigation of the Flow Field Around a Suction Slot at Supersonic Speeds. Rep. No. NAI-59-4 (BLC-116), Northrop Aircraft, Inc., Jan. 1959.

Flow measurements have been conducted in the immediate vicinity of a suction slot at different suction quantities on an ogive cylinder body of revolution at a free stream Mach number of 2.90 in the 8" × 13" supersonic wind tunnel of the University of Michigan. The potential flow is accelerated locally ahead of the slot until a shock wave reduces its speed to the undisturbed value without suction. The entropy loss of the shock can be expressed as a drag coefficient which is of the order of 20% of the suction coefficient for the present configuration. The theoretical shape of the shock wave computed from the measured Mach number distribution at the outer edge of the boundary layer is in good agreement with the observed shock pattern.

The following report is also included as an appendix:

Dunlap, R.; and Amick, T. L.: Preliminary Tests of Boundary Layer Suction Through a Single Slot on a Body of Revolution in Supersonic Flow. Rep. WTM 262, Univ. of Michigan, Sept. 1958.

Author

Availability:
N78-78477
SN-24021, Dec. 1958
NAI-59-4 (BLC-116)
N79-75703

252. Gutstadt, L. R.: Crossflow Effects on Boundary Layer Suction Slot Pressure Losses. NOR-61-231 (Contract AF33(600)-42052), Northrop Corp., Sept. 1961.

This report describes the model used, the test run, and data obtained. Pressure along a wall ahead of a slot and in the plenum below the slot were measured. Additional pressures were measured to establish boundary layer velocities and suction flow rates. A 3 times full scale slot width model was used. The slots were spaced to simulate those near the leading edge of the LFC ADP wing.

Availability:
NOR-61-231

253. Holt, Charles F.: The Laminar Boundary Layer in the Vicinity of a Suction Slot. M.S. Thesis, Pennsylvania State Univ., 1965. (Available from DDC as AD 627 025.)

The interest in suction as a means of controlling the growth of the laminar boundary layer has led to the investigation of the behavior of such a boundary layer in the vicinity of a discrete suction slot. In order to observe the effect of one such slot, detailed boundary layer profiles were measured at various stations upstream and downstream of a slot. The investigation was carried out for the three slot Reynolds numbers equal to 29, 186, and 366. At each Reynolds number slot widths of 1/16, 3/32, and 1/8 inch were tested. Variation in the displacement thickness, momentum thickness and a shape factor based on the ratio of these two parameters indicated that the slot affects a region from 20 to 30 times its own width and introduces substantial changes in the aforementioned variables. In the present tests suction created profiles after the slot with shape factors equal to or less than the asymptotic suction value.

Author

Availability:
N66-20110
AD 627 025

254. Pfenninger, W.; Bacon, J.; and Goldsmith, J.: Flow Disturbances Induced by Low-Drag Boundary-Layer Suction Through Slots. Phys. Fluids Suppl., vol. 10, no. 9, pt. II, Sept. 1967, pp. S112-S114.

Suction flow fluctuations induced at higher slot flow Reynolds numbers $Re_s \equiv \bar{v}\ s/\nu$ by oscillating slot wakes in the plenum chambers underneath the slots apparently caused premature transition on a 33° swept laminar suction wing at high wing chord Reynolds numbers. With viscous slot wakes at $Re_s \leqslant Re_{scrit}$ such disturbances were absent with full laminar flow beyond 50×10^6 length Reynolds number. Re_{scrit} increases from 100 for relatively deep plenum chambers to over 200 for shallow plenum chambers with two rows of suction holes located at opposite sides of the slot.

Author

Availability:
A68-11327

255. Ciğdem, Sabri: Laminar Boundary Layer Development Downstream of a Suction Slot. M.S. Thesis, Naval Postgraduate School, 1971. (Available from DDC as AD 742 937.)

Laminar boundary layer development downstream of a suction slot was investigated in a low velocity wind tunnel. In order to observe the effect of suction on the boundary layer, detailed boundary layer profiles were measured at various stations upstream and downstream of a suction slot for different suction flow rates. The investigation was carried out for zero suction, 53.33 SCFH/FT. and 133.33 SCFH/FT. suction, by using 1/16 inch suction slot. The velocity profiles were plotted for 22 stations with different suction flow rates with respect to the no suction flow case. At the far upstream and downstream side of the slot, suction was ineffective and velocity profiles had the Blasius velocity profile shape. Suction had the maximum effectiveness a short distance in front of and downstream of the slot. As the distance from the slot increased both upstream and downstream, the velocity profiles tended to approach Blasius velocity profiles asymptotically.

Author

Availability:
N72-31005
AD 742 937

256. Gaponov, S. A.: Stability of a Boundary Layer of an Incompressible Fluid Over a Slotted Surface. NASA TT F-16896, 1976.

Boundary layer stability of a slotted surface is analyzed for the case when the boundary conditions for perturbations of the flow parameters depend on the longitudinal coordinate. The effect of the degree of nonuniformity of the penetrability of the slotted surface is studied. Results are compared with those obtained previously for a surface with uniform penetrability.

Author

Availability:
N76-20419
A75-45327 (Original Russian)

257. Barinov, V. A.: Vliianie diskretnosti otsasyvaniia na kharakteristiki trekhmernogo laminarnogo pogranichnogo sloia na skol'ziashchem kryle. Uch. Zap., TsAGI, vol. 5, no. 1, 1974, pp. 104-107.

A scheme for calculating the characteristics of the flow past a wing with suction slots by considering a certain discrete distribution of the suction rate rather than a continuous one. Values of local Reynolds number are calculated by the method of integral relations for the profiles of the velocity components along a streamline of the external flow and in a direction perpendicular to it, and are compared with the smallest critical Reynolds numbers for the profiles investigated. A similar comparison is made for continuous distributed suction, revealing the destabilizing effect of nonporous surface segments.

Availability:
A76-37890

258. Goldsmith, J.: Calculation of Compressible Flow Losses Through Swept Suction Slots. Summary of Laminar Boundary Layer Control Research - Volume II, ASD-TDR-63-554, U.S. Air Force, Mar. 1964, pp. 509-547. (Available from DDC as AD 605 186.)

Results of laminar flow experiments performed on a supersonic 36° swept wing model indicated that it might be desirable to consider the influence of the spanwise component of velocity when calculating the losses through swept slots. If the spanwise component of velocity is of importance at 36 degrees of sweep, it certainly is logical that it would be more influential at higher sweep angles. Since a model with a sweep angle of 72 degrees was being designed, an analysis was made to determine the influence of sweep on slot losses. The conclusions derived from this analysis are presented in this report, together with the description of a workable procedure for calculating the compressible flow losses through swept slots.

Author

Availability:
N65-25567
AD 605 186

259. Yu, Yun-Sheng: Lateral Efflux From Flow Along a Wall Into a Suction-Slot. Proceedings of the Second Australasian Conference on Hydraulics and Fluid Mechanics, Univ. of Auckland (New Zealand), 1966, pp. C117-C122.

Study of the lateral efflux from flow along a wall with a single suction-slot oriented perpendicular to the direction of the free stream. The contraction coefficient - defined as the ratio of the thickness of the jet in the slot to the slot-width - has been computed by using conformal mapping for the free-stream velocity to the jet-velocity ratio varying from zero to one. Experimental results obtained in a subsonic wind tunnel agree surprisingly well with the theory.

Availability:
A67-23559

260. Watson, E. J.: Free Streamline Suction Slots. R. & M. No. 2177, British A.R.C., 1946.

The theory of free streamlines is applied to the design of suction slots, or similar entries to ducts. Although suction slots are intended for boundary layers, where potential flow does not apply, it is hoped that the slot shapes obtained here may provide a basis for experiment. These slots may be compared with those derived empirically by Fage and Sargent, but contain one novel feature in that there is, in general, a step between the flat boundaries at either side of the slot. The figures show a series of slots covering a range of slot angles and of ratios of stream velocity to slot velocity, and the coordinates of these slots are given in the Tables. The formulae by which these slots are calculated are collected in the Appendix.

Author

Availability:
N78-78492

261. Lord, W. T.: Free Streamline Jets in Shear Flow, and Their Application to the Design of Suction Slots. F.M. 1450, British A.R.C., 1950.

Solutions for the shapes of free streamline jets issuing from a gap between two flat parallel surfaces may serve as a basis for designing slots for sucking away the boundary-layer on an aerofoil. A brief description is given of some unsuccessful attempts to obtain analytical solutions for such jets when the flat surfaces are collinear and the flow at a large distance from the gap is a constant shearing motion containing vorticity of any magnitude. A method of solution for the case when the magnitude of the vorticity is sufficiently small for terms of the order of its square and higher powers to be neglected is given in detail. This method may be extended to cover the more general case when there is a step between the flat surfaces on each side of the gap.

Author

Availability:
N-17750
ATI-165 084

262. Bacon, John W., Jr.; Goldsmith, John; and Gross, Lloyd W.: Effect of Slot Configuration and Disturbances From Slot or Environment on Laminar Flow Vehicles. NCL-68-46R (Contract N00017-67-C-1112), Northrop Corp. Lab., July 31, 1968. (Available from DDC as AD 851 246.)

Availability:
X69-16041
AD 851 246

263. Rogers, K. H.: Flow Stabilization With Discrete Suction - Final Report. C78-517/301 (Contract N00140-77-C-8099), Marine Systems Div., Rockwell International Corp., June 1, 1978.

The program addresses two key technological problems related to the development of suction laminar flow undersea vehicles: the problem that ocean particles may be trapped at the entrance of the suction surface apertures and spoil the laminar flow; and the necessity to develop an economically feasible, producible suction laminar flow hull structural design. Thus the program consists of ocean particle capture/contamination tests on slotted and porous laminar suction surfaces, correlation of experiment and theory of ocean particle capture, and a study of preliminary design and producibility of laminar suction hulls.

Author

Availability:
N79-70654

264. Smith, A. M. O.: Report of Progress on Item 2B (2), Boundary Layer Control Investigation. Rep. No. E.S. 21099 (Contract No. NOa(s) 9027), Douglas Aircraft Co., Inc., Apr. 1, 1948.

100% laminar flow by control of the boundary layer has been obtained in Switzerland at Reynolds Numbers below about 5×10^6. However, studies carried out under the present contract indicate the Swiss procedure would require an impractically large number of excessively small slots at full scale conditions. Hence the Swiss method appears impractical.

This discovery caused a search for a more practical method of laminar boundary layer control. A porous sintered metal and a perforated surface were considered. The sintered metal surface should provide excellent boundary layer control but it is brittle, heavy and undoubtedly would become quickly clogged up by dust and dirt. A perforated metal surface cannot be expected to control the boundary layer because perforations are spaced too far apart to affect all parts of the boundary layer.

However, a practical method for controlling the laminar layer is believed to have been found. This method uses suction to thin the boundary layer in the presence of stable pressure gradients as proposed by Griffith. Two airfoils using this principle, applicable to the D-571, have been designed and are shown in this report. It is proposed that a 42" chord by 30" span two dimensional model be constructed and tested in the Douglas Flow Generator to check inexpensively these new principles at medium Reynolds Numbers.

Author

Availability:
N79-70003

265. Preston, J. H.; and Rawcliffe, A. G.: Note on Sintered Metal With a View to Its Use as a Porous Surface in Distributed Suction Experiments. C.P. No. 9, British A.R.C., 1950.

Considerable theoretical work has been done on boundary layer flow involving distributed suction through a permeable surface, on the other hand there have been few experiments to check the theory and these have used a series of slots to represent a porous surface. Their use in one case led to negative results because of their adverse effect on the pressure gradient. Hence the need for a truly porous surface.

Attention in this note is mainly confined to sintered bronze - a material which has wide range of porosity. A brief description of its properties is given and also the results of tests on a number of samples representative of the range available for commercial purposes. Measurements were also made of the porosity of beechwood and of Plaster of Paris.

The size of pores, their distribution and the resistance offered to the flow make porosint a very suitable material for constructing models with porous surfaces. It has the definite advantages of some mechanical strength and it can be welded and soldered. There is one disadvantage - the surface cannot be machined as the pores might be closed up, hence accuracy of model manufacture depends on the precision to which it can be moulded and the distortion present after being furnaced.

Author

Availability:
N78-78559
N-119

266. McCullough, George B.; and Gambucci, Bruno J.: Boundary-Layer Measurements on Several Porous Materials With Suction Applied. NACA RM A52D01b, 1952.

Boundary layer velocity profiles were measured on ten samples of various porous materials and on an impervious aluminum plate mounted flush with the inner surface of the side wall of a small wind tunnel. Suction was applied to the back side of the porous test materials through a 4-inch-square opening. The profiles were measured after the natural boundary layer of the tunnel wall had traversed a distance of $3\frac{1}{2}$ inches along the suction area. The boundary layer measured on the smooth impervious plate was laminar at the upstream end of the suction area, but was of the transitional type after having traversed the $3\frac{1}{2}$ inches to the downstream measuring station. Without suction none of the velocity profiles measured on the porous materials were laminar at the downstream station. The thickness of the boundary layer was increased and its form altered from that measured on the impervious plate by amounts which depended on the nature of the surface of the material. With suction applied the form of the boundary layers was greatly altered, and both the displacement thickness and the momentum thickness were reduced. The rate of thinning diminished with increasing suction, and the boundary layer displacement and momentum thicknesses on all of the porous materials appeared to be approaching a low ultimate value with increasing suction velocity.

Author

Availability:
N78-78563

267. Dannenberg, Robert E.; and Weiberg, James A.: Effect of Type of Porous Surface and Suction Velocity Distribution on the Characteristics of a 10.5-Percent-Thick Airfoil With Area Suction. NACA TN 3093, 1953.

An investigation has been made at low speed of the two-dimensional characteristics of a 10.51-percent-thick symmetrical airfoil with area suction for boundary-layer control near the leading edge. The lift and suction-flow characteristics were determined with different porous surfaces consisting of perforated plates and sintered steel for various suction velocity distributions obtained by varying the permeability arrangement. The flow requirements were ascertained over a range of free-stream velocities.

The maximum section lift coefficient was increased from 1.3 to approximately 1.8 by means of area suction from 0.3- to 3.0-percent chord. For the airfoil investigated, a lift coefficient of 1.7 was attained with a minimum section flow coefficient of 0.00090 at a free-stream velocity of 162 feet per second with a permeability arrangement which gave a suction velocity at the trailing edge of the suction area equal to 2 percent of the local velocity with no outflow at the leading edge.

The maximum lift coefficient and the minimum suction quantity for a given lift were independent of the surface of the materials tested (including filter paper, NACA TN 2847). The minimum flow coefficient required for a given increase in lift varied with free-stream velocity; the amount depended on the chordwise distribution of the porous material.

Author

Availability:
N78-78531

268. Dannenberg, Robert E.; Weiberg, James A.; and Gambucci, Bruno J.: The Resistance to Air Flow of Porous Materials Suitable for Boundary-Layer-Control Applications Using Area Suction. NACA TN 3094, 1954.

A survey has been made of the resistance to air flow of a variety of commercially available porous materials. Three general types of porous media were tested - granular (sintered bronze and steel), fibrous (felt cloth and filter paper), and perforated.

For small pressure differences across the porous material, the pressure difference increased as a constant power of the suction air velocity. With larger pressure differences, the pressure difference increased with velocity at a more rapid rate. The flow resistance of a sample of sintered bronze was independent of the air pressure at the upstream side of the material for values of absolute pressure from 830 to 3170 pounds per square foot.

The flow resistance of a sample of sintered steel was independent of the direction of the flow approaching the material.

Author

Availability:
N78-78532

269. Hunter, Paul A.; and Johnson, Harold I.: A Flight Investigation of the Practical Problems Associated With Porous-Leading-Edge Suction. NACA TN 3062, 1954.

Results of this investigation have indicated that a practical wing having porous-leading-edge suction can be constructed which has sufficient strength and durability for use in flight without adding excessive weight. For the type of porous material used in this investigation, clogging due to atmospheric dust did not appear to be a problem. For the light rain encountered in flight, the power required to produce a given flow coefficient was about 50 percent more than that required for the dry condition. Based on the ground data, it was estimated that for flight in heavy rain the power would be approximately twice that for the dry condition. At maximum blower speed, however, the porous area became cleared within 3 to 4 minutes after water ceased to impinge on the surface. Under certain conditions, tests showed a severe vibration of the porous material induced by an "organ pipe" resonance of the air column within the ducts. As expected from previous wind-tunnel results, the use of leading-edge suction with the small amount of power available and with the well-rounded airfoil section used (NACA 2412) had little effect on the maximum lift coefficient developed. In general, an appreciable drop in maximum lift coefficient occurred from the leading-edge-sealed configuration to the condition of zero suction with the porous-area configurations tested. Increments in lift coefficient due to the suction available generally brought the maximum lift coefficient back approximately to the value for the wing with the leading edge sealed. The maximum theoretical aerodynamic power, if duct losses are excluded, varied with the configurations tested from 3.65 to 9.70 horsepower.

Author

Availability:
N78-78533

270. Dannenberg, Robert E.; Weiberg, James A.; and Gambucci, Bruno J.: A Fibrous-Glass Compact as a Permeable Material for Boundary-Layer-Control Applications Using Area Suction. NACA TN 3388, 1955.

Measurements were made of the air-flow-resistance characteristics of fibrous-glass compacts consisting of blown-glass fibers and 25-percent phenolic resin by weight as the bonding agent. The permeability was controlled by the density and thickness of the compact. The permeability of constant thickness compacts was varied over the range generally required for applications of area suction for boundary-layer control.

In application, the compact could be molded to any desired shape and thickness and installed in a sandwich type of arrangement consisting of perforated metal sheets supporting a fibrous-glass compact interior.

The rigid supporting sheets could serve as structural members. Perforating only the portion of the surface sheet in the porous region would permit a joint-free installation. In operation the fibrous-glass compact could be removed and replaced if it became partially clogged.

Author

Availability:
N78-78534

271. Ferris, Donald P.; Guendel, Henry W.; Heck, Frank W.; and Comstock, Gregory J.: Navy Project for the Investigation of Porous Material Made From Metal Powders for Aircraft Boundary Layer Control. Aer-TD-413, U.S. Navy, Jan. 31, 1956. (Available from DDC as AD85 167.)

The technique of extruding spherical metal powder particles was utilized to provide a preform with varying cross-section. This strip was sintered and cold coined to provide a section of variable air permeability.

Both mathematical and graphical relationships between original thickness, final thickness, pressure differential and air flow are presented and evaluated.

The use of the accumulated data to permit the design of a preform section, which meets the requirements of predetermined aerodynamic specifications, is presented and discussed.

Author

Availability:
N79-70073
SN-30107, Apr. 1953-Jan. 1956
AD85 167

272. Yates, E. Carson, Jr.: On the Permeability of Porous Materials. NACA TN 3596, 1956.

The effects on porous-material permeability characteristics of the absolute pressure level (and associated scale effects), choking of the flow, bending the material, and other factors have been investigated. Samples of rolled 30- by 250-mesh Dutch weave Monel metal cloth and 1/16-inch-thick sintered bronze were calibrated with constant upstream pressures of 1 atmosphere and $2\frac{1}{3}$ atmospheres (varying downstream pressure) and with constant downstream pressure of 1 atmosphere (varying upstream pressure). Experiments showed permeability characteristics to be appreciably affected by absolute pressure level, flow choking, and thickness of the material. Moderate bending of the material caused no noticeable change in the permeability. Simple calculation and correlation procedures are presented for determining permeability characteristics with reasonable accuracy when experimental data are limited.

Author

Availability:
N78-78604

273. Debeau, David Edmund: Evaluation of Porous Materials for Boundary-Layer Control. WADC TR 56-486, U.S. Air Force, Nov. 1956. (Available from DDC as AD 110 582.)

Criteria were determined from designers for comparing various commercial permeable sheet materials for use in boundary-layer control associated with high-life systems. Sintered metal powders, special woven & sintered wire materials, a compressed glass-fiber product, woven wire clothes, & perforated metal sheets were evaluated & compared for the following properties: average permeability, uniformity of permeability, resistance to clogging & corrosion, mechanical properties including room temperature tensile strength, modulus of elasticity, Poisson's ratio, & minimum bend radius. An evaluation of economic factors, including production facilities, product limitations, requirements for & availability of raw materials, & cost of product, was carried out on those permeable sheet materials which attained most nearly the physical & mechanical properties desired by the aircraft designers. An appendix presents detailed information collected on boundary layer control from several aircraft companies & government agencies.

Author

Availability:
N79-70059
SN-37135, Nov. 1954-Sept. 1956
AD 110 582

274. Schrello, D. M.: A Method for Estimating the Flow Characteristics of Permeable Materials Suitable for Boundary Layer Control Applications ESO CL-1187. Rep. No. NA58H-354, North American Aviation, Inc., July 3, 1958.

A dimensional analysis of the flow through a perforated medium is found to lead to a functional relationship between three dimensionless flow parameters and two dimensionless geometric parameters. The assumed form of this relationship involves eleven arbitrary coefficients which must be determined by experiment. An IBM 704 program is then used to calculate these coefficients for data obtained from the literature on permeable materials in normal and parallel flow, and qualitative and quantitative conclusions about the effects of varying the material geometry are obtained. A method is presented for determining, approximately, the proper material geometry to be used for any given two-dimensional boundary layer control application without recourse to specific experimental measurements.

Author

Availability:
N79-70058
N-71499

275. Wortmann, F. X.; and Althaus, D.: Investigation of Laminar Boundary Layer Control by a Novel Porous Surface. Scientific Association for Air and Space Travel and German Association for Rocket Technology and Space Travel Research, Annual Meeting, Hermann Blenk, ed., Friedrich Vieweg und Sohn, 1965, pp. 158-163.

Discussion of a perforated plastic reinforced by glass fiber proposed for BLC purposes. The relation between surface thickness and hole diameter can be arbitrarily varied, so that both very light and heavy (resistant) surfaces are readily manufactured. Results of wind-tunnel experiments supporting the applicability of the surface in the practice are presented. The observed limitations are not of a basic nature and should be easily eliminated in subsequent development.

Availability:
A66-13513

276. Bedore, Robert L.: An Experimental Investigation of Materials Suitable for the Porous Skin of a Boundary Layer Control by Suction Vehicle: Progress to 9-31-75. Progress Rep., Naval Undersea Center, Jan. 16, 1976.

This investigation is an element of a program to develop a Boundary Layer Control by Suction Torpedo. The successful design of such a torpedo depends on the development of a porous skin with a satisfactory combination of permeability, strength and clogging resistance.

The purpose of the investigation is to identify suitable materials, devise suitable tests and test methods, test promising materials, and attempt to understand how flow rate and clogging rate are affected by parameters such as pore size, water quality, thickness, etc.

Eleven materials have been identified, six have been tested and several do have an acceptable combination of properties.

Continue investigation of small test specimens and start testing two inch and six inch diameter shells.

Author

Availability:
N79-70060

277. Logan, J. C.: BLCS Porous Materials. NOSC TN 352, U.S. Navy, Oct. 1977.

Availability:
X79-70072

278. Douglas Aircraft Co.: Development of Technology for the Fabrication of Reliable Laminar Flow Control Panels on Subsonic Transports. NASA CR-145125, 1976.

The feasibility of using porous composite materials (Kevlar, Doweave, and Leno Weave) as lightweight, efficient laminar flow control (LFC) surface materials is compared to the metallic 319L stainless Dynapore surfaces and electron beam drilled composite surfaces. Areas investigated include: (1) selection of the LFC-suitable surface materials, structural materials, and fabrication techniques for the LFC aircraft skins; (2) aerodynamic static air flow test results in terms of pressure drop through the LFC panel and the corresponding effective porosity; (3) structural design definition and analyses of the panels; and (4) contamination effects on static drop and effective porosity. Conclusions are presented and discussed.

Author

Availability:
N77-17038

279. Crimi, Peter: Consideration of Clogging in Boundary-Layer Control System Design. J. Aircr., vol. 14, no. 8, Aug. 1977, pp. 825-827.

A model is proposed for the clogging mechanism of boundary layer control systems that employ suction through perforated surfaces. The primary parameters are perforation size, particle size, boundary layer thickness and velocity profile, external flow static and dynamic pressures, and suction pressure. An equation describes the limiting condition for no clogging of an individual particle, which is satisfied when the moment on a particle due to drag about the furthest downstream contact point is sufficient to overcome the moment due to the suction on the portion of the particle in the whole. Curves for maximum suction for no clogging vs hole size were obtained from this condition for both laminar and turbulent boundary layers. These results are applied to some specific systems, and it was found that clogging need not be a problem for boundary layer control used to prevent leading-edge stall.

Availability:
A77-41549

280. Brazier, Grant: Flow Resistance Characteristics of a Variety of Porous and Perforated Sheets. Rep. No. ES 15218 (Contract No. NOa(s)9517), Douglas Aircraft Co., Inc., June 9, 1949.

Thirty-four specimens were tested to determine airflow characteristics. Of these eleven were porous (sintered) sheets varying in thickness from 0.030 to .090 and in porosity from 25 to 50 percent. The remaining twenty-three specimens were perforated sheets varying in perforation shape, in thickness from .002 to .064 and in open area from 12 to 46 percent. Two electro-deposited screens were classified as perforated sheets. The results of the porous specimens are presented as plots of Darcy's Permeability Coefficient, α, vs Reynolds number and the results of the perforated specimens as A.S.M.E. flow coefficient, K, vs Reynolds number. The effects of clogging by water and dust are presented for one porous specimen.

Author

Availability:
N79-70035

281. May, G.; and Giles, W. B.: Porous Material Development for Boundary Layer Control. Rep. No. 64GL207 (Contract NOW 60-0839 (d)), General Electric Co., Dec. 22, 1964. (Available from DDC as AD 461 563.)

This report describes the development of a new porous material undertaken specifically for the application of area suction boundary layer control to underwater vehicles. This material was subsequently used in the manufacture of several hydrodynamic test models varying in size from 2 in. to 12-3/4 in. o.d. The small models were tested and reported to show boundary layer stabilization. A unique property of this design is its ability to recover its original porosity with simple back flushing.

Author

Availability:
STIF (by author or title)
AD 461 563

282. Meyer, Warren A.; Goldsmith, John; and Pfenninger, Werner: Note on Preliminary Laminar Suction Experiments Through Round Holes at High Reynolds Numbers and Low Turbulence. Rep. BLC-12, Northrop Aircraft, Inc., Sept. 1953.

The purpose of the present investigation is to study the conditions under which local instability of the laminar flow in the region of a single suction hole causes premature transition at high Reynolds numbers and low turbulence. This was done as part of discovering how far the number of holes can be reduced without deviating too much from the theoretical ideal of continuous suction.

Author

Availability:
N78-78787
BLC-12

283. Goldsmith, John; and Meyer, W. A.: Preliminary Experiments on Laminar Boundary Layer Suction Through Circular Holes at High Reynolds Numbers and Low Turbulence. Rep. No. BLC-23, Northrop Aircraft, Inc., Dec. 1953. (Available from DDC as AD 30 321(c).)

Experiments have been conducted to determine the influence of boundary layer suction through holes in the wall of a tube on the behavior of the general flow in the tube. The maximum Reynolds numbers for the experiments $\left(\frac{\bar{U}x_s}{\nu}\right)$ were about 18.7 million where $\bar{U}$ is the mean velocity in the tube and x_s is the distance between the equivalent straight tube inlet and the station where observations of the state of the flow were made. The highest length Reynolds numbers based on the distance from the equivalent straight tube inlet to the suction holes $\left(\frac{\bar{U}x_h}{\nu}\right)$ were 11 million. It was observed that there is a critical suction quantity associated with each hole configuration and tube velocity. As long as the suction quantity remains less than the critical value, the airflow in the tube remains laminar; but when the critical suction quantity is exceeded, it causes premature transition in the boundary layer downstream of the suction holes.

Measurements of this critical suction quantity have been made for various configurations including single holes and up to five rows of holes with the rows oriented perpendicular to the axis of the tube.

Author

Availability:
SN-24021, Dec. 1953
BLC-23
AD 30 321(c)
N79-75683

284. Cliett, Charles B.: Structural Considerations of Perforated Materials Used in Boundary Layer Control. Res. Rep. No. 2 (Contract Nonr 223(00)), Mississippi State Coll., Sept. 20, 1952. (Available from DDC as AD 6 050.)

Perforated sheet materials have structural advantage over slots in that torsion can be carried by the sheet. Since separate chamber pressures can be eliminated by varying the porosity, an additional advantage in structural simplification results. In fact, the technique of laminar boundary layer stabilization using a perforated surface may involve little additional structure over the conventional airplane wing design. It is for this reason that this research on the structural properties of perforated sheet materials was undertaken. The structural side of boundary layer suction has caused considerable concern, but has been the subject of very little research. This paper is an effort to fill a small portion of the gap between the progress made on the aerodynamic considerations and the lack of progress made, due to little effort, on the structural considerations. A second purpose, and the more important one, is to stimulate the interest of structures-minded people and therefore lead to serious study of the subject.

Author

Availability:
N79-70025
N-21903
AD 6 050

285. Carmichael, Bruce H.: Summary of Flight Research on Nineteen Porosity Distributions Designed to Maintain Laminar Boundary Layers on a NACA Airfoil With a Single Internal Chamber. Res. Rep. No. 6 (Contract Nonr 978(01)), Aerophys. Dep., Mississippi State Coll., 1954. (Available from DDC as AD 38 681.)

This report summarizes a year's study of a process aimed at drag reduction through maintenance of complete laminar flow over external aircraft surfaces. Suction of boundary layer air through the surface was investigated as the means toward this end. Perforated skin was used in an effort to reach a suitable compromise between the practical aspects of manufacturing and maintenance and the performance requirement of suction power economy. A single internal compartment was used in a further concession toward practical considerations in view of the complexity of the structure and suction source accompanying compartmentation. Establishing the flow condition through use of a portion of a sailplane wing in free flight in the atmosphere permitted a very pure environment for the tests. The major part of this year's work was confined to transition detection and prevention under the very low disturbance level of the natural environment. Instrumentation developed since the period reported here will permit study of the boundary layer stability to fixed frequency disturbances under various applications of suction.

Author

Availability:
N-33820
AD 38 681
N79-71087

286. Ward, G. F.: Measurement of the Flow Through Small Holes. Aerodyn. Note 127, Aeronaut. Res. Labs., Dep. Supply (Melbourne), Sept. 1953.

Flow coefficients and quantities for small holes in various materials have been experimentally established for conditions within the following limits.

(i)	Reynolds numbers	1000 to 14000
(ii)	Hole diameters	0.020 in. to 0.053 in.
(iii)	Pressure differences	0.5 in. Hg to 6 in. Hg

Author

Availability:
N-34734
N78-79431

287. Goldsmith, J.: Experiments With Laminar Boundary Layer Suction Through Rows of Closely Spaced Circular Holes at High Reynolds Number and Low Turbulence. Rep. No. BLC-36, Northrop Aircraft, Inc., Mar. 1954. (Available from DDC as AD 52 586.)

A series of experiments were conducted to verify whether or not extensive laminar flow can be maintained at high Reynolds number and low turbulence by means of suction through holes. Previous experiments have indicated that one of the most satisfactory hole configurations was an arrangement of holes in a row so that they are closely spaced and form a perforated slot. The experiments with closely spaced holes include (a) the effect of multiple rows of holes, (b) the effect of small streamwise displacement of alternate holes in order to improve the structural characteristics of the surface, and (c) the effect of ending a slot or of using finite length perforated slots rather than infinite slots.

From the results of these experiments it appears that at the test Reynolds numbers there is little difference between the boundary layer control performance of several rows of closely spaced holes and the performance of continuous slots. Using ten rows of perforated slots, laminar flow was maintained through a pressure rise of 60% of the maximum dynamic pressure in the tube at a Reynolds number of about 15 million at the suction holes and about 17.5 million where the boundary layer was observed to be laminar.

Departures from the continuous straight line row of holes such as staggering alternate holes or ending a slot may reduce the maximum suction per unit slot length at which complete laminar flow can be maintained. For the case of ending a slot the disturbances causing turbulence are local. The same problem of ending a slot also occurs for the conventional continuous slot.

Availability:
N78-78475
SN-24021, Apr. 1954
BLC-36
AD 52 586

288. Meyer, W. A.: Preliminary Report on the Flow Field Due to Laminar Suction Through Holes. Rep. NAI-55-290 (Rep. No. BLC-75), Northrop Aircraft, Inc., Mar. 1955. (Available from DDC as AD 74 865.)

Previous investigations of the effect of suction through holes in the 2-inch tube setup have been reported in References 1, 2, 3 and 4. During the course of these investigations it had been noted that the critical suction quantity per hole (suction rate at which the flow downstream of the holes becomes turbulent) for certain multi-hole configurations was less than that for a single hole. This effect is graphically illustrated in Figures 7 and 8 of Reference 2. It can be seen that the critical suction quantity per hole for the case of two holes spaced 72^o, 90^o and 180^o apart was essentially the same as for one hole. It may also be seen that as the hole spacing was decreased, the critical suction quantity per hole also decreased. At the smallest hole spacing the first critical suction quantity per hole was one-eighth to one-fifth that of a single hole (Fig. 7). It should also be noted that for the smallest hole spacing, and at a constant freestream velocity, the flow became laminar, turbulent, then laminar and again turbulent with increasing suction rates. It is evident from what has been previously stated that the flow fields of adjacent suction holes must be reacting with each other, often to the detriment of the critical suction quantity. In order to understand the mechanism involved, a series of relatively low Reynolds numbers, low speed experiments, were conducted. This note is a summary of the initial results obtained from these tests.

Author

Availability:
SN-24021, Mar. 1955
NAI-55-290 (BLC-75)
AD 74 865

289. Goldsmith, John: Additional Experiments on Laminar Boundary Layer Suction Through Circular Holes at High Reynolds Numbers and Low Turbulence. Rep. No. BLC-28, Northrop Aircraft, Inc., Feb. 1954. (Available from DDC as AD 38 616(b).)

Experiments conducted to determine the influence of boundary layer suction through holes in the wall of a 2-inch diameter laminar flow tube were described in Reference 2. It was observed that there is a critical suction quantity associated with each hole configuration and tube velocity. As long as the suction quantity through the holes remains less than the critical value, the airflow in the tube remains laminar; but when the critical suction quantity is exceeded, premature transition occurs in the boundary layer downstream of the suction holes. These experiments have been continued for additional hole configurations, and the results are presented in this report. The maximum Reynolds numbers for the experiments based on the mean velocity in the tube were about 14 million at the location of the suction holes and about 17 million at the station where the state of the boundary layer was observed.

Measurements of the critical suction quantity were made for one to ten rows of holes with 20 holes spaced evenly around the circumference of the tube in each row. The results of the experiments indicate that the critical suction quantity increases as each additional row of holes is added, but that this increase for each additional row becomes small when more than about five rows are employed. It was also shown that, in order to achieve maximum critical suction quantity for a group of holes, it is often necessary to individually adjust the suction quantity in each row of holes.

Experiments with single rows of closely spaced holes (98 and 110 holes/row) indicate that the critical suction quantity is greatly increased when the centerline spacing between adjacent holes is decreased to about 0.057 inches. The hole diameter is 0.038 inches. The results also show that the critical suction quantity for 110 holes is drastically reduced if one or more of the holes is fully or even partially plugged.

Author

Availability:
SN-24021, Feb. 1954
BLC-28
AD 38 616(b)
N79-75685

290. Goldsmith, John: Investigation of the Flow in a Tube With Laminar Suction Through 80 Rows of Closely-Spaced Holes. NAI-56-293, Rep. No. BLC-86, Northrop Aircraft, Inc., Mar. 1956. (Available from DDC as AD 92 134(a).)

Laminar suction experiments have been conducted in a 2-inch diameter low turbulence tube with 80 rows of closely-spaced suction holes at the downstream end of the tube. Laminar flow has been observed for these experiments for tube length Reynolds numbers from 8.5 to 18.8 million, and pressure rises in the suction region from 36 to 69% of the maximum dynamic pressure.

Profile drag coefficients of equivalent symmetrical suction airfoils having the same pressure distribution as the tube, have been estimated from the results of these experiments. The estimated drag coefficients for both wing surfaces at zero angle of attack (including the equivalent drag due to suction power) vary from .0007 to .0010 depending on the pressure rise and Reynolds number.

Similar experiments were previously conducted for 80 slots (Ref. 1), and a comparison is made between the performance of the slots and rows of holes. It was found that the slots are generally more efficient than the rows of holes, but not so much more efficient as to eliminate the use of rows of holes where other considerations may favor them.

Author

Availability:
SN-24021, Mar. 1956
NAI-56-293
BLC-86
AD 92 134(a)
N79-75692

291. Goldsmith, John: Losses Through Holes. Summary of Laminar Boundary Layer Control Research, WADC Tech. Rep. 56-111, U.S. Air Force, Mar. 1964, p. 225. (Available from DDC as AD 130 759.)

Experiments were conducted to determine losses through holes. The results of the measured hole losses were compared with the measured losses for a laminar flow tube with smooth inlet.

Author

Availability:
N78-76390
N-53889
AD 130 759

292. Goldsmith, John: Comparison of the Calculated and Measured Laminar Suction Losses Through Small Round Holes With Sharp-Edged Inlets. Rep. No. BLC-91, Rep. No. NAI-56-1110 (Contract AF33(616)3168), Northrop Aircraft, Inc., Nov. 1956.

The pressure drop through a tube with rounded inlet is compared with measured hole losses both with and without transverse external velocity, and it is found that correlation is good, provided:

(a) the length of the hole is greater than two times the diameter

(b) the hole Reynolds number ($2a\bar{v}/\nu$) does not exceed 1600 - 2100

(c) the air accelerates into the hole (note that when there is transverse velocity of the ambient stream at the hole inlet, the suction air may decelerate or "diffuse" as it passes into the hole, but correlation of hole losses and tube losses does not occur if the "diffusion" is too great)

(d) account is taken of the dynamic pressure in the suction layer (in the case where there is external velocity)

(e) only a small portion of the boundary layer is removed in each suction hole (in the case where there is external velocity).

Since none of these provisions is inconsistent with good laminar suction design practice, the assumption that the rounded tube and sharp-edged holes are comparable can be considered a valid assumption, whenever the provisions are met. The method of accounting for the external dynamic pressure when there is external velocity (provision "d") is described in the text.

Availability:
BLC-91
NAI-56-1110
N79-75694

293. Rogers, K. H.: Experimental and Theoretical Investigations of the Pressure-Drop Through Holes and Slots in Incompressible Viscous Flow. NAI-58-19, Rep. No. BLC-104, Northrop Aircraft, Inc., Dec. 1957. (Available from DDC as AD 152 319.)

Experimental and theoretical determinations of the pressure-drop through holes and slots are shown for a wide range of Reynolds numbers and length ratios, from the regime of laminar flow through holes and channels at low Reynolds numbers to flow through thin plate orifices at high Reynolds numbers. The effect of rounding the inlet edge of the hole or slot, and the effect of pressure recovery from transverse flow at the slot inlet are shown. Most of the experiments were made to extend the existing data beyond the low Reynolds regime into the relatively unchartered intermediate regime in order to present a comprehensive performance chart over a wide range of Reynolds numbers. The report is intended to be a reference for the design or performance determination of metering holes and slots in suction systems, but it may also be found useful in other applications of fluid dynamics.

Author

Availability:
SN-24021, Dec. 1957
NAI-58-19
BLC-104
AD 152 319
N79-75701

294. Goldsmith, John: Critical Laminar Suction Parameters for Suction Into an Isolated Hole or a Single Row of Holes. Rep. No. BLC-95, Rep. No. NAI-57-529, Northrop Aircraft, Inc., Feb. 1957.

From experiments with laminar suction where suction is applied through small circular holes, it is known that there are limiting suction quantities which must be observed if laminar flow is to be maintained. The suction limit is denoted the "critical suction quantity" and if the suction is greater than a maximum critical value or less than a minimum critical value, premature transition occurs. As long as the limiting values are observed, however, suction through holes helps in maintaining laminar flow. The critical suction quantity is a function of several variables such as hole diameter, hole spacing, boundary layer thickness and numerous other quantities. Measurement of the critical suction quantity for so many variables is a task that is next to impossible. As a result, an attempt has been made to determine the form of a limited number of parameters which are made up of known quantities and which have unique values corresponding to the critical suction quantity. The derivation of the form of these design parameters and their measured critical values are presented in this report. The use of these parameters can considerably simplify the design of an aerodynamic surface employing suction through holes, since the number of variables is reduced to a minimum; for instance, the critical suction parameter for a single row of holes is nearly a unique function of a single additional parameter which describes the configuration.

This report includes the following as an appendix:

> A Physical Concept of the Causes of Transition and the Irregular Shape of the Universal Critical Suction Curve

Author

Availability:
SN-24021, Mar. 1957
BLC-95
NAI-57-529
N79-75697

295. Dannenberg, Robert E.; Gambucci, Bruno J.; and Weiberg, James A.: Perforated Sheets as a Porous Material for Distributed Suction and Injection. NACA TN 3669, 1956.

Measurements were made of the resistance to air flow of a series of perforated metal sheets having open areas ranging from less than 1 percent up to 41 percent. The results showed that the permeability of a perforated sheet is governed principally by its open-area ratio. The number of holes per square inch, the sheet thickness, and the shape of the individual holes had little or no effect on permeability.

As a porous material for boundary-layer-control applications by means of distributed suction or injection, punch-perforated sheets can be made to any desired permeability. For these applications it is usually necessary to have different permeability at different locations. To achieve a gradient permeability, the size and/or spacing of the holes in successive rows can be varied commensurately with the prescribed variation in permeability. Gradient permeability also can be achieved with uniformly perforated sheets combined with some form of resistance backing to furnish the gradient effect.

Author

Availability:
N78-78795

296. Butler, S. F. J.: Current Tests on Laminar-Boundary-Layer Control by Suction Through Perforations. R. & M. No. 3040, British A.R.C., 1957.

This note describes current experiments on laminar-boundary-layer control by suction through perforations. No attempt was made to obtain full-chord laminar flow, as this had been shown previously to be a natural consequence of applying a suitable suction distribution, providing turbulent wedges did not result from oversuction. In the present tests, the main aim therefore was to determine the flow rates at which such wedges appeared for different arrangements of perforations. In order to simplify the test procedure, most of the results were obtained using one or more closely spaced rows of perforations at a single chordwise station on an otherwise plain wing. A method is given, supported by some experimental evidence, for predicting the perforation spacing which would be required in a full-chord application from the results thus obtained at a single chordwise station.

With all the configurations tested, a limiting suction rate was found above which turbulent wedges appeared, causing premature transition. This limit exhibited an adverse Reynolds-number effect and also made it essential to use a uniform backing to obtain a satisfactory performance. It is suggested that flow curvature under three-dimensional conditions may further restrict the suction rates which could be used.

Because of the adverse Reynolds-number effect, the present tests needed to be extended to cover flight values of U_0/ν. A short programme of tests will cover the practicable diameter range with different geometrical configurations to provide two-dimensional data. If these tests are successful, the logical next step would be for an aircraft designer to choose a configuration based on the wind-tunnel results and prove it under flight conditions.

Author

Availability:
N78-78493
N-40342X

297. Gregory, N.; and Walker, W. S.: Experiments on the Use of Suction Through Perforated Strips for Maintaining Laminar Flow: Transition and Drag Measurements. R. & M. No. 3083, British A.R.C., 1958.

Wind-tunnel tests are described in which suction is applied at perforated strips, as an alternative to porous strips or slots, in order to maintain a laminar boundary layer. A test was first carried out on a single row of perforations on a cambered plate, as a preliminary to the main tests which were performed on strips of multiple rows of perforations drilled through the surface of a low-drag-type aerofoil 13 per cent thick and of 5-ft chord.

Up to a wind speed of 180 ft/sec it has been ascertained that suction may be safely applied to extend laminar flow provided the ratio of hole diameter to boundary-layer displacement thickness is less than 2, the ratio of hole pitch to diameter is less than 3 and there are at least three rows of holes in the strip. With less than three rows, the criteria are much more restrictive. It is possible to extend laminar flow by suction through perforations whose diameters and pitches exceed these values slightly, but only with the risk that excessive suction quantities will produce wedges of turbulent boundary layer originating at the holes.

A uniform distribution of suction through the holes was necessary. This was successfully obtained by two methods, the use of cells and throttle holes, and with tapered holes. In particular, tests were carried out on some panels supplied by Handley Page, Ltd., in which the cells and tapered holes had been constructed by commercial methods, and the suction distribution proved satisfactory.

The resistance of some of the cellular arrangements was measured. It was found that when the suction quantities were the minimum required to maintain laminar flow, the additional losses in total head of the sucked air due to the resistance of the throttle holes could be made small compared with the loss in total head of the sucked boundary layer.

Author

Availability:
N78-78494
N-60879X

298. Wuest, W.: Experimental Investigation on Boundary Layer Suction by Series of Slits and Holes. Bericht 60-01, Aerodynamische Versuchsanstalt (Göttingen), Feb. 19, 1960.

The development of laminar and turbulent boundary layers with pressure gradient on various permeable test walls (filter paper, slits, holes, perforations) has been studied in the low-turbulence wind-tunnel of the Aerodynamische Versuchsanstalt. The behaviour of wall-stress, dissipation and the different boundary layer parameters is deduced from the measurements.

Author

Availability:
N-86312
N79-70001

299. Roberts, Sean C.: An Investigation of Two Types of Hole Distributions for Laminar Boundary Layer Control Systems. Res. Rep. No. 37 (Contract NONR 978 (01)), Aerophys. Dep., Mississippi State Univ., April 2, 1962.

The half-scale model of the NACA 4416 airfoil was fixed to the floor of the tunnel and an incidence changing mechanism incorporated.

The following tests were completed on the impervious airfoil:

(a) Pressure distributions on the upper and lower surfaces using the belt technique.

(b) Boundary layer velocity profiles at a number of chordwise positions.

From the results of these tests, an inflow velocity distribution was calculated and applied to the airfoil in two test sections, both of which were at the same percentage chord and had the same number of holes per square inch even through the hole distributions were different, i.e., an even distribution and strip distribution. The hole size was 0.018" diameter and the distribution was 80 holes/in^2.

Author

Availability:
N62-12212

300. Groth, Eric E.: Pressure Loss of Low Density Boundary Layer Air Through Suction Slots and Narrow Holes. Rep. No. NOR 66-260 (BLC-168), Northrop Corp., July 1966.

Charts are presented for the computation of the pressure loss of the boundary layer air sucked through slots and holes into a suction chamber. They are based on the solution of the compressible, one-dimensional flow equations with friction and no heat transfer through the walls. The average inflow velocity into the slot or hole is subsonic. Limiting conditions due to choking are included.

Author

Availability:
N79-70657
CN-128,656
NOR 66-260 (BLC-168)

301. Meade, L. E. 'Roy': Material Development for Laminar Flow Control Wing Panels. Materials and Processes - In Service Performance, Volume 9 of National SAMPE Technical Conference Series, Soc. Advance. Mater. & Process Eng., 1977, pp. 305-312.

The absence of suitable porous materials or techniques for the economic perforation of surface materials has previously restricted the design of laminar flow control (LFC) wing panels to a consideration of mechanically slotted LFC surfaces. A description is presented of a program which has been conducted to exploit recent advances in materials and manufacturing technology for the fabrication of reliable porous or perforated LFC surface panels compatible with the requirements of subsonic transport aircraft. Attention is given to LFC design criteria, surface materials, surface concepts, the use of microporous composites, perforated composites, and perforated metal. The described program was successful in that fabrication processes were developed for producing predictable perforated panels both of composite and of metal.

Availability:
A78-25200

302. Jackson, Frances J.; and Heckl, Manfred A.: Effect of Localized Acoustic Excitation on the Stability of a Laminar Boundary Layer. ARL 62-362, U.S. Air Force, June 1962.

As part of a program to uncover the influence of induced surface vibrations on the stability of a shear flow boundary layer, investigations have been performed utilizing a localized surface source of acoustic energy to generate disturbances in a laminar boundary layer flow. Explorations have been carried out over a frequency range of from 50 to 10,000 cps, using input sound pressure levels of up to 145 db re 0.0002 dynes/cm^2. Results are presented which indicate the effect of sonic parameters (frequency, amplitude) on both the mean and fluctuating components of the boundary layer flow. Induced boundary layer oscillations are discussed, where appropriate, in terms of the stability theory of Tollmien and Schlichting. Studies of distortion of boundary layer oscillations are described and the role of such distortion in producing transition is discussed. Nonlinear secondary flows (streaming) generated by the localized source are also treated. Exploration of the influence of sonic excitation on premature transition produced both by increasing the free stream turbulence level and by use of a tripping wire are described.

Results indicate that localized excitation affects the stability of the laminar boundary layer in accordance with results first obtained by Schubauer and his co-workers employing a different experimental system. In the case of the tripping wire, results indicate that excitation of a certain frequency and amplitude can interact with the periodic vortex shedding in such a way as to forestall premature transition. In no case have localized sonically induced flows (streaming) been found to influence the incipient processes which govern transition.

Author

Availability:
N62-14049

303. Shapiro, Paul J.: The Influence of Sound Upon Laminar Boundary Layer Instability. Rep. No. 83458-83560-1 (Grant NSF Eng 75-17374 and Contract No. N00014-76-C-0396), Acoust. & Vib. Lab., Massachusetts Inst. Technol., Sept. 1977. (Available from DDC as AD A046 057.)

This paper presents the results of an experimental investigation into the effects of pure-tone acoustic excitation on Tollmien-Schlichting waves in a subsonic Blasius boundary layer. Longitudinal growth rates were measured for naturally-existing waves in a low-noise, low-turbulence wind tunnel, and for waves excited by an externally imposed sound field. The results were compared to numerical results from the standard Orr-Sommerfeld equation. The excited Tollmien-Schlichting waves matched the theory well in most respects, and it was concluded that the acoustic excitation merely generated a larger initial wave amplitude, ahead of Branch I of the neutral stability curve. For excitation levels larger than the residual tunnel disturbances, this initial amplitude was constant and equal to the disturbance velocity of the sound wave. The naturally-existing waves showed growth rates smaller than theory predicted. This leads to the conclusion that natural waves are not initially two-dimensional.

Availability:
N78-15854
AD A046 057

304. Miller, Gabriel; and Callegari, Andrew: The Effects of Acoustical Disturbances on Boundary Layer Transition. DAS #78/01 (Contract N00014-76-C-0183), New York Univ., Jan. 25, 1978. (Available from DDC as AD A051 497.)

The analysis of transition from laminar to turbulent flow on a flat plate has been the subject of numerous investigations. In the present work, emphasis has been placed on establishing a computational technique which can be utilized to develop a basic understanding of the effects of the propagation of acoustic waves into a boundary layer, and the ultimate effect of such disturbances on transition. The nonlinear system of unsteady compressible partial differential equations have been solved by a MacCormack predictor-corrector scheme which allows the effect of imposed disturbances to be tracked in time. The question of the mismatch in propagation velocity between Tollmein-Schlichting and acoustic waves has been studied. The program indicates that while disturbances are propagating with the speed of sound in the inviscid flow, the waves well within the boundary layer are propagating at a speed on the order of the freestream velocity and thus the boundary layer is being excited by the classical Tollmein-Schlichting waves. The analysis thus indicates that the effect of acoustical disturbances on transition is similar to the effect of other perturbations as experiments have indicated.

Author

Availability:
N78-24498
N-142753
AD A051 497

305. Mungur, Parma: On the Sensitivity of Shear Layers to Sound. AIAA Paper 77-1369, Oct. 1977.

This paper is concerned with an analysis of the mechanisms by which sound generates hydrodynamic disturbances. Two equations are derived from the linearized Navier-Stokes equation. One governs the sound field and the other governs the fluctuating vorticity field. The latter, when written in the form of an inhomogeneous Orr-Sommerfeld equation, represents the generation of fluctuating vorticity by a sound field and its convected diffusion and amplification or decay by the viscous boundary layer. The source term is discussed in detail. The main results are compatible with observations and are as follows. Coupling occurs only in the boundary layer. The most sensitive region for acoustic excitation of the shear layer of a jet is the nozzle lip; for shear layers on a flat plate or an airfoil, the sensitive region is the leading edge. The acoustically induced vorticity source strength is linearly proportional to the acoustic pressure and its derivative transverse to the mean flow; it is also a function of the frequency and directivity of the acoustic field.

Author

Availability:
A77-51120

306. Wetmore, J. W.; Zalovcik, J. A.; and Platt, Robert C.: A Flight Investigation of the Boundary-Layer Characteristics and Profile Drag of the NACA 35-215 Laminar-Flow Airfoil at High Reynolds Numbers. NACA WR L-532, 1941. (Formerly NACA MR.)

During the earlier stages of the NACA's work on the development of laminar-flow airfoils it was found that by suitably designing the profile of an airfoil a favorable or accelerating pressure gradient could be maintained over as much as 80 percent of the chord back of the leading edge. Tests of some of these airfoils in the wind tunnels and in flight showed that within the lower flight range of Reynolds numbers the laminar boundary layer extended as far back as 80 percent of the chord from the leading edge, with the result that the profile drag was extremely low.

In the higher Reynolds number ranges, say, above 20,000,000, it was expected that other methods might be required to obtain the desired extensive laminar boundary layers and resulting extremely low drags. The present investigation was undertaken with the object of investigating methods of prolonging the laminar flow at high Reynolds numbers and to give data for comparison with wind-tunnel data.

The tests were made on a test panel of 17-foot chord mounted on the left wing of a Douglas B-18 airplane just outside of the propeller slipstream.

Comparison of the results of the present flight tests on the 35-215 airfoil section with data obtained on generally similar airfoils in the original NACA low-turbulence wind tunnel showed that in flight the laminar boundary layer was maintained to values of R_δ considerably greater than the highest values that were attained in the tunnel. This result indicated that even in tunnel air streams of extremely low turbulence the effect of the residual turbulence might be appreciable, and thereby demonstrated the necessity of continued flight research on airfoils of large scale to supplement the development work of the tunnels.

Author

Availability:
N78-78520

307. Zalovcik, John A.; and Skoog, Richard B.: Flight Investigation of Boundary-Layer Transition and Profile Drag of an Experimental Low-Drag Wing Installed on a Fighter-Type Airplane. NACA WR L-94, 1945. (Formerly NACA ACR L5C08a.)

The experimental low-drag wing was installed on a P-47 airplane designated the XP-47F. This wing incorporates airfoil sections that vary from an NACA 66(215)-1(16.5), a = 1.0 at the plane of symmetry to an NACA 67(115)-213, a = 0.7 at the tip. The investigation was limited to the study of boundary-layer transition and profile drag of sections of the wing with the surfaces in the original wavy condition and also with the surfaces refinished to reduce the waviness to tolerable limits. Measurements were made at a section outside the propeller slipstream with smooth and with standard camouflage surfaces and on the upper surface of a section in the propeller slipstream with the surface smoothed.

Tests were made in normal flight - that is, in level flight and in shallow dives - at indicated airspeeds ranging from about 150 to 300 miles per hour and in steady turns at 300 miles per hour with normal accelerations from 2g to 4g. These speed and acceleration limits were imposed by structural considerations. The tests in normal flight covered a range of section lift coefficient from about 0.58 to 0.15, of Reynolds number from about 9×10^6 to 18×10^6, and of Mach number from about 0.27 to 0.53. In the tests in turns of 300 miles per hour, the range of section lift coefficient was extended to 0.63.

Author

Availability:
N78-78568

308. Hood, Manley J.; and Gaydos, M. Edward: Effects of Propellers and of Vibration on the Extent of Laminar Flow on the N.A.C.A. 27-212 Airfoil. NACA WR L-784, 1949.

The effects of propellers and of vibration on the extent of laminar flow on the N.A.C.A. 27-212 airfoil were investigated in the N.A.C.A. 8-foot high-speed tunnel by testing the airfoil in conjunction with a tractor and a pusher propeller and with a mechanical vibrator. The Reynolds numbers of the investigation ranged from 3,500,000 to 7,600,000 for the propeller tests and to 10,300,000 for the vibration tests.

The results show that neither the pusher propeller nor vibration with amplitudes up to 0.094 inch and with a frequency of 1,650 cycles per minute had any consequential effect on the extent of laminar flow but that the tractor propeller had a very pronounced effect. The tractor propeller caused transition to move from approximately midchord to a position near the leading edge; the accompanying increase in drag probably exceeded 100 percent for the N.A.C.A. 27-212 airfoil. The corresponding drag increase for the N.A.C.A. 0012 airfoil would be approximately 25 percent because this airfoil normally has a less extensive laminar boundary layer.

Author

Availability:
N78-78535

309. Garrick, I. E.; and Watkins, Charles E.: A Theoretical Study of the Effect of Forward Speed on the Free-Space Sound-Pressure Field Around Propellers. NACA Rep. 1198, 1954. (Supersedes NACA TN 3018.)

The sound-pressure field of a rotating propeller in forward flight in free space is analyzed by replacing the normal-pressure distribution over the propeller associated with thrust and torque by a distribution of acoustic pressure doublets acting at the propeller disk and subject to uniform rectilinear motion. The basic element used to synthesize the field is the pressure field of a concentrated force moving uniformly at subsonic speeds, for which an expression generalizing one of Lamb's for the fixed concentrated force is given. This result is presented both for the moving and for the fixed observer. The strength of the doublet distribution is related to the thrust and torque distribution and to its various Fourier coefficients in a convenient way. The sound field is expressed by integration over the propeller disk, and also by integration over an effective ring, and is given both for the near pressure field and, in a simpler form, for the far field. Known results for the zero-forward-speed case present themselves in the special case of Mach number $M = 0$. Some illustrative examples are calculated and discussed.

Author

Availability:
N78-78536

310. Regier, Arthur A.: Chapter on Propeller Noise. Agardograph on Aircraft Noise, G. M. Lilley, ed., [1961].

It is believed that a discussion of propeller noise is warranted to fill in various gaps, and to round out the current picture with respect to propeller and rotor applications. The methods of treating the noise of propellers have application also to fans and rotors of various kinds whether they be used in fan or by-pass engines or for helicopters or lifting devices on vertical or short takeoff aircraft. In view of several comprehensive general survey papers, the present discussion will only briefly review the standard propeller noise literature and attempt to bring it up to date by adding references to recent work which has dealt mainly with flight noise tests and synchrophasing.

Author

Availability:
N79-70672
N-95944

311. Marte, Jack E.; and Kurtz, Donald W.: A Review of Aerodynamic Noise From Propellers, Rotors, and Lift Fans. Tech. Rep. 32-1462 (Contract No. NAS 7-100), Jet Propul. Lab., California Inst. Technol., Jan. 1, 1970. (Also available as NASA CR-107568.)

Hand-calculation procedures for predicting aerodynamic noise from propellers, rotors and lift fans useful as first engineering approximations have been assembled from the literature. Considerable introductory material and a glossary of terms has been included to make the prediction procedures more meaningful. Current literature has been reviewed and a comprehensive bibliography on V/STOL aircraft noise is presented.

Author

Availability:
N70-15224

312. Morfey, C. L.: Rotating Blades and Aerodynamic Sound. J. Sound & Vib., vol. 28, no. 3, June 8, 1973, pp. 587-617.

The history of research on rotating blade noise is reviewed, from early studies of propeller radiation to current work on aircraft-engine fans. The survey is selective, with emphasis on fundamental aspects of aerodynamic sound generation by blades. The topics covered include the following: early research on propeller noise, unsteady airfoil theory, acoustic radiation and cut-off, aerodynamic sound generation, scattering by airfoils at arbitrary chord/wavelength ratios, boundary layer and vortex shedding noise from airfoils, broadband noise due to incident turbulence, high-order rotational noise from isolated rotors, rotor/tip-vortex interaction, interaction between moving blade rows, sound transmission through blade rows, the instantaneous Kutta condition, supersonic rotor noise, in-duct measurement techniques, and centrifugal flow machines.

Author

Availability:
A73-35333

313. Pfenninger, W.; Groth, E. E.; Carmichael, B. H.; and Whites, R. C.: Low Drag Boundary Layer Suction Experiments in Flight on the Wing Glove of a F94-A Airplane. Phase I - Suction Through Twelve Slots. Rep. No. NAI-55-458, Rep. No. BLC-77, Northrop Aircraft, Inc., Apr. 1955. (Available from DDC as AD 79 342(b).) (Also available in Summary of Boundary Layer Control Research, WADC Tech. Rep. 56-111, U.S. Air Force, Apr. 1957, pp. 59-79. (Available from DDC as AD 130 759.))

This report describes the first phase of a flight program dealing with the application of boundary layer control to an airfoil for the purpose of obtaining low drag coefficients. A 13%-thick cambered glove section (similar to NACA 65-213) was mounted on the wing of an F94-A airplane and suction was applied through twelve slots located between 41.5% c and 94% c.

Low drag coefficients and laminar flow extending to the trailing edge of the glove were obtained at wing chord Reynolds numbers between 12×10^6 and 30.5×10^6. The optimum test point gave, for the upper surface of the glove, a total drag coefficient of .000510 at a Reynolds number of 25.64×10^6 and an overall suction weight flow coefficient of .000344. The equivalent drag due to the suction power is included in this drag coefficient. The tests were remarkable for a nearly complete absence of difficulties in maintaining laminar flow in flight and thus proved the applicability of low drag boundary layer control on high subsonic-speed aircraft at subcritical Mach numbers.

The appendices give detailed descriptions of the design of the glove, the instrumentation, and the compressor-turbine system.

Availability:
SN-24021, June 1955
NAI-55-458
BLC-77
AD 79 342(b)
N78-76390
N-53889
AD 130 759

314. Groth, E. E.; Carmichael, B. H.; Whites, Roy C.; and Pfenninger, W.: Low Drag Boundary Layer Suction Experiments in Flight on the Wing Glove of a F94-A Airplane - Phase II: Suction Through 69 Slots. NAI-57-318, BLC-94 (Contract AF-33(616)-3168), Northrop Aircraft, Inc., Feb. 1957. (Also available in Summary of Laminar Boundary Layer Control Research, WADC Tech. Rep. 56-111, U.S. Air Force, Apr. 1957, pp. 80-113. (Available from DDC as AD 130 759.))

The low drag flight experiments on the F94-A airplane with a 13%-thick wing glove equipped with boundary layer suction which had produced full laminar flow and low drag coefficients with a 12-slot suction system, were continued by applying suction through a panel of 69 slots. The approach to continuous suction resulted in an increase of the maximum chord Reynolds number with full laminar flow to 36.34×10^6 with a total drag coefficient of 4.82×10^{-4} and a total suction weight flow coefficient of 2.91×10^{-4}. Laminar flow could be produced and maintained in flight as easily as with the 12-slot configuration. The design of such a multiple slot panel is applicable to an actual airplane wing.

Author

Availability:
SN-24021, Feb. 1957
NAI-57-318
BLC-94
N78-76390
N-53889
AD 130 759
N79-75696

315. Rooney, T. R.; Carmichael, R. F.; and Eldred, K. M.: Investigation of Noise With Respect to the LFC, NB-66 Aircraft. NOR-61-10 (Contract AF 33(600)-42052), Northrop Corp., Apr. 1961.

This report discusses the external acoustic disturbances which are anticipated to be of importance to the maintenance of laminar flow on an LFC flight vehicle. An evaluation of the boundary layer stability characteristics of experimental laminar suction surfaces in the presence of high intensity sound fields has indicated a basic relationship between the ratio of disturbance velocity to freestream velocity ($\Delta U/U_\infty$) and the transition length Reynolds' number. These data have been utilised to establish acoustic sensitivity design criteria for predicting allowable noise levels over a laminar suction surface with basic suction distribution (distribution resulting in minimum drag).

The formulation of a procedure for estimating overall sound pressure levels radiated from turbulent boundary layers has been presented in detail.

The predicted radiated boundary layer noise for the NB-66 aircraft shows that the fuselage is the dominant noise source. However, the predictions of measured in-flight noise (on the F-94 and RB-66) showed that, for particular locations, other sources dominated. Hence, there are no data which validate the prediction of noise from a long fuselage.

Estimates of the acoustic environment over the LFC wing have been made throughout the flight demonstration envelope of the NB-66.

There remains one noise source that has not been evaluated in this report, the suction compressor system. Operating parameters of the system have not been sufficiently specified at this time to make an estimate of the radiated noise from this source.

Includes appendices:

APPENDIX A - In-Flight Noise Measurements on an RB-66 Test Airplane Equipped With General Electric, CJ-805-23 Aft Fan Engines

APPENDIX B - Noise Reduction Methods

Author

Availability:
N79-70030
CN-142,350
NOR-61-10

316. Rooney, T. R.; Carmichael, R. F.; and Benner, R. C.: Environmental Vibroacoustics for the Laminar Flow Control Demonstration Aircraft. NOR-61-115 (Contract AF 33(600)-42052), Northrop Corp., July 1961.

This is an investigation of the acoustic and vibration environments of the NB-66 aircraft with regard to possible sonic fatigue damage to the aircraft structure. Satisfactory equipment vibration test specifications are formulated. In addition, this report establishes the procedure for static ground measurements of the acoustic environment on the aircraft. This test is required to substantiate the predicted acoustic intensities in critical regions of the aircraft during ground operation and to provide basic data necessary for accurate prediction of the noise environment in flight.

Availability:
NOR-61-115

317. Pfenninger, W.: Summary Report About the Investigation of a 10 ft. Chord 33° Swept Low Drag Suction Wing at High Reynolds Numbers. Northrop paper presented to Air Force Advisory Group, Oct. 14, 1965.

Low drag suction experiments were conducted in pressure tunnels on a 33° swept 10 ft chord low drag suction wing model. These experiments verified extensive laminar flow up to wing chord Reynolds numbers $R_c = 48 \times 10^6$. At $R_c = 44.8 \times 10^6$ 90% laminar flow was maintained, corresponding to a transition length Reynolds number of 40.3×10^6. The minimum equivalent wing profile drag coefficient for the test surface was 0.00088 at $R_c = 29.4 \times 10^6$ (including the equivalent suction drag); it increased to $\cong 0.0011$ at $R_c \cong 43 \times 10^6$. Observed disturbances are discussed, and possible correction steps are included. Besides the ordinary measurements on low drag suction surfaces, the following observations and measurements were conducted: flow observations at the downstream end of the front wing attachment line, measurement of the sound pressures along the suction ducts in the presence of internal noise, transition observations in the presence of noise, chordwise u' boundary layer velocity fluctuation measurements, and external tunnel noise measurements.

Availability:
N66-12749

318. Carlson, J. C.; and Bacon, J. W., Jr.: Influence of Acoustical Disturbances in the Suction Ducting System on the Laminar Flow Control Characteristics of a 33° Swept Suction Wing. NOR-65-232, Northrop Corp., Aug. 1965.

Availability:
X67-82152
CN-120,214
NOR-65-232

319. Franco, B. G.: Data Report of a High Reynolds Number Wind Tunnel Test of an Acoustically Instrumented Laminar Flow Control 33° Swept Suction Wing Conducted at the Ames Research Center 12' Pressure Tunnel - August 1965. NOR-65-312, Northrop Corp., [1965].

An acoustically instrumented 33° swept non-tapered 15% unsymmetrical low-drag laminar suction wing of a modified NACA 64-016 airfoil was tested in the Ames Research Center 12' Low Turbulence Pressure Tunnel from 4 Aug. to 30 Sept., 1965.

The purposes of the test were: (1) To achieve laminar flow on the wing to a higher unit Reynolds number than was possible at the Northrop Norair 7 × 10 ft. wind tunnel. (2) Investigate the influence of acoustical disturbances in the suction duct system on the wing laminar-flow characteristics at the higher unit RN.

This report presents tabulated data and/or plotted data on the following:

(a) Wind tunnel operating conditions.
(b) Laminar flow control coefficients.
(c) Wing pressure distribution.
(d) Sound pressure levels (db) internal and external to the wing.

Author

Availability:
NOR-65-312

320. Bacon, John W., Jr.; Pfenninger, W.; and Moore, C. Roger: Influence of Acoustical Disturbances on the Behavior of a Swept Laminar Suction Wing. Rep. No. NOR-62-124 (BLC-141), Northrop Corp., Oct. 1962.

A 30° swept, 12%-thick symmetrical laminar suction wing of modified NACA 66-012 section was investigated in the Norair 7- by 10-foot low turbulence wind tunnel at $\alpha = 0^{\circ}$ angle of attack in the presence of external sound (longitudinal and transverse sound waves) of discrete frequencies as well as with a continuous spectrum of different frequency bands. External sound usually caused transition in the region of the flat pressure distribution. The critical sound pressure at transition could be increased considerably by increasing the suction quantities either as a whole over the entire wing chord or locally in the critical area of the flat pressure distribution where transition otherwise occurred. From the standpoint of total suction quantity and drag, it was much more economical to increase suction locally in the region of the flat pressure distribution.

In the presence of external sound transition occurred on the swept laminar suction wing over a wide range of frequencies. The variation of the critical sound pressure for transition with frequency was relatively small. In the presence of open surface cavities such as nonsucking open slots, static pressure orifices, or imperfectly sealed slots the critical sound pressure at transition was reduced considerably, particularly at higher sound frequencies which correlated with those for amplified Tollmien-Schlichting oscillations of the chordwise boundary layer in the front part of the wing in the region of the open surface cavity.

For the smooth wing the critical sound particle velocity ratio at transition generally decreased at a somewhat slower rate than inversely proportional to the wing chord Reynolds number. In the presence of open surface cavities, however, or with marginal suction the critical sound particle velocity ratio for transition often decreased at a much faster rate with increasing Reynolds number.

Naphthalene sublimation pictures with external sound showed that transition in the region of the flat pressure distribution was usually preceded by the formation of closely spaced chordwise striations, indicating the presence of chordwise disturbance vortices in the presence of external sound. The formation of these vortices can probably be explained by the fact that the external disturbances superimposed on the crossflow boundary layer in the presence of external sound are of such a large magnitude (as compared with the mean crossflow velocity) that the stability limit Reynolds number of the boundary layer crossflow in the area of the flat pressure distribution is reduced to considerably lower values, as compared with the case of infinitely small external disturbances. Hot wire measurements verified amplified boundary layer oscillations in the region of the flat pressure distribution which appear sufficiently strong to appreciably reduce the crossflow stability limit Reynolds number in the presence of strong external sound fields.

Availability:
N79-70031
CN-120,213
NOR-62-124 (BLC-141)

321. Carmichael, R. F.; and Pelke, D. E.: In-Flight Noise Measurements Performed on the X-21A Laminar Flow Aircraft. NOR-64-81 (Contract AF33(600)-42052), Northrop Corp., Apr. 1964. (Available from DDC as AD 439 351.)

Sound pressure levels measured in flight by six microphones positioned around the left-hand wing of the X-21A laminar flow aircraft are presented. These measurements define the noise levels existing at the wing surface for the Mach number ranges of the aircraft at three widely separated altitudes and four engine throttle settings. Most of the noise sources are identified, and their levels compare favorably with previously developed prediction methods. It is noted, however, that not all predominating noise sources are included in the prediction methods, specifically, engine screech, and one noise of undetermined origin. Also, engine noises are masked at higher Mach numbers by radiated turbulent boundary-layer noise, which has the properties of noise generated by a quadrupole mechanism. In regard to the effects of noise on the maintenance of laminar flow, it is noted that noise spectra possessing intense, relatively narrow band spikes could be more detrimental than flat spectra with higher overall levels.

Author

Availability:
N64-25697
NOR-64-81
AD 439 351

322. Bacon, J. W., Jr.; Pfenninger, W.; and Moore, C. R.: Investigations of a 30° Swept and a 17-Foot Chord Straight Suction Wing in the Presence of Internal Sound, External Sound, and Mechanical Vibrations. Summary of Laminar Boundary Layer Control Research - Volume I, ASD-TDR-63-554, U.S. Air Force, Mar. 1964. (Available from DDC as AD 605 185.)

A 4-percent-thick straight laminar suction wing of 17-foot chord and a 30° swept, 12-percent-thick laminar suction wing of seven-foot chord were investigated in the Norair 7- by 10-foot low turbulence wind tunnel at $\alpha = 0^\circ$ angle of attack in the presence of external sound (longitudinal and transverse sound waves). The 4-percent-thick straight wing was tested, in addition, with internal sound and panel vibration. The external and internal sound consisted of discrete frequencies and octave bands of random noise in the 150 to 4000 cps. The straight wing showed a frequency dependence of transition with external sound that correlates with the stability theory for amplified Tollmien-Schlichting oscillations. On the swept laminar suction wing under the influence of external sound, however, transition occurred over a wide range of frequencies. For the swept wing in smooth condition the critical sound particle velocity ratio at transition generally decreased at a somewhat slower rate than inversely proportional to the wing chord Reynolds number.

Author

Availability:
N65-25557
AD 605 185

323. Carlson, J. C.: Low Drag Boundary Layer Suction Experiments Using a 33° Swept 15% Thick Laminar Suction Wing With Suction Slots Normal to the Leading Edge. NOR-64-281, Northrop Corp., Nov. 1964. (Available from DDC as AD 482 068.)

Availability:
X66-84941
NOR-64-281
AD 482 068

324. Lyamshev, L. M.: Estimation of the Acoustic Radiation in Slotted Boundary-Layer Suction. Sov. Phys.-Acoust., vol. 16, no. 1, July-Sept. 1970, pp. 133-134.

In an earlier paper on this subject the author disregarded the width of the slots. In reality, the slot width is always finite. In this paper it is shown how to account properly for the finiteness of the slot.

325. Garrelick, J. M.; and Junger, M. C.: The Effect of Structure-Borne Noise in Submarine Hull Plating on Boundary Layer Stability. Rep. ONR CR-289-017-1F, U.S. Navy, Nov. 1977.

This report deals with the potential boundary layer destabilizing action of machinery generated structure-borne noise in submarine hull plating. Boundary layer transition is assumed to be governed by the eigenvalues of the Orr-Sommerfeld equation and the structure-borne noise field is taken to be flexural in nature. The structure-borne noise field is decomposed into propagating wave fields and near-fields such as would surround foundation structures or other hull impedance discontinuities. It is found that for the frequency range generally associated with structure-borne noise, say 30 - 10^4 Hz, the propagating wave fields are not destabilizing in that they do not contain components which are coincident with the appropriate eigenvalues of the Orr-Sommerfeld equation. By contrast, the near-fields will contain components which are coincident with the potentially destabilizing, eigenvalues of the Orr-Sommerfeld equation. These near-fields are interpreted in terms of equivalent propagating fields to which they are found to be of (relatively) low level. Available experimental results are discussed in terms of the submarine environment and it is found that although transition may be affected by structure-borne noise levels less than, say, the expected free-stream turbulence levels, the measured noise levels required for destabilization are higher than one expects in submarine hull plating.

Finally, a mechanical analogue to the Orr-Sommerfeld equation is presented in the form of a vibrating elastic plate resting on a locally reacting foundation of specific form.

Author

Availability:
N79-70242

326. BCAC Preliminary Design Dep.: Evaluation of Laminar Flow Control System Concepts for Subsonic Commercial Transport Aircraft. NASA CR-158976, 1978.

This document constitutes the final report covering engineering development and evaluation of laminar flow control system concepts under Contract to NASA.

Work was conducted in three major tasks; namely, 1) Mission Definition and Baseline Configuration Development, 2) Concepts Evaluation, and 3) Configuration Selection and Design. The report covers the work conducted from September 1976 through September 1978. The study activity is directed toward the further development of LFC technology and solutions to critical problems which must be solved before practical application of LFC can be successful. The overall objective of the LFC program is to provide a sound basis for industry decisions on the application of LFC to future commercial transports.

Author

Availability:
N79-15942

327. Gray, W. E.: A Simple Visual Method of Recording Boundary Layer Transition (Liquid Film). Tech. Note No. Aero 1816, British R.A.E., Aug. 1946.

A method of attractive simplicity for the visual area-study of boundary layer transition, in use at the R.A.E. for the past year, is described in this report. Its application is primarily to wind-tunnel tests, and photographs show examples of laminar and turbulent regions of flow over large areas of wing with various surface finishes.

This "liquid film evaporation method" indicates transition by the drying of a film of liquid only some 10 millionths of an inch thick: it is thus a method of considerable refinement. A very wide choice of common harmless liquids can be used, and some guidance is given on drying rates. Surfaces to be tested need no special preparation, and with reasonable lighting transition can be seen easily during test.

The development of visual boundary layer methods is briefly outlined, and comparisons made both with visual and other methods.

Laminar separation can also be studied by the method and its application to heat transfer problems is briefly discussed.

Author

Availability:
N78-78558

328. Owen, P. R.; and Ormerod, A. O.: Evaporation From the Surface of a Body in an Airstream (With Particular Reference to the Chemical Method of Indicating Boundary-Layer Transition). R. & M. No. 2875, British A.R.C., 1954.

The problem of predicting the rate of transport of a gas from or into the surface of a two-dimensional body in an airstream is discussed. The principal object of the investigation is to provide a means of estimating the time required to obtain an experimental record of boundary-layer transition when a chemical technique is used. The methods evolved should, however, find an application to other forced diffusion phenomena.

The general approach is based on the analogy between mass transfer, heat transfer and skin friction, and the analysis is applied to both a laminar and a turbulent boundary layer on the surface of the body; it also includes the problem of diffusion commencing in an established boundary layer. For this problem, an approximate, alternative solution to that of O. G. Sutton, for a turbulent boundary layer, is given.

Particular attention is paid to a description of the boundary condition at the surface of the body, and it is concluded that, for evaporation, the usual assumption that the air is saturated with the diffusing substance is, in general, satisfactory.

The influence of molecular diffusion on the transfer of a gas through a turbulent boundary layer is considered; it is demonstrated that the effects of molecular diffusion in the laminar sub-layer may be important. A simple, approximate method of estimating the molecular diffusion coefficient for a pair of gases is derived.

A description is given of a wind-tunnel experiment in which measurements were made of the rates of sublimation of some chemicals from a small part of a flat plate with a turbulent boundary layer: they were found to agree fairly well with the corresponding theoretical estimates.

Finally, as an example of the application of the methods, a calculation of the effect of altitude on the rate of sublimation of a chemical from the surface of an aircraft is made; this agrees with flight tests, which had established that the rate of sublimation decreases very rapidly with increase of altitude.

Author

Availability:
N78-78495
N-32431

329. Main-Smith, J. D.: Chemical Solids as Diffusible Coating Films for Visual Indications of Boundary-Layer Transition in Air and Water. R. & M. No. 2755, British A.R.C., 1950.

Experimental investigations have been made on various chemical solids as diffusible coating films for visual indication of boundary-layer transition in air and water. Originally, the method was applicable only at low speeds in wind tunnels and water tanks, and the indications were somewhat transient. More durable coating materials have now been made available, admitting of use at subsonic and supersonic wind-tunnel speeds from 30 to 1350 m.p.h., and at ship-hull speeds from 2½ to 20 kt. The method has also proved capable of extension to aircraft in flight at speeds from 100 to 445 m.p.h. at temperatures down to -22 deg C and at altitudes up to 20,000 ft. The diffusible-solid-coating method, with its advantages of autographic indication and simplicity and rapidity of operation, has thus become a versatile technique in investigations on fluid flow in aerodynamics and hydrodynamics.

Author

Availability:
N78-78655
N-30451

330. Atkins, P. B.; and Trayford, R. S.: A Method of Boundary Layer Flow Visualization for Use in Flight. Flight Note 22, Aeronaut. Res. Labs. (Melbourne), July 1955.

A method of wetting the upper surface of a wing prepared with a coating of china clay has been developed in a wind tunnel, and flight tests have shown that the method can be successfully adopted for flow investigations in flight.

The wetting agent is sprayed from nozzles just aft of the stagnation point at high incidences, allowing the spray to cut through the stagnation streamline and be carried over the upper surface and thus wet the china clay.

Adequate coverage of the surface can be obtained quickly at this incidence, after which the aircraft is flown at the test speed until a pattern develops. The fully developed pattern can then be photographed to provide a permanent record.

Author

Availability:
N-42052
N78-79432

331. Richardson, Norman R.; and Horton, Elmer A.: A Thermal System for Continuous Monitoring of Laminar and Turbulent Boundary-Layer Flows During Routine Flight. NACA TN 4108, 1957.

A thermal system has been developed which could be used to determine whether the boundary layer on a wing in flight is turbulent or laminar. This system, when used in conjunction with continuous recording instruments such as the galvanometer in an NACA VGH recorder and a motor-driven selector switch, would permit continuous monitoring of the boundary layer during routine flight with little or no attention from the crew. Detection is based on the difference in rate of heat transfer to a turbulent boundary layer as compared with that to a laminar boundary layer. The detectors, which consist of insulated resistance-thermometer gages cemented to the wing surface, combine the functions of heating and temperature measurement. Wind-tunnel tests indicate that a usable signal is obtained when the Reynolds number per foot is about 0.15×10^6 or greater. If the detectors can be matched well enough and the gage temperature increased, they may be feasible for use at somewhat lower Reynolds numbers.

Author

Availability:
N78-78537

332. Gaster, M.: The Application of Hot-Film Gauges to the Detection of Boundary-Layer Transition in Flight. CoA Rep. AERO No. 189, Coll. of Aeronaut., Cranfield (England), Jan. 1966.

A detailed description of the construction of small hot-film gauges is given with an account of the application of these instruments to the specific problem of detecting boundary layer transition in flight. Typical oscilloscope records of gauge signals from experiments on a swept laminar flow wing are reproduced.

Author

Availability:
N66-31835

333. Zozulia, V. B.; and Cheranovskii, O. R.: Determination of the Point of Laminar-Turbulent Transition With the Aid of a Traveling Indicator. Samoletostr. Tekh. Vozdushn. Flota, no. 17, 1970, pp. 26-30.

Description of a device employing a hot-wire anemometer and an oscilloscope to determine the point of laminar-turbulent transition on a wing. With the aid of an electrically driven mechanism, the sensor is made to move in the boundary layer in opposite direction to the flow. The point of laminar-turbulent transition is determined (by linear measurements) from oscillograms of the velocity pulsations in the boundary layer.

Availability:
A71-12555

334. Kawai, Nobuhiro; and Oguni, Yasuo: Methods of Detecting Boundary Layer Transition. NAL-TR-353, National Aerospace Lab. (Tokyo), 1973.

Four methods of detecting boundary layer transition are investigated. Feasibility of measurements on three-dimensional wings in a transonic wind tunnel, and the absence of the flow disturbances due to the sensing elements on the wing are considered. The principles of these methods are as follows: (1) Liquid crystal painted on the wing surface, changes its color according to the recovery temperature, and visualizes transition. (2) Sensitive thermistors mounted flush with the wing surface, indicate the recovery temperature. The measured transition points are compared with theory. (3) Small microphones mounted flush with the surface, indicate the acoustic noise. The sound pressure level of the noise becomes maximum at the point of transition region. (4) Both direct and alternating components of electric currents through the hot films mounted flush with the wing surface, show the characteristic changes of transition and separation. The advantages and disadvantages of these are discussed. The ranges of Mach number and other flow conditions are examined.

Author

Availability:
N74-29651

335. Rawcliffe, A. G.: Suction-Slot Ducting Design. R. & M. No. 2580, British A.R.C., 1952.

The purpose of the investigation was to provide uniform suction through a narrow slot along the span of a wing, with the lowest possible losses, when the pump was situated at the root of the wing.

Models of various design were tested and modified in the light of the results obtained. From these experiments, together with a qualitative analysis of the flow through the type of ducting proposed, specific recommendations have been formulated for the attainment of uniformity of suction combined with low power losses.

Investigations were confined to suction from still air.

Losses obtained with the broad partition and with the guide-vane ducts compared well with that for the earlier models, and the distribution of velocity at the slot was quite satisfactory. The circular collector duct appeared to be more efficient, but suction was much higher at the tip than at the root.

Suction ducting is to be tested in the wall of a small wind-tunnel, so that the effect of the tunnel boundary layer may be studied.

Author

Availability:
N78-78497
N-14769

336. Rogers, K.: Preliminary Investigation of the Pressure Drop in Suction Ducts. Rep. No. BLC-13, Northrop Aircraft, Inc., Sept. 1953. (Available from DDC as AD 25 565(d).) (A discussion of this work appears in Summary of Laminar Boundary Layer Control Research, WADC Tech. Rep. 56-111, U.S. Air Force, Apr. 1957, pp. 217-252. (Available from DDC as AD 130 759.))

Availability:
SN-24021, Dec. 1953
BLC-13
AD 25 565(d)
N78-76390
N-53889
AD 130 759

337. Rogers, K. H.; and Pfenninger, W.: Experimental Investigation of the Losses in Boundary Layer Suction Ducts. Summary of Laminar Boundary Layer Control Research. WADC Tech. Rep. 56-111, U.S. Air Force, Apr. 1957, pp. 221-224. (Available from DDC as AD 130 759.)

In suction systems of low drag boundary layer aircraft, suction ducts must be provided to carry the suction air from the suction surface to the suction compressor or to a plenum or mixing chamber upstream of the suction compressor. Generally, the suction ducts on suction wings will be oriented essentially in spanwise direction and have one or more continuous inlets (for example, slots, rows of holes, suction strips, etc.) along the full length of the suction duct. The local suction rate (inflow) is controlled by the pressure difference between the duct and the suction surface. In order to control the inflow within allowable limits and to minimize ducting losses, an experimental investigation of various suction ducts was conducted. The specific objectives of the experimental program were to reduce the losses in the suction ducts, for example, by incorporating turning-vanes in the inlet, by improving the inflow into the duct, etc.

Author

Availability:
N78-76309
N-53889
AD 130 759

338. Flax, A. H.; Treanor, C. E.; and Curtis, J. T.: Stability of Flow in Air-Induction Systems for Boundary-Layer Suction. WADC Tech. Rep. 53-189, U.S. Air Force, May 1953. (Available from DDC as AD 21 700.)

Availability:
N-25770
AD 21 700

339. Pfenninger, W.; and Raetz, G. S.: Experiments on a Large-Scale Model of a Constant-Angle Suction-Slot Diffuser. Rep. No. NAI-54-559, Rep. No. BLC-56, Northrop Aircraft, Inc., Aug. 1954.

Experiments on a large-scale model of a constant-angle suction-slot diffuser, at diffuser angles of 2^o, 3^o, 4^o, and 5^o and various typical Reynolds numbers, are described. Air was sucked in from the atmosphere through the slot.

The pressure distribution along the slot was measured and the flow was observed by means of a stethoscope and tufts. In all tests, laminar separation, transition and subsequent turbulent reattachment occurred; these phenomena probably being followed at the larger diffuser angles by turbulent separation. A maximum pressure recovery factor of 0.78 was attained at a slot Reynolds number of 5000 with 3° slot diffuser angle.

Author

Availability:
NAI-54-559
BLC-56

340. Rogers, Kenneth H.: Investigation of the Pressure Distribution and Boundary Layer in a Suction Duct With Zero-Deceleration Duct Inlet. Rep. No. BLC-50, Rep. No. NAI-54-486, Northrop Aircraft, Inc., July 1954. (Available from DDC as AD 54 971.)

Experimental results of the pressure distribution along the duct and the boundary layer characteristics at the duct exit are presented for a suction duct with approximately zero deceleration of the duct inlet. The experiments cover a wide range of Reynolds numbers of the duct flow, from apparently completely laminar flow at the duct exit to completely turbulent flow at the duct exit. The results indicate that less than half the losses in the duct are due to the boundary layer. The remaining losses presumably are caused by interaction of the inlet and duct streams. If this hypothesis is correct, further reduction in duct losses may be possible by improving the inlet flow into the duct.

Preliminary experimental results of the pressure rise provided by separate jets entering the duct stream at greater-than-duct-velocity are included, bringing the report up to date with the most recent suction duct experiments. These preliminary experiments show that the pressure distribution along the duct can be altered appreciably by the use of boost jets.

Author

Availability:
SN-24021, July 1954
BLC-50
NAI-54-486
AD 54 971

341. Rogers, Kenneth H.: A Method of Calculating the Pressure Distribution in Suction Ducts. Rep. No. BLC-30, Northrop Aircraft, Inc., Feb. 1954. (Available from DDC as AD 38 616(c).)

A method of calculating the pressure distribution in suction ducts, and two examples comparing the theory with experiment are presented. The theoretical results appear to be in good agreement with the experimental results if the pressure rise due to the mixing is multiplied with an empirical "efficiency" factor. It is suspected that increased surface friction in the mixing region partly compensates the pressure rise due to mixing derived from conservation of momentum.

The method presented applies only to ducts in which the inlet flow is directed downstream in the duct; i.e., crossflow effects are neglected.

Author

Availability:
SN-24021, Feb. 1954
BLC-30
AD 38 616(c)

342. Pfenninger, W.: Some General Considerations of Losses in Boundary Layer Suction Ducting Systems. Rep. No. BLC-29, Northrop Aircraft, Inc., Feb. 1954. (Available from DDC as AD 38 616(d).) (Also included in Summary of Laminar Boundary Layer Control Research, WADC Tech Rep. 56-111, U.S. Air Force, Apr. 1957, pp. 217-220. (Available from DDC as AD 130 759.))

The friction losses $\frac{\Delta g_{friction}}{q_o}$ increase approximately with the square of the duct velocity $\frac{u_D}{U_o}$ (Fig. 2). With increasing duct velocity the velocity of 100,000 to 200,000. The sum of the losses in the ducts and in the suction compressors must then be minimized.

The present theoretical study considers various methods which reduce the losses in boundary layer suction ducting systems. Special attention is given to low drag suction.

Author

Availability:
SN-24021, Feb. 1954
BLC-29
AD 38 616(d)
N78-76390
N-53889
AD 130 759

343. Reilly, R. J.; and Pfenninger, W.: Measurements of the Spanwise Variation of the Suction Quantity With Suction Through Slots and Holes Underneath the Slots. Summary of Laminar Boundary Layer Control Research, WADC Tech. Rep. 56-111, U.S. Air Force, Apr. 1957, pp. 12-14. (Available from DDC as AD 130 759.)

This series of experiments showed that the variation in slot velocity can be reduced effectively by displacing the row of holes in a chordwise direction relative to the slot. For all experiments made, chordwise displacement of one hole radius ($y = r$) resulted in more than 50% reduction in spanwise velocity variation through the slot, and a displacement of one half the hole spacing ($y = r + s$) reduced the velocity variation to practically zero. The reduction in velocity variation as a function of displacement is shown for five typical configurations.

Author

Availability:
N78-76390
N-53889
AD 130 759

344. Pfenninger, W.; Dedon, W. W.; and Slagg, W. R.: Design of the Suction Ducting System for a Hypothetical Laminar Suction Airplane. Summary of Laminar Boundary Layer Control Research, WADC Tech. Rep. 56-111, U.S. Air Force, Apr. 1957, pp. 257-266. (Available from DDC as AD 130 759.)

The purpose of this investigation is to present some problems encountered in connection with the ducting system of a laminar suction wing and to offer possible solutions for these problems.

It has been shown that an efficient design of high aspect ratio laminar suction wings can be achieved by properly combining the suction ducting system with the structural layout and by distributing the design difficulties on the various components of such a wing. A wing structure with small duct losses and a minimum incremental structural weight due to suction is then possible. Suction through a large number of fine slots appears promising, particularly on swept laminar suction wings. Suction through many rows of closely spaced holes is often equally attractive, provided premature transition as well as contamination of the holes can be avoided.

Author

Availability:
N78-76390
N-53889
AD 130 759

345. Rogers, Kenneth H.: Investigation of the Pressure Distribution Along a Constant Area Suction Duct With 90 Degree Drilled-Hole Inlet. Rep. No. NAI-55-286 (BLC-71), Northrop Aircraft, Inc., Mar. 1955. (Available from DDC as AD 74 865(a).)

The purpose of the investigation is to provide experimental data of pressure-drop along suction ducts with 90° drilled-hole inlets and to investigate the effects of Reynolds number, length-diameter ratio, and inlet-to-duct velocity ratio.

Author

Availability:
SN-24021, Mar. 14, 1955
NAI-55-286 (BLC-71)
AD 74 865(a)

346. Rogers, Kenneth H.; and Pfenninger, W.: Further Investigations on an Improved Suction Duct. Rep. No. NAI-55-547 (BLC-70), Northrop Aircraft, Inc., May 1955. (Available from DDC as AD 79 343(a).)

A series of experimental investigations has resulted in the development of an improved suction duct which shows negligibly small losses due to secondary flow or mixing and very small losses due to formation of the boundary layer along the duct walls. In experiment 1 (velocity at the exit of the turning vanes practically equal to local duct velocity) the pressure drop due to friction and secondary flow was 15% to 19% of the dynamic pressure at the end of the duct for $\ell/d_{hyd_{\ell}} = 20$.

Furthermore, it has been shown that the pressure losses in the suction duct can be compensated by pressure recovery due to mixing of the inlet flow with the duct flow, if the inlet velocity is larger than the local duct velocity. In this manner the total-pressure can be maintained approximately constant along a very long suction duct. Examples of theoretical determination of pressure distribution along a suction duct, for three different levels of inlet-to-duct velocity ratio, show good agreement between theory and experiment.

Author

Availability:
N76-77660
SN-24021, May 1955
NAI-55-547 (BLC-70)
AD 79 343(a)

347. Goldsmith, John: Critical Suction Quantities and Pumping Losses Associated With Laminar Boundary Layer Suction Through Rows of Closely-Spaced Holes. Rep. NAI-55-287 (Rep. No. BLC-72), Northrop Aircraft, Inc., Feb. 1955. (Available from DDC as AD 74 865(b).)

The critical (limiting) laminar suction quantities have been measured for several different configurations of holes in a row. The experimental configurations include variation of (a) hole diameter, (b) the distance between adjacent hole centerlines, (c) the space between adjacent edges of the holes, and (d) the alignment of the row of holes to the airstream (effect of "sweep"). In addition, the suction pressure losses have been measured for each configuration.

The experimental results indicate that the critical suction quantities are more dependent on the closed space or gap between adjacent edges of holes than on other dimensions such as diameter and centerline spacing. The "swept" row of holes (which actually formed a sine wave in the flat pattern) have a critical suction quantity considerably reduced from the value for a similar configuration lying perpendicular to the tube axis.

Measurement of the pressure losses resulting from suction through a row of holes indicates that the dimensionless losses ($\Delta H/\bar{q}$) bear some relation to the tube parameter $t\nu/\bar{U}_h a^2$. This parameter is the theoretically derived parameter which determines the losses and other flow conditions for tubes with smooth inlet. With information already available, the losses through suction holes can be calculated to about 10% accuracy, but additional experiments (which are currently being conducted) are required before additional accuracy can be achieved.

Author

Availability:
SN-24021, Mar. 14, 1955
NAI-55-287 (BLC-72)
AD 74 865(b)
N79-75690

348. Rogers, K. H.: Experimental and Analytical Investigation of a Vee Inlet Suction Duct. NAI-56-614, Rep. No. BLC-89, Northrop Aircraft, Inc., July 1956. (Available from DDC as AD 106 068(a).)

Experimental and analytical investigations of a suction duct connected to two inlets at different pressure levels are presented. Turning vanes are installed in the inlets to direct the inflow downstream in the duct. The results show that a suction duct with turning-vanes provides appreciable pressure recovery by mixing of the high energy and low energy inflows, as compared with a duct in which the dynamic pressure of the inflow is lost by throttling through the suction surface. Variations in pressure distribution along the duct, inflow distribution along the inlets, and losses in the duct system are shown as a function of the inlet flow-rate ratio Q_H/Q_{Total}. Theoretical and experimental results are compared.

Author

Availability:
SN-24021, July 1956
NAI-56-614 (BLC-89)
AD 106 068(a)
N79-75289

349. Treanor, C. E.; and Flax, A. H.: The Effect of Boundary Layer Profile, Air Speed, and System Geometry on the Stability of Flow in Suction Systems. WADC TR-55-318, AD 97115, U.S. Air Force, July 1956.

The stability of flow in air induction systems for boundary-layer suction has been studied as a continuation of the theoretical and experimental work reported in WADC TR 53-189. In these suction systems, the dynamic head of the boundary-layer air can increase the pressure in the suction system, causing dynamic and static instability. The theoretical work reported here extends the previous analysis to include the effects of wave motion in the exit section of the suction system. The experiments include tests with both a turbulent boundary layer and an artificially produced laminar-like boundary layer, obtained by air injection through the tunnel wall. The static instability is evidenced by the appearance of unequal flows in ostensibly identical branches of the system. Inserting splitter vanes in the slot and diffuser accents this instability, the flow confining itself to separate sections of the diffuser for moderate suction rates. Several devices to remove the static instability were unsuccessful, but the use of the laminar-like boundary layer has a strong stabilizing effect. The dynamic instability occurs in the form of regular oscillations in the flow. It was shown in WADC TR 53-189 that the system could be made dynamically stable by introducing large losses in the suction slot. In the present report four stabilizing effects are investigated: small plenum volume, laminar-like boundary layer, large-chord entrance slot, and low tunnel speed. Conditions for dynamic stability are investigated theoretically, and a stability criterion is compared with the experimental results. The experiments with the dynamic instability include measurements of the amplitude and phases of the oscillations in various places in the suction system. An expression is derived for the frequency of oscillation in the case of dynamic instability. The calculated frequency agrees with the experimental measurements for large plenum volume, but is not in agreement for measurements with the small plenum. The energy balance in the dynamically unstable system is investigated theoretically and these results are compared with experiment.

Author

Availability:
N-47167
AD 97115
N78-79433

350. Schantz, H. F.: Boundary Layer Control Suction Duct No. 2 Analysis. Rep. No. 17-183 (Contract No. AF-33(600)-5006), Chase Aircraft Co., Inc., Apr. 23, 1953. (Available from DDC as AD 014 754.)

This is an investigation of the suction duct No. 2 for the boundary layer control of MS-17 airplane. The model, 0.409 of airplane size, was made of plexiglass with aluminum vanes or throttle plates, and wooden inlets. The purposes of the tests were to investigate the losses in the modified duct, to compare losses in case of inlet guide vanes or throttle plates, and to obtain a uniform speed distribution in the slot.

Author

Availability:
N79-70655
N-25622
AD 014 754

351. Krueger, W.: Systematic Wind-Tunnel Measurements on a Laminar Wing With Nose Flap. NACA TM 1119, 1947.

Results of measurements are given as a supplement to earlier tests for a laminar profile with nose flap; magnitude, form, and angle of attack of the flap were systematically changed. The experiments were carried out at an effective Reynolds number of 8.2×10^5. The maximum lift was increased to an optimum of $\Delta c_{a_{max}} \approx 0.7$. A comparison with measurements on other profiles shows that the effect of a nose flap is essentially dependent upon magnitude of the nose radius coefficient $\frac{\rho_l}{(d/l)^2}$ of the profile.

Author

Availability:
N78-78538

352. Goldsmith, John: Factors Influencing the Design of Full-Scale and Model High Lift Wings Which Utilize Boundary Layer Control. Rep. No. NAI-54-672 (Contract Nonr-775 (00)), Northrop Aircraft, Inc., Oct. 1954.

The boundary layer suction airflow required to prevent separation has been estimated for a two-dimensional NACA 0006-64 airfoil section with three combinations of leading and trailing edge flaps which give calculated potential flow lift coefficients greater than 4.0. The results of calculations for two flap configurations are given in References 1 and 2. More recently, calculations were made for the third flap configuration and the results of the three flap configurations are compared in Fig. 2 of this report. Suction was assumed to be applied by means of several finite-sized suction slots placed in the region of adverse pressure gradients. The results of the calculations indicate that separation can be prevented with suction airflow coefficients of about 0.002 using from 16 to 38 slots. Recent research in connection with low drag suction work indicates that as many as 38 slots may not be at all unreasonable.

In order to obtain high lift with such a low airflow quantity, it is necessary that the suction be distributed over the wing area in a particular manner. Since the external wing pressure varies over a large range, it is not a simple matter to obtain the desired suction distribution. The problems connected with obtaining the desired suction distribution and some solutions to these problems and the critical factors which establish the model design variables are discussed in the text. (Discusses and includes a graph on losses through small holes.)

Author

Availability:
N79-70033
N-35088
NAI-54-672

353. Burrows, F. M.; and Newman, B. G.: The Application of Suction to a Two-Dimensional Laminar Separation Bubble. Res. Rep. #27 (Contract Nonr 978(01)), The Aerophys. Dept., Mississippi State Univ., Oct. 1, 1959.

The effect of suction or blowing through a perforated surface in the vicinity of a laminar separation bubble has been investigated. The bubble was produced at a sharp corner on one wall of a small wind tunnel and the tests were made at a low Mach number under effectively two dimensional conditions. It was found that the size of the bubble and the thickness of the boundary layer downstream were both reduced by increasing the suction and were similarly increased by much smaller amounts of blowing. Five different distributions of transpiration were tested and the various parameters describing the turbulent boundary layer downstream of reattachment were found to depend on the total quantity of flow removed and to be very nearly independent of the distribution itself. The measured values of pressure rise in the region of reattachment were roughly in agreement with a simple momentum analysis which includes the effect of transpiration. It is concluded that the application of suction near a short bubble on a high-lift wing will in general be beneficial unless the possible forward movement of the separation point leads to the formation of a long bubble.

Author

Availability:
N79-70026
N-76829

354. Eppler, Richard: Gemeinsame Grenzschichtabsaugung Für Hochauftrieb und Schnellflug. Jahrb. 1962 WGLR, Hermann Blenk, ed., Friedrich Vieweg und Sohn, 1963, pp. 140-149; Discussion on pp. 148-149.

Combined boundary layer suction has recently been successfully applied in order to prevent laminar-turbulent transition as well as separation of the turbulent boundary layer. The two cases, however, require entirely different distributions of suction, particularly if applied to available conventional airfoil sections. Whereas, in the case of high lift, suction has to be applied particularly in the region of the leading edge of the wing, high speed requires the suction to be applied over the rear end of the airfoil at the region of the occurrence of adverse pressure gradients. Calculating airfoil sections from given properties of pressure distribution, boundary layer suction, serving two different purposes, can be taken into account as far as to achieve, with one suction installation only, considerable effects regarding high lift as well as high speed. Examples of airfoil sections with the appropriate distribution of suction are discussed.

Author

Availability:
A64-26974

355. Eppler, R.: Practical Calculation of Laminar and Turbulent Bled-Off Boundary Layers. NASA TM-75328, 1978.

Where bleed-off is present in an airfoil, for preservation of laminarity at high-speed flight, it will also have a certain effect in retarding the separation when it can no longer prevent the reversal during slow flight. Conversely, continuous siphoning for lift increase, i.e., for retardation of separation during slow flight, must in principle have a favorable influence on the reversal at high-speed flight during a change in pressure distribution. Up til now hardly any thought has been given to the combination of these two effects, since entirely different amounts of bleed-off are required at different points. But lately there has been some approach to this combination. A valuable aid in realizing such a bleed-off combination is a method of calculation that permits uniform treatment of all cases. This study will report on a solution of the problem.

Availability:
N78-32053

356. Mertaugh, Lawrence J.: Feasibility Study of a Combined Laminar and Turbulent Boundary Layer Control System Using Distributed Suction. AFFDL-TR-71-47, U.S. Air Force, Apr. 1971. (Available from DDC as AD 727 767.)

The objective of the investigation was to determine the feasibility of a combined low-drag, high-lift boundary layer control system intended for use in the XV-11A aircraft. The XV-11A is a low-speed aerodynamic research aircraft constructed entirely of glass reinforced plastic. The combined boundary layer control system to provide full chord laminar flow over the wing surfaces in cruise flight and prevent separation of the turbulent boundary layer under conditions of high lift coefficients in the approach configuration will utilize distributed suction over the wing surfaces with the porosity provided by rows of closely spaced suction holes. The evaluation of the laminar system was accomplished on a glove section installed on the wing of a TG-3 glider.

Availability:
N71-37609
AD 727 767

357. Gross, Lloyd W.: Investigation of the Behavior of Boundary Layer Suction in Decelerated Flows. Volume I: Experiments and Comparison With Theory. AFFDL-TR-68-117, Vol. I, U.S. Air Force, Aug. 1968. (Available from DDC as AD 846 963L.)

Separation of a turbulent boundary layer in a pressure rise approximately that of the forward 25% of a 12% thick airfoil section with a 30% chord flap deflected 60° was prevented by means of suction through a large number of fine slots. Attached turbulent boundary layer flow was maintained at ambient Mach numbers from $M_\infty = 0.2$ to $M_\infty = 0.315$ corresponding to maximum Mach numbers on the surface of the model $M = 0.48$ to 0.935 and Reynolds numbers $R_C = 4.1 \times 10^6$ to 6.3×10^6. The minimum observed optimum suction flow coefficient (defined where the sum of the boundary layer kinetic energy loss and the pumping power was least) varied from $C_{M_t} = 1.58 \times 10^{-3}$ at $M_\infty = 0.2$ to $C_{M_t} = 1.48 \times 10^{-3}$ at $M_\infty = 0.315$. The corresponding values of minimum energy loss coefficient were $C_{p_t} = 13 \times 10^{-3}$ and $C_{p_t} = 22 \times 10^{-3}$ respectively. The Reynolds numbers and flow coefficients are based on model dimensions and will change when applied to an actual case (see Volume 2).

For the pressure distribution of these tests one-half of the pressure rise occurred within 15% of the airfoil chord while the remainder of the pressure rise occurred over the aft 70% of the chord. The tests indicated that from the standpoint of minimum energy loss it was advantageous to maintain a thin boundary layer by means of strong suction in the forward region where the pressure gradient was strongest. Weaker suction with increasing boundary layer thickness was then possible in the after section where the flow deceleration was less.
Author

Availability:
N78-77795
AD 846 963L

358. Pfenninger, Werner: Investigation of the Behavior of Boundary Layer Suction in Decelerated Flows. Volume II: Application of Results. AFFDL-TR-68-117, Vol. II, U.S. Air Force, Aug. 1968. (Available from DDC as AD 395 145.)

Availability:
N79-74734
AD 395 145

359. Mee, Thomas R.: An Investigation of Atmospheric Factors That May Affect Laminar Flow Control. MR164, R212a, Meteorology Research, Inc., Dec. 1, 1964.

A brief investigation was conducted to obtain an estimate of the frequency of occurrence of atmospheric conditions that might have an adverse effect on laminar-flow-control aircraft. The investigation also involved a feasibility study of instrumentation that would be appropriate for installation on the X-21 aircraft to help in making a quantitative evaluation of the effects of atmospheric factors of interest.

Results of the investigation indicate that in the 25,000-foot regime of present interest (from an altitude of approximately 20,000 feet to 45,000 feet) there is, on a world-wide basis, a likelihood of 25 to 50 per cent that visible clouds or airborne ice-crystal aerosols would be found somewhere within the regime. This does not mean that an aircraft flying within this altitude zone would necessarily be in clouds that percentage of the time, since the average cloud thickness would seldom exceed about 5000 feet. At some special geographical locations, such as above the tropical convergence zone, the probability of finding cirrus clouds will quite likely be greater than 50 per cent. At other locations, such as in subtropical high pressure areas, the probability of encountering clouds at any altitude would be significantly less than 25 per cent and would probably approach zero. Even though the occurrence of high clouds appears to be rather common, a careful consideration of the data available has led to the tentative conclusion that long-range flights can be conducted in a cloud-free environment for all but a very small percentage of the time. If the flight level is carefully chosen and if it is altered appropriately whenever clouds are encountered, it should be possible to avoid clouds throughout the greatest portion of a flight over most of the world.

From the instrument-feasibility study it was concluded that several atmospheric parameters should be measured from the X-21. These parameters include atmospheric turbulence, electric charge on the aircraft, cloud particle size distribution, hydrometeor type, and humidity if possible. In addition it was concluded that instrumentation should be included to give the flight crew the capability of electrically charging and discharging the aircraft in flight.

Author

Availability:
CN-150,358
N79-75671

360. Glauert, Muriel: A Method of Constructing the Paths of Raindrops of Different Diameters Moving in the Neighbourhood of (1) a Circular Cylinder, (2) an Aerofoil, Placed in a Uniform Stream of Air; and a Determination of the Rate of Deposit of the Drops on the Surface and the Percentage of Drops Caught. R. & M. No. 2025, British A.R.C., Nov. 10, 1940.

The present investigation has been undertaken with a view to determining the paths of raindrops of different sizes (1) in front of a circular cylinder, (2) near the nose of an aerofoil, moving in a uniform stream of air. The rate of deposit of the drops on the surface was also calculated and the percentage of drops caught was determined.

Such an investigation was suggested by Prof. G. I. Taylor in R. & M. 2024 (Jan., 1940) dealing with the problem of de-icing.

Author

Availability:
N78-78513

361. Effect of Clouds on LFC Applications. Syst. Eng. Group, Res. & Technol. Div., Wright-Patterson AFB, Dec. 1964. (Available from DDC as AD 454 476.)

This is a preliminary operations research study on the effect clouds would have on laminar flow control (LFC) in cargo and transport applications. This study assumes that LFC does not work in visible clouds regardless of their makeup but that it does work perfectly outside of visible clouds. Expected cloud experience is converted into equivalent head wind experience and compared with wind data. The study concludes that clouds will probably have a smaller adverse effect on range than winds.

Author

Availability:
N65-18431
AD 454 476

362. Hall, G. R.: On the Mechanics of Transition Produced by Particles Passing Through an Initially Laminar Boundary Layer and the Estimated Effect on the LFC Performance of the X-21 Aircraft. Northrop Corp., Oct. 1964.

Numerous flight tests of the X-21 aircraft have shown total loss of LFC while flying within, or in the proximity of, visible clouds. In addition, erratic LFC performance has been observed in conditions of light haze when the humidity of the air is relatively high.

An investigation of the phenomena which might account for loss of LFC in, or near clouds and for the erratic performance in light haze has been conducted. The phenomena considered in the investigation are classified as either thermodynamic effects or mechanical effects. The results derived from the study of thermodynamic effects are documented in Reference 1. All of the thermodynamic phenomena considered appeared highly unlikely in contributing to the loss of LFC in clouds and light haze conditions. The results and conclusions from the study of mechanical effects, which have led to probable identification of the problem, are presented in this document. Recommendations for follow-on work are also presented.

Author

Availability:
N79-70656

363. Worth, R. N.: Effect of Environmental Exposure on Boundary Layer Control Surfaces and Operations. Rep. No. NOR-61-211 (BLC-133), Northrop Corp., Sept. 1961.

The object of these investigations was to determine the effects of exposure to various climatic environment on typical boundary layer control skin configurations with respect to the operational characteristics and maintenance requirements of the suction system.

Author

Availability:
NOR-61-211 (BLC-133)
N79-77154

364. Hill, W. L.: Effect of Weathering on Nonperforated Honeycomb Core Adhesives Required for Use in Boundary Layer Construction. Rep. No. NOR-60-261, Northrop Corp., Aug. 29, 1960. (Available from DDC as AD 294 275.)

The purpose of this work was to determine if an unsealed sulfuric acid anodized surface is acceptable for bonding purposes in boundary layer construction, to determine if bonded honeycomb assemblies can be sulfuric acid anodized and sealed without degradation of the honeycomb bond or the honeycomb core, and to choose the best nonperforated honeycomb core adhesive for use in boundary layer construction. It was concluded that sulfuric acid anodizing of skins prior to bonding is not satisfactory for boundary layer applications because of the inferior low temperature (-67°F) bond strengths and because it does not solve the corrosion problem peculiar to boundary layer construction. Therefore, it is recommended that sulfuric acid anodizing prior to bonding should not be considered for use in boundary layer construction.

Author

Availability:
N65-85878
NOR-60-261
AD 294 275

365. Worth, R. N.: Effect of Weathering on Typical Bonded Boundary Layer Control Structure. Summary of Laminar Boundary Layer Control Research - Volume II, ASD-TDR-63-554, U.S. Air Force, Mar. 1964, pp. 809-821. (Available from DDC as AD 605 186.)

The weathering tests on boundary layer control panels conducted during this program indicated that suction flow rates can be held to within 2.5 percent of the design values with present methods for washing and steam cleaning of aircraft. Results from salt spray exposure tests indicated the desirability of providing protection for the slots and holes by either an anodizing or an Iriditing process. Ground operation or storage of BLC aircraft without special protection seems feasible. Results of the ninety-day industrial exposure and the sixty-day tropical exposure tests indicate that vacuum cleaning from the slot side only can restore the flow rate to within 5 percent of the original value while steam cleaning at 100 psi from the slot side only can restore the flow rate to within 1.5 percent of the original values. The results of the metal to metal strength tests to determine adhesive strength characteristics showed no deterioration of the bond during the weathering exposures. The results of the honeycomb peel and tensile tests indicated that the adhesive was attacked somewhat by humidity weathering conditions. However, all strength values were adequate for future LFC work.

Author

Availability:
N65-25571
AD 605 186
N79-77174
BLC-128
NOR-59-608

366. Goldsmith, J.: Laminar Flow at the Juncture of Two Aeroplane Components. Boundary Layer and Flow Control, Volume 2, G. V. Lachmann, ed., Pergamon Press, 1961, pp. 1000-1006.

The approach to the problem of maintaining laminar flow past a juncture is complicated by the fact that generally the pressure field on the surface of at least one of the intersecting components is 3-dimensional in nature. Using W. Pfenninger's 2-dimensional results as a guide, the 3-dimensional requirements can be estimated. Suction is accomplished by use of slots to provide the estimated values. Experimental results verify the predictions to a degree satisfactory for initial designs.

367. Pfenninger, W.; and Meyer, W. A.: Critical Wing Wake Reynolds Numbers for Laminar Flow on a Fuselage Downstream of a Wing Root Juncture. Rep. No. NAI-54-560, Rep. No. BLC-58, Northrop Aircraft, Inc., Aug. 1954. (Also available in Summary of Laminar Boundary Layer Control Research, WADC Tech. Rep. 56-111, U.S. Air Force, Apr. 1957, pp. 184-203. (Available from DDC as AD 130 759.))

Complete laminar flow was maintained in an 8-inch ID 37-foot straight tube downstream of a laminar suction wing located in the entrance nozzle of the tube, by means of boundary layer suction on this wing. Acceleration between the suction wing and the tube considerably increased the critical wake Reynolds number at the trailing edge of this suction wing. The same critical wake Reynolds numbers as on this suction wing were observed behind circular cylinders and flat plates, under otherwise the same conditions. The critical wake Reynolds number was not appreciably affected by the tube length Reynolds number with laminar flow within a range of $5.6 \cdot 10^6$ to $35 \cdot 10^6$.

A turbulent wake in the middle of the tube did not affect transition at $5.6 \cdot 10^6$ tube length Reynolds number as long as the edge of the turbulent wake did not extend too close to the edge of the laminar boundary layer of the tube.

These experiments thus confirm that considerably larger critical wake Reynolds numbers (for laminar flow on the rear fuselage) in the region of a wing fuselage juncture can be tolerated by accelerating the flow locally downstream of the trailing edge of the juncture. Thin turbulent wakes, originating from the trailing edge of laminar suction wings, can probably be tolerated at relatively small distances from the fuselage surface.

Besides wing fuselage junctures, these results are also applicable to intersections between a fuselage or a nacelle with wings, struts, tail surfaces, etc., of a laminar suction airplane, and possibly to blade root intersections in certain turbo-machines and propellers.

Further work is required in order to develop laminar flow junctures with laminar flow on the rear fuselage.

Author

Availability:
NAI-54-560
BLC-58
N78-76390
N-53889
AD 130 759

368. Pfenninger, W.; and Sipe, O. E., Jr.: Note on the Reduction of Wing-Strut Interference. Rep. No. NAI-55-289 (BLC-74), Northrop Aircraft, Inc., Mar. 1955. (Available from DDC as AD 74 865(d).)

With the low friction drag on laminar suction airplanes, the induced drag is becoming increasingly important, especially at high altitudes. Long wings with low induced drag are therefore preferable in order to obtain the full benefit from low drag suction, provided such long wings can be built sufficiently light in weight. It has been suggested that a strut-braced wing design be used to reduce the structural weight of such long wings. The saving in induced drag with a strut-braced design could be considerably larger than in the parasite drag of the strut, for the same critical Mach number, provided the advantages of a strut-braced construction are fully utilized & the interference drag between wing & strut is kept at a minimum. In order to reduce the interference drag between wing and strut & to obtain a high critical Mach number on the lower wing surface and the strut, care must be taken to obtain a smooth pressure distribution without excessive negative pressure peaks on the strut and the lower wing surface. Basically, this can be achieved by cutting out part of the lower wing surface in the region of the strut, thus providing more cross-section and reduced velocities in the gap between wing & strut. The effects of such cutouts on the flow in the gap between the wing & strut were investigated.

Author

Availability:
SN-24021, Mar. 14, 1955
NAI-55-289 (BLC-74)
AD 74 865(d)

369. Bacon, John W., Jr.; Fiul, A.; and Pfenninger, W.: WADC 10-Ft Transonic Wind Tunnel Tests on Strut-Braced Boundary Layer Airplane. NAI-57-826, Rep. No. BLC-99, Northrop Aircraft, Inc., June 1957. (Available from DDC as AD 140 583(a).)

The application of suction boundary layer control to airplanes results in a very low value for friction drag. Consequently, the drag due to lift becomes the major portion of the total subsonic airplane drag. Since the drag due to lift is reduced by increasing the wing span, the designer of a laminar suction airplane finds that strut-bracing wings leads to better range and altitude performance.

In order to verify the transonic characteristics and wave drag of a strut-braced configuration, the subject model of this report was built for the WADC 10-Ft Transonic Wind Tunnel.

The results of the test are satisfactory. The drag rise is delayed to a Mach number of almost 0.9 with the 35° swept wing. In addition, the maximum L/D ratio of over 19 for an average wing chord Reynolds number of 1×10^6 is quite good. Moreover, the schlieren pictures suggest that further delay in drag rise and reduction of wave drag could be attained by improving the wing-fuselage fairing.

Author

Availability:
SN-24021, June 1957
NAI-57-826
BLC-99
AD 140 583(a)
N79-75727

370. Pfenninger, W.: Further Basic Investigations on the Critical Wing Wake Reynolds Number for Laminar Flow on a Fuselage Downstream of a Wing Fuselage Juncture. Rep. No. NAI-57-659, Rep. No. BLC-96, Northrop Aircraft, Inc., May 1957. (Available from DDC as AD 140 589(a).)

This experiment confirms that relatively large critical wake Reynolds numbers for laminar flow on the rear fuselage are possible in the region of the wing fuselage juncture with a sufficient flow acceleration downstream of the wing trailing edge in the juncture region.

Author

Availability:
SN-24021, June 1957
NAI-57-659
BLC-96
AD 140 589(a)
N79-75698

371. Goldsmith, J.: Preliminary Experiments on the Maintenance of Laminar Flow by Means of Suction in the Region of a Wing Leading Edge and Fuselage Juncture. Rep. No. NAI-58-249 (BLC-106), Northrop Aircraft, Inc., Apr. 1958.

The experimental results demonstrated that laminar flow is possible for the upstream region of the juncture and that the suction requirements for maintenance of laminar flow past the leading edge of a wing fuselage juncture need not exceed about ¼ the suction requirements of the isolated wing if the wing is of moderate or greater aspect ratio. Not all of this suction is directly chargeable to the juncture since some suction would be required in this region even on an isolated fuselage. Improvements in design technique will probably result in additional reductions in the suction requirements. The results gave no indication that laminar flow could not be extended to or beyond the trailing edge.

Since the design and experimental results are believed to be unprecedented they are described in somewhat more detail than usual. In particular, the comparison of the design criteria with the experimental results may serve as a guide for future designs.

Author

Availability:
N78-75633
SN-24021, Mar. 1958
NAI-58-249 (BLC-106)

372. Goldsmith, J.: Experiments With Laminar Flow Near the Juncture of a Fuselage and Wing Trailing Edge. Rep. NOR-59-306 (BLC-120), Northrop Aircraft, Inc., June 1959.

It was demonstrated that it is possible to achieve laminar flow in and downstream of the juncture of a wing and flat plate. Laminar flow was facilitated by installing two small vortex generators in the wing trailing edge near the intersection of the wing and plate. This tends to "sweep" the wing wake away from the plate.

Availability:
SN-24021, June 1959
N79-77133

373. Gregory, N.; and Walker, W. S.: Wind-Tunnel Tests on the Use of Distributed Suction for Maintaining Laminar Flow on a Body of Revolution. R. & M. No. 3145, British A.R.C., 1960.

Experiments were carried out in the National Physical Laboratory 13-ft × 9-ft Wind Tunnel on a 15-ft long body of revolution of fineness ratio 10:1. Observations were made of the effects of Reynolds number, yaw, and of isolated excresences on the position of transition on the solid body, and the possibilities of increasing the extent of laminar flow by means of area suction were examined.

At zero angle of yaw, the maximum Reynolds number at transition on a solid version of the body was 4½ million. When the body was set at a small angle of yaw, the transition position was much farther forward along certain generators of the body than on others, owing to the instability of the three-dimensional boundary layer. The critical heights of small conical excrescences which just precipitated transition were found to be much the same as those required on a two-dimensional aerofoil.

The 'suction' version of the body was porous over the central third of the length and was attached to the overhead tunnel balance by means of a porous wing. There appeared to be no fundamental difficulty in obtaining extended laminar flow over the body with distributed suction up to a tunnel speed of 80 ft/sec. Even with laminar flow right around the intersection to the trailing edge of the wing, the laminar wake from the wing rapidly became turbulent downstream of the trailing edge and gave rise to a spreading wedge of turbulent boundary layer on the body. Further investigation of this difficulty would best be carried out on a simple part model, such as the junction of a stub wing with a flat plate.

Partly in consequence of the large suction quantity needed for laminar flow, and partly because the flow on the body in the wake of the wing and aft of 0.82 of the body length remained turbulent when suction was applied, there was only a small reduction in the effective drag coefficient of the model with suction. The analysis shows, however, that the potential gains at high Reynolds numbers would be large, provided the porous surface were satisfactorily smooth and extended sufficiently far back to enable full-length laminar flow to be achieved.

Author

Availability:
N78-78045
N-59117X

374. Clauser, Milton; and Clauser, Francis: The Effect of Curvature on the Transition From Laminar to Turbulent Boundary Layer. NACA TN 613, 1937.

In the flow over the upper surface of a wing, a discrepancy between the predicted and actual point of transition from laminar to turbulent boundary layer had been found. This effect may be due to the comparatively small radius of curvature of the upper surface of the wing. The present tests were undertaken to investigate this effect.

Three types of measurement were made: (a) Traverses were made with a total-head tube to determine the character of the boundary layer at various Reynolds Numbers. (b) The turbulence distribution in the boundary layer was investigated by means of a hot wire and a vacuum-tube amplifier. (c) A similar investigation of the mean velocity distribution in the boundary layer was made by a hot-wire anemometer. It was found that, by using an abbreviated form of the turbulence-level traverses, critical Reynolds Numbers for the transitions could be established. These critical Reynolds Numbers are plotted as a function of the ratio of the distance of the transition from the leading edge of the plate to the radius of curvature of the plate for both the convex and concave side of the plate. The experimental points for the convex and concave side of the sheet are consistent with each other. The variation is of such an order of magnitude that the curvature ordinarily used on the upper surface of an airplane wing might double the critical Reynolds number.

Author

Availability:
N78-78798

375. Görtler, H.: On the Three-Dimensional Instability of Laminar Boundary Layers on Concave Walls. NACA TM 1375, 1954.

This is a study of the stability of laminar boundary-layer profiles on slightly curved walls relative to small disturbances, in the shape of vortices, whose axes are parallel to the principal direction of flow. The result in an eigenvalue problem by which, for a given undisturbed flow at a prescribed wall, the amplification or decay is computed for each Reynolds number and each vortex thickness. For neutral disturbances (amplification null) a critical Reynolds number is determined for each vortex distribution. The numerical calculation produces amplified disturbances on concave walls only. The variation of the dimensionless $\frac{U_o \vartheta}{\nu}\sqrt{\frac{\vartheta}{R}}$ with respect to $\alpha\vartheta$ is only slightly dependent on the shape of the boundary-layer profile. The numerical results yield information about stability limit, range of wave length of vortices that can be amplified, and about the most dangerous vortices with regard to the transition from laminar to turbulent flow. At the very first appearance of amplified vortices the flow still is entirely regular; transition to turbulent flow may not be expected until the Reynolds numbers are higher.

Author

Availability:
N78-78794

376. Smith, A. M. O.: On the Growth of Taylor-Görtler Vortices Along Highly Concave Walls. Douglas Aircraft Rep. No. E.S. 17110, 1953. (Available from DDC as AD 106 824.) (An excellent version of this report may be found in Q. Appl. Math., vol. XIII, no. 3, Oct. 1955, pp. 233-262.)

The primary objective of this study was to prepare a chart for computing the growth of Taylor-Görtler vortices in laminar flow along walls of both high and low concave curvature. Taylor-Görtler vortices are streamwise vortices having alternate right- and left-hand rotation that develop in the laminar boundary layer along a concave surface.

The equations of motion are derived anew and re-examined with regard to the importance of the various terms. The final equations used in preparation of the chart are shown to be valid for radii of curvature as small as 30 times the boundary layer thickness. Furthermore, it is shown that the equations are not restricted in validity to cases of constant wall curvature, constant free stream velocities, or to boundary layers of constant thickness. Whereas the previous analyses by G. I. Taylor and Görtler assumed the vortex to grow exponentially as a function of time, the present study recasts the growth into a more convenient form in which the vortex grows as a function of distance.

The solution is an eigenvalue problem, which in the present study has been solved mainly by Galerkin's method, a variational method. Both the eigenvalues and the eigenfunctions are presented, the former in the aforementioned chart. It is possible to compare the solutions for neutral stability with those given by Görtler. The two solutions are in approximate agreement.

A second method of solution also is described. This method is believed to offer considerable improvement, provided a high-speed digital computer is available. One case was checked by this second method; the two methods agreed within 2%.

Finally, the stability chart was applied to all the known experimental data concerning the effect of concave curvature on the transition point. The well known parameter $R_\theta\sqrt{\frac{\theta}{r}}$ is shown to be inadequate as an indicator of the transition point. Instead, the experimental data indicate that an apparent amplification factor, $\exp\int\beta\,dx$, is a much better measure. Available results show that transition of this type will occur when $\int\beta\,dx$ reaches a value of about ten.

Author

Availability:
AD 106 824

377. Rogers, K. H.: Preliminary Experimental and Analytical Investigations of a Two-Dimensional Wing With Concave Cutout and Auxiliary Airfoil. Rep. No. NAI-57-1164, Rep. No. BLC-103, Northrop Aircraft, Inc., July 1957.

Transition experiments were conducted in the BLC-wind tunnel in the region of a concave curvature on the lower wing surface of a thin cambered airfoil. The surfaces upstream and downstream of the concave region were flat. A uniform chordwise velocity distribution along the lower wing surface was achieved by means of an auxiliary airfoil located opposite to the lower wing concave surface. Transition due to Taylor-Goertler-type vortices generated by the concave surface occurred downstream of the concave region for an amplification factor $\int\beta\,dx \cong 7$. Similar results for strongly accelerated flow on the lower surface of the wing (at high angle of attack) indicate that the transition due to Taylor-Goertler-type vortices is substantially independent of the chordwise velocity and pressure distribution.

Author

Availability:
N78-78049
SN-24021, Sept. 1957
NAI-57-1164
BLC-103

378. Aihara, Yasuhiko: Stability of the Compressible Boundary Layer Along a Curved Wall Under Görtler-Type Disturbances. Rep. No. 362, Aeronaut. Res. Inst., Univ. of Tokyo, Feb. 1961.

The neutral stability of the compressible laminar boundary layer along a curved wall is examined under three-dimensional disturbances of the form of a row of streamwise vortices. It is an extension to the compressible flow of the well-known Görtler's analysis on the stability of the corresponding incompressible flow. The calculations are carried out only for the two limiting cases in which the Mach number is much less than and much greater than unity respectively. The results indicate the general instability of the compressible boundary layer along a concave wall under three-dimensional disturbances. The critical values of the Görtler parameter $R_\theta\sqrt{(\theta/r)}$ and wave number $\alpha^*\theta$ are reduced as the Mach number is increased.

Author

Availability:
N78-78203
N-95084

379. Hämmerlin, G.: Über die dreidimensionale Instabilität laminarer Grenzschichten. Z. Angew. Math. & Mech., vol. 35, no. 9/10, 1955, pp. 366-367.

380. Tani, Itiro; and Aihara, Yasuhiko: Görtler Vortices and Boundary-Layer Transition. Z. Angew. Math. Phys., vol. 20, Sept. 25, 1969, pp. 609-618.

Current interpretation of the boundary-layer transition in the presence of Görtler vortices. It is suggested that the effect of Görtler vortices on boundary-layer transition on a concave surface is rather indirect in that they are responsible for inducing a spanwise variation of boundary-layer thickness and modifying the development of instability oscillations (Tollmien-Schlichting waves). The breakdown of instability oscillations leading to turbulent motion appears first at the spanwise position where the boundary layer is thickest, the way in which the breakdown proceeds being somewhat different from that in a two-dimensional boundary layer on a flat plate.

Availability:
A70-10539

381. Mzyk, E.: The Effect of Wall Curvature on the Hydrodynamic Stability of a Laminar Boundary Layer. Bull. Acad. Pol. Sci., Ser. Sci. Tech., vol. XVII, no. 4, 1969, pp. 31-38.

Study of the effect of a convex, longitudinal wall on the hydrodynamic stability of a laminar incompressible boundary layer with respect to a small perturbing wave of the Tollmien-Schlichting type. The investigation is based on various assumptions regarding the curvature, the velocity distribution, and the pressure. It is concluded that a small longitudinal curvature of the wall imparts a small instability to the flow and affects the shape of the curve of neutral stability, so that for a positive wall curvature inviscid instability occurs not only for velocity profiles with a positive pressure gradient, but also for profiles with a zero pressure gradient.

Availability:
A69-36587

382. Rintel, Lionel: Görtler Instability of Boundary Layers. Phys. Fluids, vol. 14, no. 4, Apr. 1971, pp. 753-759.

The problem of centrifugal instability of the laminar boundary layer over a concave wall is posed as one of convective instability penetrating in neutrally stable fluid. It is found that the perturbations have a finite wavenumber; the mechanism of penetration is therefore essential for the selection of the shape of the perturbations. The critical conditions for a number of boundary-layer-like profiles are computed and compared with the experimental results. It is found that the stability characteristics of the boundary layer depend on the presence of points of inflection in the velocity profile.

Author

Availability:
A71-27840

383. Bippes, H.: Experimental Study of the Laminar-Turbulent Transition on a Concave Wall in a Parallel Flow. NASA TM-75243, 1978.

The instability of the laminar boundary layer flow along a concave wall was studied experimentally. Detailed observations of these three-dimensional boundary layer phenomena were made using the hydrogen-bubble visualization technique. With the application of stereo-photogrammetric methods in the air-water system it was possible to investigate the flow processes qualitatively and quantitatively. In the case of a concave wall of sufficient curvature, a primary instability occurs first in the form of Görtler vortices with wave lengths depending upon the boundary layer thickness and the wall curvature. At the onset the amplification rate is in agreement with the linear theory. Later, during the non-linear amplification stage, periodic spanwise vorticity concentrations develop in the low velocity region between the longitudinal vortices. Then a meandering motion of the longitudinal vortex streets subsequently ensues, leading to turbulence.

Author

Availability:
N78-21412

384. Mzyk, E.: The Effect of Curvature and Wall Flexibility on the Hydrodynamic Stability of a Laminar Boundary Layer. Fluid Dyn. Trans., vol. 5, pt. II, [1971], pp. 165-173.

The behavior of a laminar incompressible boundary layer flow is theoretically analyzed with respect to its hydrodynamic stability under the influence of curvature of the flow surrounding rigid and flexible walls. The obtained results are compared with the findings of other investigators.

Availability:
A72-18134

385. Kahawita, René A.; and Meroney, Robert N.: The Stability of Parallel, Quasi-Parallel and Stationary Flows. THEMIS Tech. Rep. No. 24 (CER73-74-RK-RNM), Colorado State Univ., Sept. 1973. (Available from DDC as AD 770 883.)

The methods of linear perturbation theory have been used to study the stability of various flows, among them being (1) The stability of boundary layers along concave heated walls; (2) The stability of boundary layers along concave walls with suction; (3) The stability of wall jets along concave and convex walls; (4) The spin up of a two-dimensional cylinder in an infinite medium; (5) The stability of stationary layers of fluid with arbitrary temperature stratification; (6) The stability of natural convection flow along inclined plates. During the course of this work, three different solution techniques were employed; one of them was an approximate analytic technique, the remaining two were numerical. Three-dimensional spatially and temporally amplifying disturbances were considered in the study.

Author

Availability:
N75-76556
AD 770 883

386. Kobayashi, Ryǒji: Taylor-Görtler Instability of a Boundary Layer With Suction or Blowing. AIAA J., vol. 12, no. 3, Mar. 1974, pp. 394-395.

Suction (or blowing) from a slightly concave permeable wall is examined from the viewpoint of effects on the instability of an incompressible two-dimensional laminar boundary layer as manifested by the onset of longitudinal vortices. Emphasis is placed on the role of the normal velocity component in the Taylor-Görtler instability. Suction (or blowing) from a permeable wall induces a notable normal velocity component in the boundary layer, and it is found that the boundary layer is less stable when the normal component is considered.

Availability:
A74-23217

387. Kobayashi, R.: Taylor-Görtler Instability of a Boundary Layer With Suction or Blowing. Rep. No. 289, Inst. High Speed Mech., Tōhoku Univ., vol. 32, 1975, pp. 129-148.

This paper is concerned with centrifugal instability of the two-dimensional incompressible laminar boundary layer along a slightly concave wall to the onset of longitudinal vortices. Attention is concentrated on a role of normal velocity components, which are induced through the permeable concave wall by suction or blowing, in this instability problem. Neutral stability curves representing the relation of the Görtler parameter G to the dimensionless wave-number of the longitudinal vortices and also distributions of the perturbation velocities at the onset of the vortices are presented. The results show that the suction increases the critical value of the Görtler parameter and stabilizes the boundary layer, while the blowing has little influence on the present instability.

Author

Availability:
A76-22672

388. Herbert, Th.: On the Stability of the Boundary Layer Along a Concave Wall. Arch. Mech. Stosow., vol. 28, no. 5-6, 1976, pp. 1039-1055.

Various approaches for investigating the linear stability of the laminar boundary layer along a concave wall with respect to Görtler vortices are compared concerning their order in the two small parameters, wall curvature and inverse Reynolds number, as well as the treatment of the curvature terms. Numerical results show separately the effects of wall curvature, streamline curvature and its finite extent on the neutral conditions. The influence of the growing boundary layer thickness on the stability characteristics is estimated and found to be of first order.

Author

Availability:
A77-29371

389. Molded Wings. Aviat. Age, vol. 17, no. 4, Apr. 1952, pp. 46-53.

This is a report on the work of the R.A.E. with plastic wings. In order to keep the flow over wings laminar, the surface must be very smooth. This fact aroused interest of the Royal Aircraft Establishment in the development of new aircraft materials. The use of plastics in aircraft construction has promise of decreasing aircraft weight, as well as being more economical to manufacture. An overview of manufacturing methods, material properties and structural design is given in this paper.

390. Gordon, J. E.: Plastics and Plastic Structures. Third Anglo-American Aeronautical Conference, Joan Bradbrooke and E. C. Pike, eds., R. Aeronaut. Soc., 1952, pp. 177-198H.

The research which is described is the work of a team at R.A.E. This paper may be considered as a progress report on the use of plastics in aircraft manufacture. Methods of molding plastics, especially of the "Durestos" type, are described. These methods sound more complicated than they are, and probably will be much improved in the future. Aerodynamically smooth surfaces can be realized more easily and more cheaply than with other materials. It remains to be seen whether such surfaces can be maintained under service conditions. Pages 198A through 198H include the discussion that followed the lecture.

Availability:
N78-78245
N-15966

391. Cheranovskiy, O. R.; and Zozulya, V. B.: Plastic Wing With Laminar Profile. FTD-HT-23-400-70, U.S. Air Force, Aug. 26, 1970. (Available from DDC as AD 716 526.)

A brief review is presented of the design and fabrication problems of plane and trapezoidal fiberglass wings with laminar profiles to be used in aerodynamic tests on an automatic airborne laboratory under real flight conditions. Techniques for manufacturing such plastic wings with required specifications and surface roughness and configuration allowances are described. The properties and fabrication of the wing rigging are discussed, and a version of a slotted plastic wing producing laminarization is described. A lower production cost, a simpler manufacturing technology, and higher aerodynamic properties are noted as the advantages of these plastic wings over riveted or wooden wings.

Author

Availability:
N71-19574
AD 716 526

392. King, J. C.; and Trollope, D. H.: A Method of Testing Smooth Wings for Initial Shape and Resistance to Distortion Under Load. R. & M. No. 2531, British A.R.C., 1951.

The development of special smooth wing constructions for laminar-flow aerofoils calls for a simple testing technique to check the suitability of these new designs. In the method now used a short parallel length of wing bounded by ribs is tested under uniform bending with torsion and internal pressure superimposed when necessary. A standard specimen and standard testing technique are described. A review of the existing instruments for measuring surface irregularities is included.

Author

Availability:
N78-78201
N-11529

393. King, J. C.: An Experimental Investigation Into the Suitability of a Corrugated Construction Wing for a Laminar-Flow Aerofoil. R. & M. No. 2530, British A.R.C., 1951.

This report describes a detailed experimental investigation into the structural features of a 6-ft chord wing specimen having thick skin reinforced by spanwise corrugations. The tests included surface distortion, proof and ultimate tests on the specimen and compression tests on two panels. A short length of parallel specimen was used with a simplified test rig built for the purpose.

These tests showed that for this specimen, provided the wing can be made smooth in the first place, it will not be adversely affected by loads imposed in service. The major portion of the surface distortion in flight will be due to the aerodynamic suction; the effect of direct and shear stresses being negligible.

In the ultimate tests failure was due to elastic instability of the skin and corrugations at a compressive stress of 11.1 t/sq in. This compares favourably with the compressive stress at failure of the panels, which, when corrected for the shear stress present in the wing, reduces to 11.3 t/sq in.

Author

Availability:
N78-78209
N-13042

394. Cliett, Charles B.: Structural Comparison of Perforated Skin Surfaces With Other Means of Effecting Boundary-Layer Control by Suction. Aeronaut. Eng. Rev., vol. 12, no. 9, Sept. 1953, pp. 46-54.

The results of a series of studies to determine the structural feasibility of perforated sheet materials, which could be used as a means of effecting boundary-layer control by suction, are presented. These results include the ultimate tensile and shear strengths of perforated plywoods, the ultimate tensile and shear strengths of perforated 24ST-3 aluminum-alloy sheet, and the flexure-fatigue strength of this perforated aluminum-alloy sheet.

Empirical methods of predicting ultimate failure in tension and shear for these perforated materials have been found. A comparison between predicted results by these empirical equations and actual experiment has been made, and good agreement is shown to exist.

From the structural point of view, a comparison of this means of effecting boundary-layer control by suction is made with other methods and materials previously advocated.

Author

395. Mansfield, E. H.: Structural Aspects of Suction Wings. C.P. No. 87, British A.R.C., 1951.

This report considers the structural design problems arising directly from the use of distributed wing suction. Possible types of construction are discussed and estimates are made of the increase in aircraft all up weight due to these constructions and due to the extra power required for suction.

Author

Availability:
N-16790
N78-78810

396. Slagg, W. R.; and Wieder, J. E.: Summary of Structural Investigations of Laminar Suction Wings and of Their Components. Summary of Laminar Boundary Layer Control Research, WADC Tech. Rep. 56-111, U.S. Air Force, Apr. 1957, pp. 254-256. (Available from DDC as AD 130 759.)

It has been shown that 100% laminar flow can be achieved in flight by means of boundary layer suction (for example, through rows of closely spaced holes, relatively few slots or a large number of closely spaced spanwise slots). The practical application of low drag suction to an airplane design requires the integration of the suction system in the structural design and sets forth new design requirements. For high subsonic speed airplanes, the surface waviness has to be kept small at high Reynolds numbers (of the order of 1/1000 in./in. or less). Contour tolerances must be small and camber distortion must be minimized. The external surfaces of a laminar suction airplane should be free of large gaps or steps. Leakage from the inner structure to the outside should be avoided. These pages summarize the work on the structural investigations.

Availability:
N78-76390
N-53889
AD 130 759

397. Dedon, W. W.; Slagg, W. R.; and Pfenninger, W.: Structural Design Considerations for Low Drag Boundary Layer Control. NAI-55-945, Rep. No. BLC-81, Northrop Aircraft, Inc., Oct. 1955. (Available from DDC as AD 89 596.)

Very low profile drags have been obtained by keeping 100% laminar flow at high Reynolds numbers by means of boundary layer suction in wind tunnels and in flight (References 12 and 13).

These drag reductions have profound effects on range, altitude, payload, fuel consumption, power plant requirements and other performance parameters. However, obtaining the maximum benefit from laminar flow requires the complete integration of the aerodynamic, propulsive and structural systems.

The structural designer is faced with a most exacting task. The purpose of this paper is to familiarize him with the principles that are unique to the design of a wing incorporating low drag boundary layer control. Many of the requirements of such a wing are so unusual that some general discussion of methods and reasons should be greatly expeditious.

What are believed to be the most important deviations from conventional design considered here are:

(1) Control of the physical condition of the outer skin surface

(2) Control of the distortions of the airfoil section

(3) Incorporation of internal ducting with a minimum weight penalty

(4) Aerodynamically and structurally efficient methods for conducting air through the outer skin surfaces of the aircraft.

Author

Availability:
SN-24021, Oct. 1955
NAI-55-945
BLC-81
AD 89 596
N79-75725

398. Wieder, J.; and Pfenninger, W.: Structural Aspects of Low Drag Suction Airfoils. Paper No. 61-150-1844, Inst. Aerosp. Sci., June 1961. (Also available in Summary of Laminar Boundary Layer Control Research, Volume II, ASD-TDR-63-554, U.S. Air Force, Mar. 1964, pp. 794-800. (Available from DDC as AD 605 186.))

A description of the structure of low drag suction wings is presented, keyed to a generalized high subsonic wet wing. The results of component load tests, corrosion effects, surface irregularities, concentration factors, and the effects on strength and rigidity are discussed.

Author

Availability:
N65-25560
AD 605 186

399. Worth, Robert N.: Skin Ducting System Configurations for LFC Aircraft Main Structural Box. Summary of Laminar Boundary Layer Control Research - Volume II, ASD-TDR-63-554, U.S. Air Force, Mar. 1964, pp. 801-808. (Available from DDC as AD 605 186.)

A wing skin system configuration for a boundary layer control (BLC) aircraft is described. It is a double skin design with extensive use of honeycomb sandwich material, and can provide efficient support for binding and torsional loads, and an efficient ducting system which allows the passage of suction air from the wing surface to the compressor system. This configuration consists of a basic structural outer skin supported on multiple stringers, and an inner skin below the stringers which imparts stability to the stringer flanges and also provides a lower wall to complete the ducting passage.

Availability:
N65-25570
AD 605 186
N65-25560

400. Worth, R. N.; and Slagg, W. R.: A Method of Manufacture of Suction Slots for a Laminar Suction Airplane. Rep. No. BLC-55, Rep. No. NAI-54-490, Northrop Aircraft, Inc., July 1954. (Available from DDC as AD 54 971.)

The success of a laminar suction airplane is to a large extent dependent upon an efficient and producible structural design. Of the number of possible methods to manufacture such a wing as presented in report BLC-40, this report will deal only with the manufacture of a large number of closely spaced, fine slots. The primary problems to be solved are the fabrication of a surface with a sufficiently small surface waviness and roughness, with slots of close tolerances.

This report sets forth the methods investigated with the individual problems that must be overcome. The recommended solution proposed here of cutting the slots with slitting saws after assembly of the panels is supported by test results included herein.

Author

Availability:
SN-24021, July 1954
BLC-55
NAI-54-490
AD 54 971

401. LFC Manufacturing Engineering: Laminar Flow Control Demonstration Program Final Report - LFC Manufacturing Techniques. NOR-61-142 (Contract AF33(600)-42052), Northrop Corp., Mar. 1964. (Available from DDC as AD 439 329.)

The manufacturing techniques required to build the laminar flow control differed from those used on conventional turbulent aircraft for two basic reasons: The X-21A wings required extremely smooth wave-free external surfaces, and provisions had to be incorporated for removing by suction a portion of the boundary layer from the wing surfaces. Extensive manufacturing effort was expended in several major areas: (1) the development of panel bonding fixtures and methods to maintain the extreme smoothness criteria of the external wing surfaces; (2) the milling, drilling, and slotting equipment to maintain size and location accuracy of wing slot and hole patterns; (3) the building-in of the air ducts as part of the basic structure for air passage through the wing; and (4) the development of modulation valves for the suction system. Results of this effort indicate that the manufacture of airplane structure to laminar flow control tolerance is feasible, and that this type of manufacture can be done with the present day state-of-the-art equipment. Appendices are presented that deal with wing assembly sequence, bond fixture perimeters, bond fixture fabrication sequence, bond tool material sketches, a panel trim sketch, tornetic controlled drilling and sawing specifications, tornetic settings and depth control, and saw blade specifications.

Availability:
N64-25616
NOR-61-142
AD 439 329

402. Weiss, D. D.; and Lindh, D. V.: Development of the Technology for the Fabrication of Reliable Laminar Flow Control Panels. NASA CR-145124, 1977.

Various configurations of porous, perforated and slotted materials were flow tested to determine if they would meet the LFC surface smoothness and flow requirements. The candidate materials were then tested for susceptibility to clogging and for resistance to corrosion. Of the materials tested, perforated titanium, porous polyimide, and slotted assemblies demonstrated a much greater resistance to clogging than other porous materials.

Author

Availability:
N77-18131

403. Meade, L. E.; Kays, A. O.; Ferrill, R. S.; and Young, H. R.: Development of the Technology for the Fabrication of Reliable Laminar Flow Control Panels. NASA CR-145168, 1977.

Materials were assessed and fabrication techniques were developed for use in the manufacture of wing surface materials compatible with the application of both aluminum alloys and nonmetallic composites. The concepts investigated included perforations and slots in the metallic test panels and microporosity and perforations in the composite test panels. Perforations were produced in the metallic test panels by the electron beam process and slots were developed by controlled gaps between the metal sheets. Microporosity was produced in the composite test panels by the resin bleed process, and perforations were produced by the fugitive fiber technique. Each of these concepts was fabricated into test panels, and air flow tests were conducted on the panels.

Author

Availability:
N77-22178

404. Swinford, G. R.: A Preliminary Design Study of a Laminar Flow Control Wing of Composite Materials for Long Range Transport Aircraft. NASA CR-144950, 1976.

The results of an aircraft wing design study are reported. The selected study airplane configuration is defined. The suction surface, ducting, and compressor systems are described. Techniques of manufacturing suction surfaces are identified and discussed. A wing box of graphite/epoxy composite is defined. Leading and trailing edge structures of composite construction are described. Control surfaces, engine installation, and landing gear are illustrated and discussed. The preliminary wing design is appraised from the standpoint of manufacturing, weight, operations, and durability. It is concluded that a practical laminar flow control (LFC) wing of composite material can be built, and that such a wing will be lighter than an equivalent metal wing. As a result, a program of suction surface evaluation and other studies of configuration, aerodynamics, structural design and manufacturing, and suction systems are recommended.

Author

Availability:
N76-25146

405. Pfenninger, W.: Propellers for Long Range Laminar Suction Airplanes Flying at High Subsonic Speeds. Rep. No. BLC-37, Northrop Aircraft, Inc., Apr. 1954. (Available from DDC as AD 52 586.) (Also discussed in Summary of Laminar Boundary Layer Control Research, WADC Tech. Rep. 56-111, U.S. Air Force, Apr. 1957, pp. 206-252. (Available from DDC as AD 130 759.))

Availability:
SN-24021, Apr. 1954
BLC-37
AD 52 586
N78-76390
N-53889
AD 130 759
N79-75734

406. Newton, J. S.; and Pfenninger, W.: Studies of Gas Turbine Powerplants Suitable for Laminar Suction Airplanes. Rep. No. BLC-49, Rep. No. NAI-54-485, Northrop Aircraft, Inc., July 1954. (Available from DDC as AD 54 971.) (Also included in Summary of Laminar Boundary Layer Control Research, WADC Tech. Rep. 56-111, U.S. Air Force, Apr. 1957, pp. 217-220. (Available from DDC as AD 130 759.))

Laminar suction airplanes can be efficiently propelled during cruising by means of gas turbines, fed with undisturbed ram air, driving separate suction compressors and, in certain cases, additional ducted fans or propellers. This report presents results of cycle calculations of such powerplants driving a long range high altitude laminar suction airplane at high subsonic speed. Various powerplant arrangements and suction compressor drive systems as well as some solutions for off-design conditions (take-off, climb, flight at very high altitudes, supersonic dash) will be discussed in subsequent reports.

Gas turbines fed with suction air show increased specific fuel consumption and will therefore not be discussed further.

Author

Availability:
SN-24021, July 1954
BLC-49
NAI-54-485
AD 54 971
N78-76390
N-53889
AD 130 759

407. Newton, J. S.: Effects of Power Plant Components on the Performance of Laminar Suction Airplanes. Rep. No. NAI-54-798 (BLC-63), Northrop Aircraft, Inc., Oct. 1954. (Available from DDC as AD 66 065(a).)

Availability:
SN-24021, Nov. 1954
NAI-54-798 (BLC-63)
AD 66 065(a)

408. Pfenninger, W.: Propulsion Studies of Laminar Suction Airplanes of Moderate Size. Rep. No. NOR-59-260 (BLC-118), Northrop Aircraft, Inc., Apr. 1959.

The purpose of the study is to show how turboprop engines like the Rolls Royce Tyne or the Allison T61 can be adapted to propel a moderately large low drag BLC airplane efficiently at high subsonic cruising speeds.

Availability:
SN-24021, Apr. 1959
N79-75730
NOR-59-260 (BLC-118)

409. Pfenninger, W.: Design Considerations of Propulsion Systems for Low Drag BLC Airplanes Cruising at High Subsonic Speeds. Rep. No. NOR-59-418 (BLC-122), Northrop Aircraft, Inc., July 1959.

Availability:
SN-24021, July 1959
NOR-59-418 (BLC-122)
N79-75733

410. Pfenninger, W.: Cycle Calculations of the Propulsion System of a Subsonic Laminar Suction Airplane With Turbofan Gas Turbines With Suction Compressors Driven by a Bleed and Burn Cycle. Rep. No. NAI-58-489 (BLC-110) (Contract AF 33(616)3165), Northrop Aircraft, Inc., July 3, 1958.

For a turbofan engine of large bypass ratio, the required bleed air quantities and the power to drive the suction compressors for best cruise are sufficiently low to render the bleed and burn cycle drive system for the suction compressors a practical, efficient, and flexible drive method with a low noise level.

Author

Availability:
SN-24021, June 1958
NAI-58-489 (BLC-110)
N79-75736

411. Connors, J. W.; Pfenninger, W.; and Smith, C. B.: Propulsion Systems for Laminar Flow Aircraft. Aerosp. Eng., vol. 20, no. 8, Aug. 1961, pp. 16-17, 70-79.

It is expected that within the near future the first laminar flow aircraft will be a reality and that thereafter such installations will become common. In aircraft of this type, the propulsion system must provide a large percentage of its power to operate internal flow pumps, and is more intimately integrated with the airframe than has been the case in the past. The distinction between what is drag and what is thrust ceases to be clear; the significance of such traditional parameters as specific fuel consumption breaks down and new criteria for optimizing the installation arise. This paper undertakes to classify the various possible forms of propulsion systems for this application, determines the criteria for optimizing such configurations, establishes a rational division between aircraft and propulsion systems, and presents representative propulsion system data required by the aircraft designer to undertake preliminary design analysis of aircraft of this type.

Author

Appendix A: Compatible Definitions of Lift-to-Drag Ratio and Specific Fuel Consumption.
Appendix B: Relationship Between Suction Drag and Viscous Drag.
Appendix C: Criteria for Minimum Specific Fuel Consumption.

Availability:
N79-70044
N-92268

412. Torenbeek, Ir. E.: The Propulsion of Aircraft With Laminar Flow Control. Rep. VTH-150, Dep. Aeronaut. Eng., Delft Univ. Technol., Nov. 1968.

A systematic approach is given for a cycle analysis of various practical suction and propulsion systems for gas-turbine powered subsonic aircraft with laminar flow control. Definitions of thrust, drag, and various system efficiencies are discussed, and the range parameter is evaluated as a criterion for cruise performance assessment. Generalized calculations and diagrams are presented for preliminary estimation of the range parameter for aircraft with arbitrary extent of laminarization. Conditions for the optimum value of system parameters are derived, resulting in maximum specific range.

Author

Availability:
N69-27475

413. Wattson, R. K., Jr.: Investigation of Boundary Layer Pumping Systems. Rep. No. 1309-5 (Contract NONR 856(00)), Cessna Aircraft Co., Sept. 1952.

This is a preliminary study of systems for the pumping of air used in boundary layer control on aircraft. Data on weights and performance of power units for these systems were gathered, and an attempt was made to predict weights and performances of complete systems. Thermodynamic analyses were prepared for systems which were thought to show promise. A study was made of the application of certain of these systems to a hypothetical fighter-type aircraft in an effort to anticipate preliminary design problems for aircraft designed to use boundary layer control.

Author

Availability:
N-23171

414. Davidson, I. M.: On Engine Considerations Associated With Aircraft Boundary Layer Control by Suction. Nat. Gas Turbine Estab. Memo. No. M.172., British Min. Supply, Feb. 1953.

Availability:
X79-70266
N-23899

415. Conrad, E. William: Preliminary Analysis of Performance of Turbojet Engines Used as Pumps for Boundary-Layer Control. NACA RM E55E20a, 1955.

The effects of engine performance of using turbojet engines as pumps for boundary-layer control by suction at the engine inlet or by bleeding air from the compressor outlet were calculated for two current production engines. Limited experimental data for a third engine currently in production are included with intercompressor bleed. Compressor-outlet bleed flows of between 32 and 43 percent could be obtained before the engine net thrust was reduced to zero. For the use of suction, the maximum flow was equal to the engine air flow. A variable-area turbine would offer no advantage other than allowing higher bleedoff pressure.

Author

Availability:
N78-78576

416. Edwards, Jay Thomas: Distributed Boundary Layer Suction Utilizing Wing Tip Effects. M.S. Thesis, A & M Coll. of Texas, May 1962. (Available from DDC as AD 276 394.)

The effect of a self-induced boundary layer suction device on the performance of a three-dimensional NACA 23015 airfoil was experimentally determined. Von Karman's momentum equation, as adapted by Prandtl to include suction through the surface, was used to calculate the suction distribution, quantity flow requirements and distribution of perforations for control of the boundary layer growth. From these calculations, perforations of the model were made in an effort to maintain a constant momentum thickness over the porous area. The low pressure area on the upper surface of a Hoerner tip was used as the pumping device to supply the necessary pressure differential to draw air from the upper surface of the wing. Thinning of the boundary layer in this fashion showed an improvement in the drag polar, and lift curve slope without the disadvantage of added weight, power requirements, or increased maintenance.

Author

Availability:
N-110,717
AD 276 394

417. Air Pumping System for a Laminar Flow Control Aircraft. [Preprint] 745C, Soc. Automot. Eng., Sept. 1963.
Collins, W. L.; and Monahan, W. A., Jr.: Part 1.
Getz, D. L.; and Wallace, F. B., Jr.: Part 2.

This report is a description of the design and operation of the pumping system used to remove boundary-layer air from the wing surfaces of X-21A laminar flow control airplanes. Included are comments on pumping system requirements and design characteristics for future applications. Discussed are the initial problem statement, system selection, and system operation. Pumping design and development are outlined.

Availability:
A63-25875

418. Fromme, W. M.: A Note on the Effects of Some Emergency Conditions on the Performance of Transport Type Airplanes With and Without Laminar Flow Control. Norair Div., Northrop Corp., Dec. 1961.

Results of a study on selected emergency conditions are presented for four transport airplanes, two of which incorporate Laminar Flow Control. It is shown that although the Laminar Flow Control airplanes have higher thrust loadings (engines of lower thrust) than the equivalent turbulent flow designs, their performance under one-engine-out emergency conditions meets all operational requirements for transport aircraft. Further, the additional weight and complexity of "cross over" provisions in the suction system, to maintain complete laminar flow on all LFC surfaces with one engine out, does not appear to be justified by the one-engine-out range performance benefits obtained.

Author

Available from STIF by author and title.

419. Anscombe, A.; and Illingworth, L. N.: Wind-Tunnel Observations of Boundary-Layer Transition on a Wing at Various Angles of Sweepback. R. & M. No. 2968, British A.R.C., 1956.

Visual observations have been made of boundary-layer transition on a wind-tunnel model of constant chord at zero lift over a range of sweepback angles from zero to 50 deg. At each angle above 25 deg, a critical speed could be found within the speed range of the tunnel (400 ft/sec) at which striations appeared within the laminar boundary layer, while the transition line itself lay at 50 per cent to 60 per cent chord. As the speed was further increased, transition started to move forward, finally occurring close to the leading edge. The wind speed at which the striations appeared and the forward movement of transition started, decreased with increasing angle of sweepback.

Author

Availability:
N78-78498

420. Gregory, N.: Transition and the Spread of Turbulence on a 60° Swept-Back Wing. J. R. Aeronaut. Soc., vol. 64, no. 597, Sept. 1960, pp. 562-564.

Two interesting flow phenomena have been observed during the course of some transition measurements carried out on a swept-back wing with a curved tip. Firstly, the influence of leading-edge sweep angle on the type of instability responsible for transition has resulted in two distinct types of transition occurring simultaneously over different portions of the wing under certain critical conditions. Secondly, unlimited spanwise turbulent contamination of the flow was observed with an excrescence located close to the leading edge. The circumstances in which this occurred are believed to be somewhat exceptional, although much further work is desirable on this point.

The experiments were made in the N.P.L. 13 ft. x 9 ft. wind tunnel on a 60° swept-back RAE 101 wing 9 per cent thick. The chord of the inboard part of the wing was 36 in. along wind and the wing had a curved tip. Details of the plan form are given by Garner and Walshe. The china-clay technique was used to show the transition front over the whole span of the wing.

Author

421\. Gregory, N.; and Love, E. M.: Laminar Flow on a Swept Leading Edge: Final Progress Report. NPL AERO MEMO. No. 26, British A.R.C., Oct. 1965.

This note describes the further work carried out after the account given in reference (1) on the state of the attachment line flow on the leading edge of an 18 in. chord model with variable sweep in the NPL 13 ft x 9 ft and 9 ft x 7 ft wind tunnels.

The model was fitted with an improved bump with permanent flush hot films (section 4), but test with the instrumentation (section 1) showed that hot wires were needed to observe the details of turbulent flow decay (section 6). Tentative critical roughness data for two-dimensional wires were confirmed and results also obtained with isolated conical excrescences (section 2). Turbulent spot propagation speeds were measured over a range of Reynolds numbers (section 3). The bump was more successful than the previous version modelled in plasticene (section 5) but it is observed that suction devices are likely to be more effective in practice (section 7). A more detailed account of whole investigation is in course of preparation.

Author

Availability:
N79-71089
CN-142467

422\. Gaster, M.: On the Flow Along Swept Leading Edges. CoA-AERO-167, College of Aeron., Cranfield (England), Oct. 1965. (Also available in Aeronaut Q., vol. XVIII, pt. 2, May 1967, pp. 165-184.)

Flight tests on a suction wing showed that turbulence, generated at the wing root, can propagate along the leading edge and cause the whole flow to be turbulent. The flow on the attachment line of a swept wing was studied in a low speed wind tunnel with particular reference to the problem of turbulent contamination. The critical Reynolds number, R_{θ_L}, of the attachment line boundary layer for the spanwise spread of turbulence was found to be about 100 for sweep angles in the range 40°-60°. A device was developed to act as a barrier to the turbulent root flow so that a clean laminar flow could exist outboard. This device was shown to be effective up to an R_θ of at least 170. With the aid of this bump experiments were possible on a laminar boundary layer at Reynolds numbers above the lower critical value. The behavior of Tollmien-Schlichting waves was also investigated by exciting the flow with sound emanating from a small hole on the attachment line. Measurements of the perturbation phase and amplitude were made downstream of the source.

Author

Availability:
N66-31958

423. Bacon, John W., Jr.; and Pfenninger, W.: Transition Experiments at the Front Attachment Line of a 45° Swept Wing With a Blunt Leading Edge. AFFDL-TR-67-33, U.S. Air Force, June 1967. (Available from DDC as AD 818 962.)

Availability:
X67-23005
AD 818 962

424. Pfenninger, W.; and Bacon, J. W., Jr.: Amplified Laminar Boundary Layer Oscillations and Transition at the Front Attachment Line of a 45° Swept Flat-Nosed Wing With and Without Boundary Layer Suction. Viscous Drag Reduction, C. Sinclair Wells, ed., Plenum Press, 1969, pp. 85-105.

Discussion of experiments performed in the Northrop 7 x 10 ft tunnel, in which transition at the attachment line of a 45° swept flat-nose wing was observed. For a wing with suction through closely spaced chordwise slots, the wind tunnel screen turbulence was found to induce regular amplified attachment-line boundary layer oscillations. The oscillations were generally modulated and superimposed on random low-frequency oscillations induced by free-stream large-scale eddies. The high-frequency boundary-layer velocity fluctuations arising near the attachment line were found to grow, leading finally to turbulent spots in combination with the random low-frequency oscillations. Without suction, transition started at attached line transition Reynolds numbers of 240 and 310 at potential flow velocity/kinematic viscosity ratios of 5.5×10^6 and 3.5×10^6, respectively.

Availability:
A69-33251

425. Kozlov, L. F.; and Tsyganiuk, A. I.: Velocity Pulsations and Their Spectral Levels in a Boundary Layer With Suction. Gidromekhanika, no. 31, 1975, pp. 21-25.

The experiments described confirmed the effectiveness of boundary layer control by distributed suction of small amounts of water from the boundary layer. In the frequency range between 5 and 600 Hz, the turbulent velocity pulsation levels were found to decrease by 10 to 30 dB.

Availability:
A76-25729 (Original Russian)

426. Gorlin, S. M.; and Ismail, Mokhamed Nabil Ali: Effect of the Level of Flow Turbulence in a Wind Tunnel on the Characteristics of Laminar Profiles. Vostn., Moskovskii Univ., Ser. I - Mat., Mekh., vol. 20, Nov.-Dec. 1965, pp. 60-63.

Results from some experimental studies of wind-tunnel testing techniques. It is shown that initial wind-tunnel turbulence in a test must be no more than 0.1 to 0.15% and that the Reynolds number must not be less than 10^6, if aerodynamical peculiarities are to be revealed in laminar profiles.

Availability:
A66-17857 (Original Russian)

427. Hopkins, Edward J.; Keating, Stephen J., Jr.; and Bandettini, Angelo: Photographic Evidence of Streamwise Arrays of Vortices in Boundary-Layer Flow. NASA TN D-328, 1960.

Photographs are presented of various models coated with fluorescent oil to show evidence of surface vortices at a Mach number of 3.03. Vortex formation was evidently present on models with forward-facing steps, rearward-facing steps, wires, discrete surface particles, or unswept flat surfaces with sharp leading edges. Some photographs are also presented for the models coated with a sublimation material which clearly indicates the location of boundary-layer transition; however, it does not show the vortices as clearly as the fluorescent oil. The study was made on the models at an angle of attack of 0° at unit Reynolds numbers of 7.7 and 10.7 million per foot. The spacing of the vortices as indicated by the flow studies on the unswept model was smaller at the higher Reynolds number in accordance with Görtler's theory. The flow studies also indicated that stable surface vortices produced by either steps or surface roughness persisted over model areas known to have turbulent boundary layers.
Author

Availability:
N62-70902

428. Kuethe, A. M.; and Deitrick, R. A.: Hot-Wire Measurements on a Boundary Layer Control Body of Revolution. Rep. No. 2644-1-P, Eng. Res. Inst., Univ. of Michigan, June 21, 1957. (Available from DDC as AD 140 583.)

Availability:
SN-24021, June 1957
AD 140 583

429. Kuethe, A. M.: Hot-Wire Measurements on a Boundary-Layer Control Body of Revolution. 2644-2-F, Northrop Aircraft, Inc., Sept. 12, 1957. (Appendix to NAI-58-335.)

The purpose of the work described was to determine the source of the generation of turbulent bursts on the ellipsoidal body of revolution. These bursts resulted in a turbulent boundary layer at the higher Reynolds numbers even with the highest suction quantities obtainable.

In the final report, the work was extended to a higher speed and more reasonable suction.

Availability:
SN-24021, Oct. 1957
NAI-58-335

430. Schuh, H.: The R.A.E. 4-ft × 3-ft Experimental Low-Turbulence Wind Tunnel. Part IV. Further Turbulence Measurements. R. & M. No. 3261, British A.R.C., 1962.

Further measurements of turbulence in the working section are given with 2 and 3 screens in the bulge. The extended region of high intensity turbulence near the walls of the working section, which was observed with 9 screens in the bulge, disappeared when the number of screens was reduced from 9 to 2 or 3. The longitudinal component of turbulence is approximately independent of the number of screens; the lateral component does not change, if the number of screens is reduced from 9 to 3, but increases by a factor 2.5 to 3, if the number of screens is further reduced from 3 to 2.

In order to explain the origin of the turbulence in the working section, further turbulence measurements have been made at the end of the second diffuser, before the rapid expansion and in the bulge. The intensities of turbulence are about 12 percent of mean speed at the end of the second diffuser and drop to about 4 to 6 percent before the rapid expansion. However, this turbulence seems to be reduced by the screens in the rapid expansion and in the bulge below the level of disturbances set up by inhomogeneities of the last screen. These disturbances are the origin of the lateral components of turbulence in the working section. The extended region of high intensity turbulence near the walls of the working section is connected with the existence of a return flow in the bulge, but several possible explanations exist as to how this produces the region of high intensity turbulence in the working section.

Author

Availability:
N62-15254

431. Squire, H. B.; and Winter, K. G.: The Royal Aircraft Establishment 4 ft × 3 ft Experimental Low Turbulence Wind Tunnel. Part I - General Flow Characteristics. R. & M. No. 2690, British A.R.C., 1953.

The 4 × 3 ft Wind Tunnel was erected as a model of larger tunnels to investigate unconventional design features directed towards obtaining a high standard of flow. Diffusers of 5 deg cone angle are used, except for the rapid expansion through three wire-gauze screens up to the maximum section. The contraction ratio is 31.2:1 and nine screens are fitted in the maximum section. A speed control is used operating independently of the fan by means of a by-pass duct.

The velocity distribution across the working-section is constant to $\pm\frac{1}{4}$ per cent. The standard deviation of the velocity with time measured over a period of 50 sec is 0.03 per cent.

The flow in the diffusers shows no tendency to separate and the velocity distribution approaching the first screen is very satisfactory.

The installation of cascades with gap/chord ratio of ¼ gives uniform outlet flow without appreciable increase in the pressure drop.

There is no separation in the rapid expansion of the bulge, but the flow in the contraction cone is not satisfactory. A longer contraction would have been advantageous.

The power factor has been measured as 0.27 with all screens fitted but could be improved slightly if all the leaks were sealed.

The speed control is satisfactory in operation.

Author

Availability:
N78-78496
N-26854

432. Schuh, H.; and Winter, K. G.: R.A.E. 4ft × 3ft Experimental Low Turbulence Wind Tunnel. Part II: Measurements of Longitudinal Intensity of Turbulence. Rep. AERO.2285, British R.A.E., Aug. 1948.

Availability:
X79-70774

433. Schuh, H.; and Winter, K. G.: Investigation of the Turbulence Characteristics of an Experimental Low-Turbulence Wind Tunnel. Symposium on Turbulence, NOLR 1136, U.S. Naval Ord. Lab., July 1, 1950, pp. 49-66.

This paper describes measurements of the longitudinal intensity of turbulence in the RAE 4 foot x 3 foot wind tunnel. The tunnel was built between 1944 and 1946 to provide information on the design of tunnels of very low turbulence. In addition to the hot-wire tests, some measurements of the noise intensity were made since it was known that in low turbulence tunnels there may be considerable contribution to the apparent turbulence from the particle velocities associated with noise.

Author

Availability:
N79-70099
N-264

434. Wortmann, F. X.: Experimental Investigations on New Laminar Profiles for Gliders and Helicopters. TIL/T.4906, British Minist. Aviat., Mar. 1960.

Based on theoretical concepts, new laminar aerofoil sections have been designed and tested in a low turbulence wind tunnel together with two NACA laminar aerofoil sections at Reynolds numbers between 0.7×10^6 and 1.8×10^6. The theoretical concepts had to be completed and corrected. At the same low drag range, the aerofoil sections of the final design show a reduction in drag of 15 to 20 per cent or, for the same drag, a 25 per cent increase of the low drag range when compared with the corresponding NACA aerofoil sections.

Author

Availability:
N78-78550
N-87474

435. Speidel, L.: Measurements Made on Two Laminar Profiles for Gliders. TIL/T.4905, British Minist. Aviat., Feb. 1960.

The laminar aerofoil section FX 1057-816 theoretically developed for a glider by F. X. Wortmann, and the corresponding American laminar aerofoil section NACA $65_{(215)}$-714 have been measured over the range of Reynolds numbers from 0.6×10^6 to 1.6×10^6. The profile drag was obtained from wake traverse measurements, the normal force and the moment coefficients from integration of the pressure distribution. A comparison of the polar diagrams gives the same minimum drag but a higher design c_a and a wider trough of low drag than for the NACA aerofoil section.

Author

Availability:
N-86774
N78-78790

436. Preston, J. H.: The Boundary-Layer Flow Over a Permeable Surface Through Which Suction is Applied. R. & M. No. 2244, British A.R.C., 1948.

A brief review of existing work is given and the possibility of certain simple solutions for velocity distributions of the type $U = kx^m$ with their appropriate suction distribution is indicated. An improved approximate calculation of the "entry flow" along a flat plate, through which constant suction is applied, is given in some detail. Also Prandtl's original calculation (based on the momentum equation) for boundary-layer flow with constant suction and a constant adverse velocity gradient is repeated, using Howarth's accurate solution for flow without suction. It is also demonstrated (subject to the accuracy of the approximations) that distributed suction should be much more economical in quantity than suction flow through the minimum number of isolated slots required to prevent separation in the flow under a constant adverse velocity gradient.

Practical applications of porous suction are then considered and illustrated by simple examples. These fall under two headings:- (a) the stabilisation of laminar flow against disturbances, (b) the prevention of separation.

It is also suggested that porous suction could be used as a valuable research tool to thin the boundary layer and thus simulate high Reynolds number conditions at small test Reynolds numbers for both incompressible and compressible flow.

Some consideration is given to the practical realisation of a porous surface which approximates to the mathematical concept. It is concluded that porous bronze, made by sintering metallic powder, is the most suitable existing material for laboratory experiments. There seems to be no reason why a similar "surface" should not be made in light alloy for the flight applications. It is considered that the simulation of a porous surface by the use of isolated slots is not suitable unless their spacing and width are small compared with the boundary-layer thickness.

It is concluded therefore that porous suction may have important practical applications to flight at both small and large C_L's. Experiments are needed to confirm the ideas put forward in this report. Also accurate solutions of the boundary-layer equations for the flow under an adverse pressure gradient with porous suction are required to check the approximate treatment used herein.

Author

Availability:
N65-89827

437. Wuest, W.: Development of a Laminar Boundary Layer Behind a Suction Point. NACA TM 1336, 1952.

A theoretical investigation is made of the development of a laminar boundary layer behind a suction slot that is assumed to cut off part of the boundary layer without exerting any sink effect. The development, which is approximate, is based on the heat conduction equation. The heat conduction equation enters the analysis through a linearization of the Prandtl-Mises form of the boundary-layer equation.

Availability:
N78-78543

438. Wuest, W.: Näherungweise Berechnung und Stabilitätsverhalten von laminaren Grenzschichten mit Absaugung durch Einzelschlitze. Ing-Arch., Bd. XXI, no. 2, 1953, pp. 90-103.

Author gives approximate computation of development of laminar boundary layer along a flat plate with suction slots. Stability of the laminar flow with the resulting velocity distributions is computed by the Tollmien method. Purpose is to compare stabilization obtained with slots with that for continuous suction.

Author concludes that critical Reynolds number cannot be increased very much by series of slots except for small velocity and large boundary-layer thickness.

Author notes the several assumptions made, including use of one-parameter family of velocity distributions, neglect of sink pressure field of slots, and application of Tollmien theory to periodic variation of boundary layer.

Abstract Courtesy APPLIED MECHANICS REVIEWS

Availability:
N-60686

439. Ulrich, A.: Theoretical Investigation of Drag Reduction in Maintaining the Laminar Boundary Layer by Suction. NACA TM 1121, 1947.

Maintenance of a laminar boundary layer by suction was suggested recently to decrease the friction drag of an immersed body, in particular an airfoil section. The present treatise makes a theoretical contribution to this question in which, for several cases of suction and blowing, the stability of the laminar velocity profile is investigated. Estimates of the minimum suction quantities for maintaining the laminar boundary layer and estimates of drag reduction are thereby obtained.

Author

Availability:
N78-78544

440. Fabula, A. G.: Theoretical Laminar Boundary Layer Development and Transition on a Reichardt Ovoid With Area Suction. Tech. Note P508-3, U.S. Naval Ord. Test Stat., July 1959.

The zero-yaw, incompressible flow case of laminar boundary-layer development and transition is calculated for a particular body of revolution which will be tested in a towing basin. The modified Schlichting analysis given in NACA TN 4350 is used to consider both the case of a solid shell and of nearly uniform suction applied to the boundary layer to prevent transition. The calculations show that the neutral-stability points with respect to Tollmien-Schlichting waves occur just before the point at which suction will begin. However because of the short length in which wave amplification occurs before suction, transition is not expected from this cause. Roughness particles as small as approximately 0.001 inch in height could cause transition near the nose for the highest test speed of 45 knots.

Author

Availability:
N79-70027
N-73121

441. Owen, P. R.; and Randall, D. G.: Boundary Layer Transition on a Sweptback Wing: Effect of Incidence. Tech. Memo. No. Aero. 375, British R.A.E., Oct. 1953.

Some of the results obtained in previous papers by the authors on boundary layer transition on a sweptback wing are summarised. The method employed by the authors to discuss the stability of the laminar boundary layer on a sweptback wing is used to investigate the effect of incidence on the stability. The flow in the boundary layer over a wing with an RAE.102 section is considered for various angles of incidence. It is found that the flow is more stable on the upper surface and less stable on the lower surface than for the case of no incidence. The decrease in the stability of the flow over the lower surface with increase of C_L is considerable.

Author

Availability:
N78-78555
N-36985

442. Hirschel, E. H.: The Influence of the Free-Stream Reynolds Number on Transition in the Boundary Layer on an Infinite Swept Wing. Fluid Motion Problems in Wind Tunnel Design, AGARD-R-602, Apr. 1973, pp. 1-1 - 1-11.

The three-dimensional compressible laminar boundary layer on an infinite swept wing at different sweep angles is calculated and stability and transition criteria are applied to it for free-stream Reynolds numbers ranging from values possible nowadays in transonic wind tunnels to values typically for full-scale flight. The distribution of the inviscid flow is taken from experiments on airfoils, and exhibits for subsonic free stream Mach numbers supersonic regions terminating in shock waves at about 20 percent chord length. Results are given for four different wing sections. The techniques employed and their shortcomings are discussed.

Author

Availability:
N73-26279

443. Beasley, J. A.: Calculation of the Laminar Boundary Layer and Prediction of Transition on a Sheared Wing. R. & M. No. 3787, British A.R.C., 1976.

A method is described of calculating the laminar boundary layer in incompressible flow on a sheared, infinite wing; the boundary layer equations are solved by a finite difference procedure. Transition from laminar to turbulent flow following leading-edge contamination, cross-flow instability or instability of the Tollmien-Schlichting type, and re-laminarization are considered. The suitability of existing criteria for predicting transition, when applied to a sheared wing, is investigated by comparing theoretical estimates with the experimental results of Boltz, Kenyon, and Allen.

Author

Availability:
N77-21058

444. Carter, James E.: STAYLAM: A FORTRAN Program for the Suction Transition Analysis of a Yawed Wing Laminar Boundary Layer. NASA TM X-74013, 1977.

A computer program called STAYLAM is presented for the computation of the compressible laminar boundary-layer flow over a yawed infinite wing including distributed suction. This program is restricted to the transonic speed range or less due to the approximate treatment of the compressibility effects. The prescribed suction distribution is permitted to change discontinuously along the chord measured perpendicular to the wing leading edge. Estimates of transition are made by considering leading edge contamination, cross flow instability, and instability of the Tollmien-Schlichting type. A program listing is given in addition to user instructions and a sample case.

Author

Availability:
N77-18390

445. Kozlov, L. F.: Laminar Boundary Layer in the Presence of Suction. NASA TT F-602, 1970.

This monograph attempts to systematically expound the theory of laminar boundary layer control by means of suction of fluid through the porous surface of a body. The boundary layer of an incompressible fluid is studied, and the relevant differential equations are derived. The available exact solutions to the equations for a laminar boundary layer with suction are presented. Approximate methods of calculating a two-dimensional boundary layer are discussed. The problem of a three-dimensional boundary layer on a gliding airfoil, as well as on a body of revolution and elongated bodies of arbitrary shape, is considered. Existing methods of calculating a laminar boundary layer with slit suction are discussed. Fundamental problems of optimum suction of a laminar boundary layer to achieve a substantial reduction of the drag on a body moving at high velocities are examined. These problems are examined both from the viewpoint of hydrodynamic stability theory, and from the viewpoint of the theory of transition from a laminar to a turbulent boundary layer, taking into account the initial flow turbulence and the roughness of the body surface. This approach makes it possible to develop methods for estimating the optimal suction of a laminar boundary layer, taking into consideration the principal factors encountered in technical applications.

Availability:
N70-32331
A69-10615 (Original Russian)

446. Bushnell, Dennis M.; Cary, Aubrey M., Jr.; and Harris, Julius E.: Calculation Methods for Compressible Turbulent Boundary Layers - 1976. NASA SP-422, 1977.

Calculation procedures for nonreacting compressible two- and three-dimensional turbulent boundary layers are reviewed. A summary of integral, transformation, and correlation methods, as well as finite-difference solutions of the complete boundary-layer equations is included. Alternative numerical solution procedures are examined, and both mean field and mean turbulence field closure models are considered. A discussion of physics and related calculation problems peculiar to compressible turbulent boundary layers is included. A listing of available solution procedures (finite-difference, finite-element, and weighted-residual methods) is provided. Detailed consideration is given to influence of compressibility, low Reynolds number, wall blowing, and pressure gradient upon mean field closure constants.

The information contained in this publication was presented at the 1976 Von Kármán Institute for Fluid Dynamics Lecture Series "Compressible Turbulent Boundary Layers," March 1-5, 1976, Rhode-St.-Genèse, Belgium.

Author

Availability:
N78-13371

447. Barinov, V. A.: Three-Dimensional Boundary Layer in a Vicinity of the Critical Line of the Sliding Wing With Nonuniform Suction. FTD-MT-24-0423-75, U.S. Air Force, Feb. 13, 1975. (Available from DDC as AD A007 194.)

A numerical method for calculating the equations of the incompressible boundary layer is presented, which is a generalization of the method for determining integral relationships of the three-dimensional boundary layer. Results are given of the performance calculation of the boundary layer for different distribution laws of suction along the leading edge of a wing.

Author

Availability:
N75-22293
AD A007 194

448. Kozlov, L. F.: Calculation of the Incompressible Laminar Boundary Layer on a Plate With Slot Suction. J. Eng. Phys., vol. 9, no. 4, Oct. 1965, pp. 293-295.

Discussion of the behavior at high Reynolds numbers of the incompressible laminar boundary layer of a viscous fluid past a plane plate with transverse porous sections, the normal component of velocity of which is constant and differs from zero. The dependence of the characteristics of such a layer on the rate of suction of the fluid through porous sections is investigated applying the momentum equation.

Availability:
A68-28210
A66-13654 (Original Russian)

449. Thompson, B. G. J.: The Prediction of Boundary-Layer Behavior and Profile Drag for Infinite Yawed Wings: Part II - Flow Near a Turbulent Attachment Line. C.P. No. 1308, British A.R.C., 1974.

In the region of strong favourable pressure gradient between the leading-edge attachment line and the pressure minimum, comparisons with the measurement of Cumpsty and Head, on a 62.5° swept wing, show that current turbulent boundary layer methods do not predict the boundary layer growth accurately enough for practical design applications. Physically, the conditions are severe as there are strong cross-flows developing in the presence of large wall curvature.

Calculations, using the entrainment method show that, even at flight Reynolds numbers, a conventional swept wing with turbulent attachment line flow could be affected by a prolonged region of reverse transition. Simple assumptions are used to estimate the effect of this on boundary-layer development. It is found that the profile drag could be affected by several per cent and it is thought that the shock-induced separation and scale effects for 'peaky' transonic aerofoils would be even more susceptible to the presence of laminar reversion and that the use of an attachment line criterion for turbulent flow (such as C*) is inadequate on its own.

Finally, calculations using the same boundary-layer method are employed to provide charts from which a basic experiment at low speeds can be designed to investigate these problems on a yawed circular cylinder (suitably faired). Results are provided for the 13ft × 9ft wind tunnel at RAE Bedford and for the 5ft × 4ft wind tunnel at the Cambridge University Engineering Laboratory.

Author

Availability:
N75-29043

450. Walz, A.: Näherungstheorie für Grenzschichtabsaugung durch Einzelschlitze. DVL Ber. Nr. 184, June 1962.

This paper describes work with the single slit principle as applied to boundary suction; while most previous theories are concerned with continuous suction. With this new theory, only two unknowns are introduced for the velocity profile - a thickness parameter and a form parameter. The basic thought of the suction theory now is whether the parameter values after the suction slit can be ascertained from the parameter values before the slit. This is necessary because the approaching velocity profile is cut into by the suction mass as in the continuity condition, and sets the parameters for the residual profile. Within these parameters, the values behind the slit are computed. The theory is developed for turbulent boundaries only, based on the velocity profile after the usual power onset.

Availability:
N62-16345 (Original German)

451. Mills, R. D.: On Boundary-Layer Suction Through Narrow Slots. Q. J. Mech. & Appl. Math., vol. XXIV, pt. 4, 1971, pp. 461-471.

An analytical treatment is given of the laminar boundary layer on a flat plate with a narrow suction slot. When this flow is expanded in a certain perturbation series about the Blasius solution, it becomes possible to determine the first-order solution in integral form. This solution tends uniformly to the Blasius solution as the suction velocity and/or slot width tend to zero. An approximation is obtained for the wall shear stress distribution in terms of the incomplete gamma function. Comparisons are made between the results of the present analysis, Rheinboldt's solution and numerical solutions. The first-order solution was found to be quite accurate when the suction parameter is small.

Author

Availability:
A72-14461

452. Kozlov, L. P.: Flow of Viscous Gas in the Region of a Slot With Strong Suction. NASA TM-75241, 1978. (Also available in Soviet Appl. Mech., vol. 10, no. 1, Jan. 1974, pp. 109-111.)

The flow of a perfect viscous gas was studied in the region of a slot with strong suction. Velocity and temperature distribution fields are computed of the case of thermally insulated and heat conducting surfaces. The dependence of the flow characteristics on the suction gas discharge is obtained for a single slot with strong suction.

Author

Availability:
N78-21411
A74-27292 (Original Russian)

453. Lugt, Hans J.; and Oh, Sin K.: Boundary-Layer Suction With Slots on Axisymmetric Bodies. Rep. 4038, Naval Ship. Res. & Develop. Center, Nov. 1972. (Available from DDC as AD 917 269L.)

Availability:
X74-76137
AD 917 269L

454. El-Gamal, H. A.; and Barclay, W. H.: Laminar Streamwise Corner Flow With Suction. Aeronaut. J., vol. 79, no. 778, Oct. 1975, pp. 466-469.

Flow along a corner formed by two semiinfinite intersecting flat plates, with the corner line parallel to the streamlines of a uniform incident flow pattern, is analyzed for uniform suction applied at the plate surfaces. The flow is broken down into four distinct regions: a region of potential flow, a three-dimensional viscous boundary layer region, a corner layer at the intersection line, and outside these a region in which viscous forces are absent to at least first order. The problem is simplified by assuming zero streamwise pressure gradient and considering only flow sufficiently far downstream of the leading edge for the flow in two-dimensional regions far from the corner line to have attained an asymptotic state.

Availability:
A76-13117

455. Gersten, Klaus; and Gross, Joseph F.: Flow and Heat Transfer Along a Plane Wall With Periodic Suction. J. Appl. Math. Phys., vol. 25, 1974, pp. 399-408.

Consideration of a three-dimensional incompressible laminar boundary layer in a flow moving at zero incidence angle past a flat plate and undergoing suction at the plate wall at a slightly sinusoidal transverse suction rate distribution. The flow-perpendicular and flow-parallel components of the wall shear stress and the heat transfer, along with its dependence on the Prandtl number, are determined for the asymptotic flow conditions prevailing far downstream.

Availability:
A74-43363

456. Saric, William S.; and Nayfeh, Ali Hasan: Nonparallel Stability of Boundary Layers With Pressure Gradients and Suction. Laminar-Turbulent Transition, AGARD-CP-224, Oct. 1977, pp. 6-1 - 6-21.

Availability:
N78-14316

457. Betchov, Robert; and Criminale, William O., Jr.: Stability of Parallel Flows. Academic Press, 1967.

This volume deals with the problems of stability of parallel laminar flows. All systems are considered, including channel flows, pipe flows, jets, wakes, free-shear layers, and the boundary layer.

The first part of the book is an introduction to the subject, leading the reader to a physical comprehension of flow oscillations. Part Two is in the form of a monograph providing researchers with an up-to-date picture of the state of the art.

Throughout the book, numerical techniques and methods are introduced to analyze and solve problems. Emphasis is on the physical basis of the problems. Experimental knowledge and results are presented in detail. Numerous illustrations and graphs amplify the text.

458. Joseph, Daniel D.: Stability of Fluid Motions I. Springer-Verlag, 1976.

Joseph, Daniel D.: Stability of Fluid Motions II. Springer-Verlag, 1976.

The study of stability aims at understanding the abrupt changes which are observed in fluid motions as the external parameters are varied. It is a demanding study, far from full grown, whose most interesting conclusions are recent. I have written a detailed account of those parts of the recent theory which I regard as established.

Author

459. Van Ingen, J. L.: A Method of Calculating the Transition Region for Two-Dimensional Boundary Layers With Distributed Suction. Paper presented at 6th European Aeronautical Congress (Munich), Sept. 1-4, 1965.

Use of the linear stability theory to calculate the "amplification factor" c_a of unstable disturbances in the laminar boundary layer. It is shown that at the experimentally determined transition position this factor σ_a has roughly the same value for different experiments with and without suction. Hence, in reverse the transition position can be calculated assuming that transition occurs as soon as σ_a has reached this critical value. It is shown that an earlier method for the prediction of transition for two-dimensional boundary layers without suction is also applicable in the case of suction through a porous surface. Using this method, it is possible to design rational suction distributions for a given airfoil, or to improve the design of the airfoil section itself.

Availability:
A66-21408

460. Kaups, K.: Transition Prediction on Bodies of Revolution. Rep. No. MDC J6536 (Contract No. N66001-74-C-0020), Douglas Aircraft Co., Apr. 1974. (Available from DDC as AD 778 045.)

The purpose of the study was to evaluate transition prediction methods for axisymmetric configurations at high Reynolds numbers in incompressible flow. Methods selected for comparison were those of Michel, Smith and Gamberoni, Hall and Gibbings, and Granville. Evaluation against the limited amount of experimental data available at relatively low Reynolds numbers indicates that no single method gives consistently satisfactory answers. The method of Smith and Gemberoni is given some discussion. All four methods were also applied to the calculation of transition points on four specified configurations and to a series of four semi-infinite bodies with elliptic nose caps.

Author

Availability:
N74-27757
AD 778 045

461. Mack, Leslie M.: On the Application of Linear Stability Theory to the Problem of Supersonic Boundary-Layer Transition. AIAA Paper No. 74-134, Jan.-Feb. 1974. (Also available in AIAA J., vol. 13, no. 3, Mar. 1975, pp. 278-287.)

Linear stability theory is used to calculate the amplitude ratio of constant-frequency disturbances as a function of Reynolds number for insulated and cooled-wall flat-plate boundary layers between Mach numbers 1.3 and 5.8. The growth curves are used to examine the consequences of using a fixed amplitude of the most unstable frequency as a transition criterion. The effect of free-stream Mach number on insulated-wall boundary layers is calculated, assuming that the initial disturbance level is constant, is proportional to the square of the free-stream Mach number and to the square root of the energy density of the one-dimensional power spectra of free-stream disturbances measured in supersonic wind tunnels.

Author

Availability:
A74-18818

462. Berger, S. A.; and Aroesty, J.: "e^9": Stability Theory and Boundary-Layer Transition. R-1898-ARPA (Contract No. DAHC15-73-C-0181), Rand Corp., Feb. 1977. (Available from DDC as AD A038 908.)

Successful low-drag design employs methods of boundary-layer control to delay the transition of unstable laminar boundary layers, but a suitable comprehensive theory is needed to guide prediction and control of boundary-layer transition for low-drag hydrodynamics. This report suggests new and less formal nonlinear theories, which combine the growth rates and frequency dependence of the two-dimensional Tollmien-Schlichting waves (which are the basis of the 'e-9' method) and the three-dimensional nonlinear processes of modern stability theory. These could ultimately lead to improvements in the understanding and manipulation of the transition process in low-drag hydrodynamics, and to the inclusion of disturbance effects.

Availability:
N77-28448
AD A038 908

463. Mack, Leslie M.: Transition Prediction and Linear Stability Theory. Laminar-Turbulent Transition, AGARD-CP-224, Oct. 1977, pp. 1-1 - 1-22.

Linear stability theory is used in computing the amplitude ratio for other than two-dimensional instability waves. The wave motion is obtained from the ray equations of kinematic wave theory, and the amplitude ratio by simply integrating the spatial amplification rate of the parallel flow theory along a ray. Both the temporal and spatial theories are examined for two- and three-dimensional incompressible and two-dimensional compressible boundary layers. The dispersion relation is most directly obtained with the temporal theory, but the magnitude and direction of the group velocity have to be computed to give the spatial amplification rate, and then only approximately. The spatial theory gives the spatial amplification rate directly, but only after the direction of the group velocity is known. Transition prediction methods, divided into amplitude-density and amplitude methods, are discussed.

Author

Availability:
N78-14316

464. Brown, W. Byron: Numerical Calculation of the Stability of Cross-Flow Profiles in Laminar Boundary Layers on a Rotating Disc and on a Swept-Back Wing and an Exact Calculation of the Stability of the Blasius Velocity Profile. Rep. No. NAI-59-5 (BLC-117) (Contract No. AF33(616)-3198), Northrop Aircraft, Inc., Jan. 1959. (Available from DDC as AD 314 541.)

A numerical method of finding exact solutions of the Orr-Sommerfeld stability equation has been developed and applied to the Blasius profile and eight three-dimensional profiles similar to those occurring in the laminar boundary layers of swept-back wings. Very exact agreement with experiment was found for the Blasius two-dimensional profile. Reasonably good agreement was obtained for the stagnation profile of a swept wing.

In the case of the rotating disc profile, the agreement between theory and experiment is not as good as in the two-dimensional case, indicating that more complete equations than the Orr-Sommerfeld may be needed for an accurate solution of the three-dimensional type profiles.

Author

Availability:
SN-24021, Feb. 1959
NAI-59-5 (BLC-117)
AD 314 541
N79-75704

465. Mack, L. M.: The Stability of the Compressible Laminar Boundary Layer According to a Direct Numerical Solution. Recent Developments in Boundary Layer Research, Part I, AGARDograph 97, May 1965, pp. 329-362.

Two direct numerical methods are used to obtain eigenvalues and eigenfunctions of the complete linearized stability equations and of the inviscid stability equations. For the inviscid equations, new families of amplified solutions are found. The maximum amplification rates and frequencies of these solutions are computed as functions of M_1, the free-stream Mach number, and as functions of wall temperature (cooled wall only) at $M_1 = 5.8$. It is found that one of the new families of solutions is the most unstable and is destabilized by cooling. For finite Reynolds numbers, neutral stability curves are computed, and at a fixed Reynolds number the maximum amplification of disturbances of constant frequency is computed as a function of M_1 and of the wall temperature at $M_1 = 5.8$. The maximum amplification decreases with increasing M_1 at low supersonic Mach numbers, rises to a peak near $M_1 = 5$, and then decreases with further increases in M_1. Cooling the wall is found to have little effect on the maximum amplification.

Author

Availability:
N65-34646

466. Brown, W. Byron: Exact Numerical Solution of the Complete Lees-Lin Equations for the Stability of Compressible Flow. Summary of Laminar Boundary Layer Control Research - Volume I, ASD-TDR-63-554, U.S. Air Force, Mar. 1964, pp. 55-67. (Available from DDC as AD 605 185.)

A numerical solution of the Lees-Lin equations has been described and used to compute the neutral stability curves for two series of flat plate profiles from M = 0 to M = 5.0. The two series are those whose velocity and temperature profiles have been previously published. In the first series, the stagnation temperature of the air stream was taken as 100° F, appropriate to many wind tunnel experiments. In the second series, the freestream static temperature was taken as -67° F, appropriate to high flying airplanes. In addition, some calculations have been made for M = 5.8 to compare with data previously published. Another series of experiments was carried out at M = 5.8. In order to compare these results with the theoretical solutions, velocity and temperature profiles were computed for this case. It is concluded that to a Mach number of about 1.6, the Lees-Lin equations agree very closely with observed stability data in both upper and lower branches of the neutral stability curve. From there up to 5.8, neutral stability calculations with the Lees-Lin equations agree well with experimental data for the lower branch of the neutral curve. The calculations do not agree with the data in the upper branch.

Availability:
N65-25552
AD 605 185

467. Brown, W. Byron: Exact Numerical Solution of the Complete Linearized Equations for the Stability of Compressible Boundary Layers. Rep. No. NOR-62-15, Northrop Corp., Jan. 1962.

The importance of the terms in the Lees-Lin equations that are omitted in the Dunn-Lin equations has been pointed out by Lees and Reshotko. Reshotko showed that, at a Mach number of 5.6, the addition of some of the principal terms involving temperature derivatives of the viscosity increased the computed R.N. several hundred per cent. Dr. Pfenninger suggested the extension to the complete linearized equations of Lees and Lin of an exact numerical method of solution that had been developed for the Orr-Sommerfeld equation in the incompressible case and for the Dunn-Lin equations in the compressible case. This was done and it appears evident that the more the calculations are refined, the better the results agree with experiments at higher Mach numbers.

Author

Availability:
NOR-62-15
N79-75705

468. Brown, W. Byron: Crossflow Stability Calculations on Highly Swept (65° Sweep) Supersonic Low Drag BLC Wing (Mach Number 1.8) With and Without Cooling. Rep. No. NOR-61-263 (BLC-138), Northrop Aircraft, Inc., Feb. 1962. (Also available in Summary of Laminar Boundary Layer Control Research - Volume I, ASD-TDR-63-554, U.S. Air Force, Mar. 1964, pp. 68-72. (Available from DDC as AD 605 185.))

A simplified version of the complete Lees-Lin equations has been used to compute the stability of the crossflow profiles on a highly swept (65-degree sweep) supersonic low drag BLC wing at Mach number of 1.86 with and without cooling. Two crossflow profiles (velocity and temperature) were considered. Four stability curves were computed, two for each profile. Because the boundary condition at the wall is different for high and low disturbance frequencies, each condition was computed for each profile. For comparative purposes the

Orr-Sommerfeld equation was applied to the two velocity profiles, the temperature profiles being neglected.

Availability:
NOR-61-263 (BLC-138)
N65-25553
AD 605 185

469. Brown, W. Byron: Incompressible Crossflow Stability Calculations With Various Angles of the Wave Fronts With the Potential Flow Direction. Summary of Laminar Boundary Layer Control Research - Volume I, ASD-TDR-63-554, U.S. Air Force, Mar. 1964, pp. 73-95. (Available from DDC as AD 605 185.)

The suction profiles on a swept wing close to the wing trailing edge have been computed and used, in turn, to compute four neutral stability curves. Among these four, the transverse profile has the lowest value for the critical Reynolds number. The curves show that both the critical Reynolds number and the range of wave numbers in which amplification is possible depends on ε, which measures the direction of the profile plane. It is concluded that the critical Reynolds number computed from the transverse boundary layer profile at a station close to the trailing edges of a swept laminar suction wing is within about ten percent of the lowest value for any plane profile.

Availability:
N65-25554
AD 605 185

470. Brown, W. Byron: Stability of Compressible Flow Over a Flat Plate. Theoretical Investigations of Boundary Layer Stability. AFFDL-TR-64-184, U.S. Air Force, Sept. 1966, pp. 89-109. (Available from DDC as AD 809 388.)

Availability:
X67-20406
AD 809 388

471. Brown, W. Byron: Numerical Solution of the Complete Three Dimensional Stability Equations of the Compressible Boundary Layer on a Flat Plate. Contract No. AF33(657)-11618, Norair Div., Northrop Corp., Oct. 1964.

Availability:
X67-20407

472. Merkle, Charles L.: Stability and Transition in Boundary Layers on Reentry Vehicle Nosetips. AFOSR-TR-76-1107, U.S. Air Force, June 1976. (Available from DDC as AD A035 712.)

The stability characteristics of the boundary layer on the nosetip of a reentry vehicle have been investigated for a wide range of conditions. Results based upon classical parallel-flow stability theory indicate that boundary layers on smooth-walled nosetips are stable by a wide margin at realistic Reynolds numbers. The addition of nonparallel effects, including the axisymmetric vortex stretching that is encountered as the boundary layer is swept over the nosetip, moves the neutral stability curve to lower Reynolds numbers, but by only negligible amounts, indicating that the parallel-flow analysis is more than adequate for the present problem. The stability results for rough-surfaced nosetips, which are based on a phenomenological model for the effects of roughness on the mean flow profiles, yield completely different conclusions. The presence of roughness can produce large, strongly unstable regions on the nosetip. In particular, the interaction between roughness and other parameters is especially important. The results indicate that in the presence of roughness, wall cooling is strongly destabilizing, whereas the effects of the pressure gradient are very weak. Both of these predictions are completely different from smooth-wall stability results but are in agreement with numerous experimental transition results. The calculations also indicate that surface mass addition is destabilizing in the presence of smooth walls (but by much smaller amounts than indicated in the experiments of Demetriades), while it has very small effects in the presence of wall roughness. A general observation based on these results is that boundary layer transition on nosetips occurs because of the simultaneous effects of surface roughness, strong favorable pressure gradients, and wall cooling.

Author

Availability:
N77-26449
AD A035 712

473. Benney, David J.; and Orszag, Steven A.: Stability Analysis for Laminar Flow Control - Part I. NASA CR-2910, 1977.

This report develops the basic equations for the stability analysis of flow over three-dimensional swept wings and then surveys numerical methods for their solution. The equations for nonlinear stability analysis of three-dimensional disturbances in compressible, three-dimensional, non-parallel flows are given. Efficient and accurate numerical methods for the solutions of the equations of stability theory are surveyed and analyzed.

Author

Availability:
N78-12363

474. Ko, D. R. S.; Merkle, C. L.; and Kubota, T.: The Effect of Axisymmetric Geometry on Boundary-Layer Transition as Predicted by Linear Stability Theory. AFOSR-TR-75-0192, U.S. Air Force, Sept. 1974. (Available from DDC as AD A004 787.)

Computations of the linear stability of laminar boundary layers have been used to obtain predictions of the ratio of the transition Reynolds number on a cone to that on a flat plate. The results show that this ratio is not given by a simple constant, but depends upon various parameters. In particular, the predictions indicate that transition will not occur at the same value of Reynolds number (deflected flow) on both the cone and the plate. Similarly, the results show that the ratio of transition Reynolds numbers is not equal to the ratio of the critical Reynolds numbers for the two bodies. If either of these suppositions were true, the transition Reynolds number ratio would be three; stability results indicate that this ratio can be less than unity. Among other things, the ratio depends upon the disturbance level in the free-stream. High free-stream disturbances push the ratio near three, while sufficiently small disturbances allow transition to occur earlier on the cone than on the plate. This is a consequence of the fact that on a plate the transition location is more sensitive to free-stream disturbances than it is on a cone.

Availability:
N75-27319
AD A004 787

475. King, William S.: The Effects of Wall Temperature and Suction on Laminar Boundary-Layer Stability. R-1863-ARPA (Contract No. DAHC15-73-C-0185), Rand Corp., Apr. 1976. (Available from DDC as AD A025 337.)

An integral solution of the two-dimensional boundary-layer equations for water with pressure gradient, heat transfer, and suction was employed to investigate laminar boundary-layer stability. It was shown that the effects of suction, wall heating, and pressure gradient on critical Reynolds numbers could be correlated as a function of universal boundary-layer parameters. It was indicated that suction is the most effective and pressure gradient the least effective means to stabilize a boundary layer. However, the effectiveness of suction is enhanced by a favorable pressure gradient.

Availability:
N77-11355
AD A025 337

476. Yao, Lun-Shin; and Catton, Ivan: The Buoyancy and Variable Viscosity Effects on a Water Laminar Boundary Layer Along a Heated Longitudinal Horizontal Cylinder. R-1966-ARPA, Rand Corp., Feb. 1977. (Available from DDC as AD A036 377.)

Small cross flow is induced in an otherwise axially symmetric laminar boundary layer when a uniform horizontal stream flows along the inner or outer surface of a heated horizontal cylinder. The magnitude of this cross flow depends on the ratio of the Grashof number to the square of the Reynolds number, based on the radius of the cylinder, and in its early stages grows linearly in the downstream direction. The report shows that the variable-viscosity effect can increase the velocity gradient and, hence, stabilize the laminar boundary layer; the cross-flow effect will decrease the velocity gradient and destabilize the laminar boundary layer over the upper half of the cylinder (or the pipe flow). Also, the boundary beyond which the cross-flow effect can overwhelm the variable-viscosity effect has been determined.

Author

Availability:
N77-28459
AD A036 377

477. Gaponov, S. A.; and Maslov, A. A.: Numerical and Asymptotic Solution of the Problem Concerning the Complete Stabilization of a Boundary Layer. J. Appl. Mech. & Tech. Phys., vol. 13, no. 3, May-June 1972, pp. 313-316.

The numerical method given in [1] is used here for calculating the temperatures of complete stabilization for a supersonic boundary layer at a flat plate with the boundary condition $\theta(0) = 0$, where θ denotes the amplitude of temperature perturbations. According to the results, the conclusion in [2] that there exist two regions of complete stabilization is wrong. The asymptotic method used in [2] is analyzed here. It is shown that two regions of complete stabilization appear to exist, because the equations used in [2] had been set up for the viscous case and, therefore, are not applicable at low surface temperatures. The results of this analysis are confirmed by direct numerical integration.

Author

Availability:
A72-41659 (Original Russian)

478. Gaponov, S. A.; and Maslov, A. A.: Numerical Solution to the Problem of the Complete Stabilization of a Supersonic Boundary Layer. J. Appl. Mech. & Tech. Phys., vol. 13, no. 2, Mar.-Apr. 1972, pp. 164-167.

A procedure is proposed for numerically solving the problem of complete stabilization of a supersonic boundary layer, without any constraints on the product of the disturbance wave number and the Reynolds number. It is shown that the neutral stability curve of a supersonic boundary layer splits into two curves when the flow surface is exposed to intense cooling. The complete stabilization temperatures are calculated for both curves. A comparison of these results with the results of asymptotic calculations shows that the asymptotic method develops an error when the Mach number exceeds 2.

Availability:
A72-33155 (Original Russian)

479. Gaponov, S. A.: Stability of a Supersonic Boundary Layer on a Porous Surface With Heat Transfer. Izv. Akad. Nauk. SSSR, Mekh. Zhidk. Gaza, Jan.-Feb. 1977, pp. 41-46.

The effect of the cooling of a porous surface on the stability of a supersonic boundary layer on the surface is investigated. It is shown that in contrast to the case of a nonporous surface, intense cooling can lower the critical

Reynolds number. Common points of continuous and discrete spectra are found in the perturbation region.

Availability:
A77-27081 (Original Russian)

480. Savel'ev, Iu. P.: Influence of External-Flow Turbulence on Laminar-Turbulent Transition for Some Classes of Self-Similar Flows. Inzh. Fiz. Zh., vol. 30, Mar. 1976, pp. 519-527.

The method proposed for calculating the stability of flows of the Falkner-Skan type is based on the assumption that laminar-turbulent transition occurs at a Reynolds number where the laminar and turbulent oscillation energies are alike. Solutions are obtained with and without allowance for the influence of the perturbed motion on the main flow. Values of the transition Reynolds number are calculated as a function of the external-flow turbulence intensity. It is shown that for very low pulsation levels at the external side of the laminar boundary layer, the energy of the neutral oscillations within the layer can attain values high enough to cause turbulent transition.

Availability:
A76-34705

481. Lekoudis, S. G.: Stability of Boundary Layers Over Permeable Surfaces. AIAA Paper 78-203, Jan. 1978.

The stability of a two-dimensional, incompressible boundary layer over a perforated surface is examined. The spacing of the perforations is assumed to be small compared to the wavelength of the disturbances. If, under the perforations, there exists a chamber that permits traveling waves to exist, it can, under certain conditions, stabilize the flow. If instead there exist small chambers that sustain compressible waves created by the disturbance in the boundary layer, their effect on the stability of the flow is negligible, for the range of frequencies of interest.

Author

Availability:
A78-22597

482. Chen, T. S.; and Huang, L. M.: Hydrodynamic Stability of Boundary Layers With Surface Suction. AIAA J., vol. 10, no. 10, Oct. 1972, pp. 1366-1367.

This Note is intended as a supplement to the work of Chen et al. and treats the stability of a flat plate boundary-layer flow with similarity suction. The main object of the study is to find the effect of the main flow transverse velocity on the stability characteristics of the flow.

Author

Availability:
A73-10749

483. Glauert, M. B.: The Design of Suction Aerofoils With a Very Large C_L-Range. R. & M. No. 2111, British A.R.C., 1945.

This paper considers four aerofoils (GLAS I, GLAS II, GLAS III, and GLAS IV), designed on the basis of their velocity distributions in two-dimensional incompressible potential flow. The design method used was that of Lighthill's exact theory.

The principal feature in the design is the replacement of the region of falling velocity over the rear part of the aerofoil by a single discontinuity in velocity, at which point boundary-layer suction is applied. Thus adverse pressure gradients are completely eliminated throughout a wide range of incidence. The boundary layer remains thin and laminar flow may be achieved, even on aerofoils of very great thickness. At the discontinuity the mathematical shape is a logarithmic spiral, but this must be modified in practice to include the suction slot. In one aerofoil the spiral is avoided by having a steep fall of velocity over a short distance of the surface instead of a complete discontinuity, but this may detract from the performance.

The paper discusses the relative merits of the aerofoils and considers possible improvements. Zero pitching moment is very desirable and can readily be achieved. A process has been devised by which a leading-edge radius of curvature may be incorporated, and it is applied in the design of GLAS IV. Tables give ordinates and characteristics of GLAS II and GLAS IV. The shapes and velocity distributions are given for all four aerofoils.

Author

Availability:
N78-78567

484. Gregory, N.: Note on Sir Geoffrey Taylor's Criterion for the Rate of Boundary-Layer Suction at a Velocity Discontinuity. R. & M. No. 2496, British A.R.C., 1952.

Sir Geoffrey Taylor's criterion for the rate of boundary-layer suction at a velocity discontinuity is described, and is compared with experimental results obtained from boundary-layer explorations. It is found that, despite neglect of the pressure gradient due to the curvature of the flow, the criterion gives reasonable estimates of the suction quantity. On the other hand, close agreement with velocity profiles is only obtained when the pressure gradient is taken into account.

Author

Availability:
N78-78511
N-17216

485. Preston, J. H.; Gregory, N.; and Rawcliffe, A. G.: The Theoretical Estimation of Power Requirements for Slot-Suction Aerofoils, With Numerical Results for Two Thick Griffith Type Sections. R. & M. No. 2577, British A.R.C., 1953.

This report describes a method for assessing the performance of slot-suction aerofoils in terms of an effective drag coefficient, which takes into account the power requirements of the suction pump neglecting slot entry and duct losses. When the suction-slot is located at a velocity discontinuity the suction flow required to prevent separation can be calculated, using the elementary theory suggested by Sir Geoffrey Taylor.

The method is applied to two Griffith type aerofoils (30 per cent and 31.5 per cent thick) and the drags are compared with those of normal thin aerofoils 20 per cent thick. When transition is forward the drags are nearly equal; but when transition is at the slot the drags of the suction aerofoils are very much less than that of a normal thin aerofoil with transition at its most rearward feasible position.

The gains afforded by the use of suction near the trailing edge of an aerofoil arise partly from reduction of form drag, and partly from an economy in power when the loss of head in the boundary layer is restored by means of a pump instead of appearing as a loss of momentum in the wake to be overcome by a thrust. Further gains will result if the pump efficiency is greater than the propulsive efficiency.

Author

Availability:
N78-78510
N-23938

486. Gregory, N.; and Curtis, A. R.: A Comparison of Three Thick, Symmetrical, Multi-Slot Suction Aerofoils. C.P. No. 20, British A.R.C., 1950.

This note investigates the possible gains in performance which might be achieved by including additional slots, with and without associated small velocity discontinuities, in the forward part of sections resembling the Griffith 30% suction aerofoil. By sucking away the boundary layer near the nose of the aerofoil, wedges of turbulent flow due to roughness and imperfection of the surface would be absorbed, and laminar flow would therefore be obtained over the rest of the aerofoil where favourable conditions existed. In addition, by designing for velocity discontinuities at the slots, the aerodynamic characteristics of the aerofoil might be further improved: for a given maximum value of the velocity over the aerofoil (U/U_0), much greater favourable velocity gradients might be obtained; for a given maximum thickness, it would be possible to achieve a larger low-drag C_L range.

Two symmetrical thick suction aerofoils with additional small velocity discontinuities over the forward part of the aerofoil are compared with the 30% Griffith aerofoil. For a given transition position, the suction quantities and ideal effective drag coefficients are higher than for the 30% Griffith aerofoil, but more favourable velocity gradients and an increased C_L range are obtained.

The drag and suction quantities are equal to those obtained when the additional suction slots are inserted (in the Griffith aerofoil) without the associated small velocity discontinuities.

In all cases, reductions in drag are achieved with extra slots if extents of otherwise turbulent flow are replaced by laminar flow.

Author

Availability:
N78-78560
N-2803

487. Williams, J.: Some Improvements in the Design of Thick Suction Aerofoils. C.P. No. 31, British A.R.C., 1950.

In wind-tunnel tests on GLAS II and GLAS III shapes designed by exact theory, the suction quantities required to prevent separation were considerably larger than estimated theoretical values and with the GLAS II aerofoil, unstable conditions were found in which separation occurred intermittently. On the other hand, the 30% symmetrical Griffith aerofoil designed by approximate theory and the Australian experimental modification of the GLAS II shape both worked reasonably well.

In this paper an attempt has been made to design more satisfactory thick suction aerofoils than have hitherto been obtained with the exact method. Methods have been developed for representing more closely the physical conditions corresponding to an abrupt velocity fall with suction at a slot, and less severe types of velocity fall have also been considered. Experiments are needed to decide which is the best method of improvement and to clarify the difficulties encountered with the original exact theory shapes.

Author

Availability:
N-4975
N78-79451

488. Dowlen, E. M.: A Comparison of the Calculated Profile Drag Coefficients of Various Low Drag Wing Sections. Rep. No. 35, Coll. of Aeronaut., Cranfield (England), Apr. 1950.

The profile drag-coefficients of a number of low-drag wings with straight trailing edges have been calculated.

A comparison is made with other low-drag and conventional sections which indicates an increase in profile drag, for a given transition point position, with rearward movement of the position of maximum velocity and with increase of trailing edge angle. Some experimental results obtained at low Reynolds number are included for comparison.

A shortened method of calculating the profile drag coefficient of an aerofoil is developed.

Author

Availability:
N78-78050
N-20

489. Wortmann, F. X.: A Contribution to the Design of Laminar Profiles for Gliders and Helicopters. TIL/T.4903, British Minist. Aviat., Feb. 1960.

The problem of choosing a pressure distribution suitable for the design of aerofoil sections giving as little drag as possible is investigated. Theoretical calculations of drag indicate that, in comparison with the familiar laminar flow sections, considerable drag losses can be avoided, firstly, by a pressure distribution which makes the turbulent flow just not separate, and secondly, by a variation of the lift distribution. These conclusions are supported by preliminary experimental evidence.

Author

Availability:
N78-78572
N-86772

490. Eppler, R.: Laminar Profiles for Gliders. TIL/T.4904, British Minist. Aviat., Feb. 1960.

A novel idea for the computation of laminar aerofoil sections is presented, primarily with emphasis on Reynolds number range of gliders. Two series of profiles are given which may be considered as a modification of the well known NACA-6 series.

Author

Availability:
N78-78573
N-86773

491. Eppler, R.: Laminarprofile für Reynolds-Zahlen grösser als $4 \cdot 10^6$. Ing.-Arch., Bd. 38, 1969, pp. 232-240.

Investigation of possible improvements of conventional laminar airfoils for Reynolds numbers greater than 4,000,000. Known theories regarding potential and boundary layer flows are utilized in the study, and an improved criterion for the boundary layer transition is considered. It is found that with increasing distance from the wing nose a smaller pressure gradient has to be introduced to achieve optimal drag coefficients. The behavior at high lift coefficients can be improved by renouncing large laminar buckets.

Availability:
A70-10930

492. Design Procedure for Low-Drag Subsonic Airfoils. NASA Tech Brief B75-10256, 1975.

A procedure has been developed for designing an airfoil for use at subsonic speeds. The airfoil has the least amount of drag under the given restrictions of:

Boundary-layer transition position
Lift coefficient
Thickness ratio
Reynolds number based on the airfoil chord.

Low-drag subsonic airfoils are not only suitable for use as wing and propeller aircraft sections operating at subsonic speeds but also for hydrofoil sections for boats and blades for fans, compressors, turbines, and windmills.

Author

Availability:
B75-10256

493. Carmichael, Bruce H.; and Niehuss, Oswin: Computer Study To Establish the Lower Limit of Length-to-Diameter Ratio Advisable for Low-Drag Bodies. SID 64-1938, North American Aviation, Inc., Oct. 1964. (Available from DDC as AD 664 610.)

A computer study has been conducted to establish theoretically the lowest advisable ratio of length to diameter for a 30-inch-diameter body moving at 45 knots, submerged in the ocean, at zero angle of attack.

If the boundary layer is turbulent over the entire body, it appears inadvisable to decrease the ℓ/d much below the DOLPHIN I value of 3.33. If laminar flow extends to the minimum pressure point at 58 percent of the length, an ℓ/d of 2.62, as suggested in Reference 1, may be permitted (see Figure 1). There is a good theoretical basis for expecting laminar flow to extend to the minimum pressure point with $\ell/d = 2.62$.

The drag of a fin-stabilized, 30-inch-diameter body of $\ell/d = 2.62$ at 45 knots could be as low as 375 pounds compared to 550 pounds for a body with $\ell/d = 3.33$, as shown in Figure 2. (See the conclusion in this report for comparison with present practice.)

Author

Availability:
N68-83869
AD 664 610

494. Zolotov, S. S.; and Khodorkovsky, Ya. S.: Optimum Suction Distribution To Obtain a Laminar Boundary Layer. Int. J. Heat & Mass Transfer, vol. 6, Oct. 1963, pp. 897-901.

Development of an approximate method for calculating the laminar boundary layers for boundary layer control using optimum suction. A first approximation for a plate with optimum suction distribution is used which enables the plotting of graphs which greatly simplify the calculation of local skin friction and critical Reynolds number along the length of such a body. Derived are formulas for the calculation of the optimum rate of suction and for the rate of damping/momentum thickness.

Availability:
A63-25398

495. Kozlov, L. F.: Optimal Suction of the Boundary Layer Taking Account of Initial Turbulence and Surface Roughness. J. Fluid Mech., vol. 31, pt. 1, Jan. 8, 1968, pp. 53-64.

Derivation of simple formulas for properties of a laminar boundary layer with suction. An equation relating the transition point critical Reynolds number to initial turbulence and surface roughness is given. An approximate method is developed for the prediction of optimal suction of a boundary layer, including the main effects controlling transition of a laminar boundary layer into a turbulent one.

Availability:
A68-17949

496. Anderson, G. F.; and Sutera, S. P.: Drag Reduction on Bodies of Revolution by Use of Area Suction. AIAA J., vol. 3, no. 10, Oct. 1965, pp. 1970-1972. (Also available as AIAA Paper No. 65-561.)

Results of drag measurements on a slender body of revolution (L/D = 12) which has a porous cylindrical body and blunt nose and tail sections. Retarded fluid was removed through the porous walls and ejected axially at the tail section by a variable-speed fan located internally. A single adjustable slot in the tail was used to delay separation of the laminar boundary layer. Except for a wedge-shaped turbulent wake which was generated by a supporting strut and which blanketed about 25% of the body surface, full-length laminarization was achieved. Significant drag reductions were measured. It appears that theoretical (flat plate) predictions of potential drag reduction are only slightly optimistic. Measurements of suction quantity required for full-length laminarization indicate that optimum suction distribution must be approximated if large suction quantities are to be avoided. Possible methods for reducing the controlled boundary layer's sensitivity to surface roughness are considered. In every case these have the purpose of thickening the boundary layer before subjecting it to suction.

Author

Availability:
A66-11564
A65-26551

497. Tokhunts, A. D.: Laminarization of the Boundary Layer on a Wing Profile by Means of Distributed Suction. NASA TT F-12,021, 1968.

Laminarization of the boundary layer on a wing profile is investigated by means of distributed suction on the basis of Prandtl's equations and the general theory of hydrodynamic stability. The effects of various aerodynamic and geometric characteristics of a profile on the minimal flow rate of evacuated air is also examined. Specific examples for the calculation of the aerodynamic and geometric characteristic and minimum flow rate of evacuated air are shown.

Author

Availability:
N69-14262
A68-33608 (Original Russian)

498. Thiede, Peter; and Otte, Franz: Theoretische Untersuchungen zur Laminarhaltung der kompressiblen Grenzschicht durch Schlitzabsaugung. Z. Flugwiss., vol. 23, no. 1, Jan. 1975, pp. 9-24.

On the basis of former investigations of incompressible flows, this paper deals with the problem of keeping the compressible boundary layer laminar on two-dimensional and axisymmetric body shapes using slot suction. The new values of the boundary layer behind a slot are approximately determined according to Walz's amputation principle extended to compressible flows, whose reliability is backed up by boundary layer solutions obtained from a finite-difference method of higher approximation ('Mehrstellen-verfahren') and solutions of the Navier-Stokes equations with the fast Fourier transformation. The calculation of the boundary layer at the adiabatic wall is based on Walz's method II using the integral conditions of impulse and energy. A suction with a minimal number of slots is of interest with regard to technical application. Since a universal optimization of slot suction referring to a minimum number of slots is too complicated, a pre-optimization of the relative suction height is conducted, on which the development of a general strategy of optimization is based. The results of the pre-optimization of suction height are compared with the suction tests by Pfenninger.

Author

Availability:
A75-22033

499. Thiede, Peter: Theoretical Investigation of Maintaining the Boundary Layer of Revolution Laminar Using Suction Slits in Incompressible Flow. NASA TM-75329, 1978.

The transition of the laminar boundary layer into the turbulent state, which results in an increased drag, can be avoided by sucking of the boundary layer particles near the wall. The technically-interesting case of sucking the particles using individual slits is investigated for bodies of revolution in incompressible flow. The results of the variational calculations show that there is an optimum suction height, where the slot separations are maximum. Combined with favorable shaping of the body, it is possible to keep the boundary layer over bodies of revolution laminar at high Reynolds numbers using relatively few suction slits and small amounts of suction flow.

Availability:
N78-24082
A72-19737 (Original German)

500. Krüger, H.: Über den Einfluss der Absaugung auf die Lage der Umschlagstelle an Tragflügelprofilen. Ing.-Arch., Bd. XIX, Heft 6, 1951, pp. 384-387.

Laminar boundary-layer growth over two 15% thick profiles is calculated for the case of uniform continuous suction. A Joukowsky and a laminar profile at zero angle of attack are considered. Curves are presented for the laminar instability and separation points as functions of airfoil Reynolds number and suction velocity.

Abstract courtesy APPLIED MECHANICS REVIEWS

501. Serby, J. E.; Morgan, M. B.; and Cooper, E. R.: Flight Tests on the Profile Drag of 14% and 25% Thick Wings. R. & M. No. 1826, British A.R.C., 1937.

The purpose was to measure in flight, at as high a Reynolds number as possible, the increase in profile drag of wing sections as the thickness/chord ratio is increased to 0.25.

Using the momentum method the profile drags of two smooth wing sections, both with R.A.F.28 centre line, one 14 per cent. thick, the other 25 per cent. thick, have been measured over a range of Reynolds number 5.7×10^6 to 8×10^6. The boundary layer transition points were also located. The drag results are compared with calculated values.

With ideally smooth surfaces transition points as far back as 0.36c are possible and the resultant drags are low, viz. 0.0065 and 0.0080 for 14 per cent. and 25 per cent. thick wings. It is estimated that if the transition points moved forward to 0.15, as is likely in practice, these drags would rise to 0.0078 and 0.0108.

Author

Availability:
N78-78479

502. Stephens, A. V.; and Haslam, J. A. G.: Flight Experiments on Boundary Layer Transition in Relation to Profile Drag. R. & M. No. 1800, British A.R.C., 1938.

The purpose was to continue the experiments on Profile Drag begun in R. & M. 1688 by exploring the Boundary Layer in flight on wings whose drag had been measured and to examine the conditions under which Transition occurs.

Transition points were determined, by means of small-bore pitot tubes, over a wide range of lift coefficients on two smooth wings of 10 per cent. and 17.5 per cent. maximum thickness respectively: determinations were also made behind specified ridges on the wing surface. Several techniques were developed and are described.

The physical circumstances of transition were measured and grouped into non-dimensional parameters in an attempt to explain and predict its occurrence.

The full-scale determination of the transition point which is of the first importance in the consideration of the profile drag of a wing and its possible reduction, can be made by a simple apparatus and technique suitable for use by the aircraft industry.

A spanwise ridge on the wing surface of 0.002 in. height was found sufficient to bring forward the transition point from 0.34 chord to 0.27 chord, at Reynolds numbers of 5×10^6 and more.

A disturbance (by means of a very small ridge) introduced into the boundary layer from the inside caused transition to move forward but not right up to the ridge, the origin of disturbance.

The analysis of the measured conditions under which transition occurred did not yield any basis for prediction of transition.

Exploration of the boundary layer velocity profile gave points in very close agreement with the theoretical curves based on Pohlhausen's analysis.

Author

Availability:
N78-78480

503. Young, A. D.; and Morris, D. E.: Note on Flight Tests on the Effect of Slipstream on Boundary Layer Flow. R. & M. No. 1957, British A.R.C., 1939.

Transition point measurements have been made on an Anson and a Courier at various stations inside and outside the slipstream both in level flight and on the glide with engine throttled back. The main object of these tests was to investigate the effect of a large change in propeller working conditions on the position of the transition point in the slipstream. In neither case was there any marked difference between the transition point positions in the slipstream in level flight and in the glide. On the Anson at 160 m.p.h. it was found that in the slipstream the boundary layer remained laminar for a distance varying from 0.06c. to 0.10_5c., whilst well outside the slipstream transition occurred at 0.17c. Immediately outside the slipstream there was a region of disturbed air about 0.04c. thick where transition occurred at about 0.11c. On the Courier at 140 m.p.h. transition occurred at about 0.05c. in the slipstream and 0.25c. well outside the slipstream. These results are discussed and it is suggested that in general on smooth wings with conventional sections transition will occur in the slipstream within the range 0.05c.-0.10c.

Author

Availability:
N78-78481

504. Young, A. D.; and Morris, D. E.: Further Note on Flight Tests on the Effect of Slipstream on Boundary Layer Flow. Rep. No. B.A. 1404b, British R.A.E., 1939.

Further transition point measurements have been made on an Anson and a Courier at various stations inside and outside the slipstream both in level flight and on the glide with engine throttled back. The main object of these tests was to investigate the effect of a large change in airscrew working conditions on the position of the transition point in the slipstream. In neither case was there any marked difference between the transition point positions in the slipstream in level flight and in the glide. On the Anson at 160 m.p.h. it was found that in the slipstream the boundary layer remained laminar for a distance varying from 0.06c to 0.10_5c, whilst well outside the slipstream transition occurred at 0.17c. Immediately outside the slipstream there was a region of disturbed air about 0.04c thick where transition occurred at about 0.11c. On the Courier at 140 m.p.h. transition occurred at about 0.05c in the slipstream and 0.25c well outside the slipstream. These results are discussed and it is suggested that in general on smooth wings with sections now in common use transition will occur in the slipstream within the range 0.05c - 0.10c.

Author

505. Bicknell, Joseph: Determination of the Profile Drag of an Airplane Wing in Flight at High Reynolds Numbers. NACA Rep. 667, 1939.

Flight tests were made to determine the profile-drag coefficients of a portion of the original wing surface of an all-metal airplane and of a portion of the wing made aerodynamically smooth and more nearly fair than the original section. The wing section was approximately the N.A.C.A. 2414.5. The tests were carried out over a range of airplane speeds giving a maximum Reynolds Number of 15,000,000. Tests were also carried out to locate the point of transition from laminar to turbulent boundary layer and to determine the velocity distribution along the upper surface of the wing.

The profile-drag coefficients of the original and of the smooth wing portions at a Reynolds Number of 15,000,000 were 0.0102 and 0.0068, respectively; i.e., the surface irregularities on the original wing increased the profile-drag coefficient 50 percent above that of the smooth wing.

Author

Availability:
N78-78519

506. Zalovcik, John A.; Wetmore, J. W.; and Von Doenhoff, Albert E.: Flight Investigation of Boundary-Layer Control by Suction Slots on an NACA 35-215 Low-Drag Airfoil at High Reynolds Numbers. NACA WR L-521, 1944. (Formerly ACR 4B29.)

Results of a flight investigation of suction slots as a means of extending the laminar boundary layer are presented. The tests were made with an NACA 35-215 airfoil section built into a test panel and mounted on the wing of a Douglas B-18 airplane. The tests covered an approximate range of Reynolds number from 21×10^6 to 31×10^6. The investigation of boundary-layer control by means of suction slots in the NACA two-dimensional low-turbulence tunnel is briefly reviewed in the appendix.

The results of the investigation have shown that with nine slots spaced about 5 percent of the chord the laminar boundary layer on the upper surface could be maintained, by withdrawing air from the boundary layer, to or slightly beyond 45 percent of the chord, or just about to the minimum-pressure point, over a range of airplane lift coefficient from 0.19 to about 0.35 with the corresponding range of Reynolds number from 30.8×10^6 to 23×10^6.

Author

507. Zalovcik, John A.: Flight Investigation of Boundary-Layer and Profile-Drag Characteristics of Smooth Wing Sections of a P-47D Airplane. NACA WR L-86, 1945. (Formerly ACR L5H11a.)

Measurements were made at three stations on the wing: boundary-layer measurements were made on the upper surface of the left wing in the slipstream at 25 percent semispan; pressure-distribution measurements were made on the upper surface of the left wing at 63 percent semispan; and wake surveys were made at 63 percent semispan of the right wing. The tests were made in straight flight and in turns over a range of conditions in which airplane lift coefficients from 0.15 to 0.68, Reynolds numbers from 7.7×10^6 to 19.7×10^6, and Mach numbers from 0.25 to 0.69 were obtained.

The results of the investigation indicated a minimum profile-drag coefficient of 0.0062 for the smooth section at 63 percent semispan. At the highest Mach number attained in the tests, the critical Mach number was exceeded by at least 0.04 with no evidence of compressibility shock losses appearing in the form of increased width of the wake or increased profile-drag coefficient. For flight conditions approaching the critical Mach number, variations in Mach number of as much as 0.17 appeared to have no effect on the profile-drag coefficient.

In the slipstream, transition occurred at least as far back as 20 percent chord on the upper surface at low lift coefficients.

Author

Availability:
N78-78660

508. Zalovcik, John A.; and Daum, Fred L.: Flight Investigation at High Speeds of Profile Drag of Wing of a P-47D Airplane Having Production Surfaces Covered With Camouflage Paint. NACA WR L-98, 1946. (Formerly NACA ACR L6B21.)

A flight investigation was made at high speeds to determine the profile drag of a P-47D airplane wing having production surfaces covered with camouflage paint. The profile drag of a wing section somewhat outboard of the flap was determined by means of wake surveys in tests made over a range of airplane lift coefficients from 0.06 to 0.69 and airplane Mach numbers from 0.25 to 0.78.

The results of the tests indicated that a minimum profile-drag coefficient of 0.0097 was attained for lift coefficients from 0.16 to 0.25 at Mach numbers less than 0.67.

Author

Availability:
N78-78569

509. Smith, F.; and Higton, D. J.: Flight Tests on "King Cobra" FZ.440 To Investigate the Practical Requirements for the Achievement of Low Profile Drag Coefficients on a "Low Drag" Aerofoil. R. & M. No. 2375, British A.R.C., Aug. 1945.

Describes measurements of profile drag made on the wing of the King Cobra aircraft, which has a low-drag profile of N.A.C.A. design. The profile drag was high with the original surface finish and although it was improved when the surface was polished the profile drag was still much too high for a low-drag aerofoil.

By reduction of the surface waviness to ± one thousandth of an inch low drag coefficients of the order of 0.0028 were obtained.

The report describes the technique used to reduce the waviness and also the effect of flies, dust, water, high Mach number and normal acceleration upon the low drag characteristics of the wing.

Author

Availability:
N78-78482

510. Plascott, R. H.; Higton, D. J.; Smith, F.; and Bramwell, A. R.: Flight Tests on Hurricane II, Z.3687 Fitted With Special Wings of "Low-Drag" Design. R. & M. No. 2546, British A.R.C., Sept. 1946.

Describes flight tests to investigate the profile-drag characteristics of a 'low-drag' section wing built by Armstrong Whitworth, Ltd., using a new type of construction. A section of the wing was pressure-plotted and the results showed that it should be possible to obtain laminar flow over a range of lift coefficient from 0.12 to 0.50. A few preliminary profile-drag measurements were made and a fairly low profile-drag coefficient (C_D = 0.0046 to 0.0050) was recorded over a lift coefficient range of 0.20 to 0.40; there was, however, a rapid rise in the profile drag coefficient at lift coefficients less than 0.20, and investigation of the surface waviness showed that the failure to maintain laminar flow at higher speeds was probably due to the excessive waviness present, which amounted to a variation of about ±2½ thousandths of an inch from the mean deflection curve on a two-inch gauge length.

A further series of profile-drag measurements was made when the surface waviness had been reduced to ±1 thousandth of an inch variation from the mean deflection curve on a two-inch gauge length. It was found that, provided no flies or other insects were picked up during the flight, the drag coefficient had been reduced to 0.0044 over a range of lift coefficient from 0.12 to 0.50. This corresponds to transition from 50 to 60 per cent. chord. With the reduced surface waviness, it was possible to maintain laminar flow up to Reynolds numbers of nearly twenty millions.

Author

Availability:
N78-78566
N-21208

511. Plascott, R. H.: Profile Drag Measurements on Hurricane II Z.3687 Fitted With "Low Drag" Section Wings. Rep. No. Aero. 2153, British R.A.E., Sept. 1946.
(This version contains the ordinates for the airfoil used.)

This report describes flight tests to determine the improvement obtained by reducing the surface waviness on the experimental "low drag" wings fitted to this aircraft to ± one thousandth of an inch variation from the mean deflection curve on a two inch gauge length.

Provided no flies or other insects were picked up during the flight, the drag coefficient has been reduced to 0.0044 over a range of lift coefficient from 0.1 to 0.5. This corresponds to transition at 50-60% chord. With the reduced surface waviness it was possible to maintain laminar flow up to Reynolds Numbers of nearly twenty millions.

Author

Availability:
N-21208(B)
N79-74741

512. Keeble, T. S.: Flight Tests of the Suction Wing Glider. Rep. A.71, Aeronaut. Res. Lab. (Melbourne), May 1951.

An account is given of the first 34 flights of a glider fitted with the modified GLAS II wing. It is based primarily on interim notes issued during the progress of the work and is intended to summarize the information contained in them.

A description of the aircraft is given and the flight test results are compared with information obtained in the wind tunnel.

Whilst there are several outstanding problems which did not appear in the pre-flight wind tunnel work, the aerodynamic behaviour of the wing in flight is very promising. In spite of its great thickness, the minimum "total" (extra to induced) drag of the aerofoil as tested is much the same as that of a conventional aerofoil of lesser thickness.

The wake drag is less than that of any wing measured so far in flight, much the greater part of the total drag being due to the pump. When the slot losses can be reduced to those obtained in model tests and the local flow instability can be prevented, very substantial reductions should be possible in total drag; it should then be comparable with that of a thin low drag section.

Author

Availability:
N79-70043
N-11615

513. Raspet, August: Boundary-Layer Studies on a Sailplane. Aeronaut. Eng. Rev., vol. 11, no. 6, June 1952, pp. 52-60.

The sailplane possesses some special advantages over even the low-turbulence wind tunnel for boundary-layer research. It has been pointed out by numerous boundary-layer researches that noise, because it is a pressure fluctuation, can act as a cause of transition. Around a low-loss sailplane, the noise level is much lower than that in most wind tunnels. In addition, the turbulence of the free atmosphere has been shown to have an insignificant effect as a cause of transition. The powerful source of vibration, the engine, is absent, and only the vibration induced by aerodynamically unsteady flows is present. This is of an extremely low level.

Coupled with these primary advantages of the sailplane are those of mechanization of a test section. It is relatively simple and quick to modify a section to a new airfoil by planking with balsa over the original contour. By filling with putty and sanding, the contour can be made stable and wave-free to the desired geometric precision. This paper is offered as an example of the unique possibilities of the sailplane in boundary-layer research. The study described began first with an examination of the mechanism of trailing-edge suction. The study was planned to determine whether trailing-edge suction exercised any control over the laminar boundary layer or prevented the separation of the turbulent boundary layer near the trailing edge. Concurrently, experimental studies on the source for automatic trailing-edge suction were carried out.

Author

514. Carmichael, B. H.: Flight Observations of Suction Stabilized Boundary Layers. Res. Rep. No. 4 (Contract Nonr 978(00)), Mississippi State Coll., Jan. 20, 1953. (Also available in Aeronaut. Eng., vol. 13, no. 2, Feb. 1954, pp. 36-41.)

The goal of the present research is to determine whether the entire surface of a lifting wing in flight can be maintained laminar and what portion of the external gain is consumed by the power needed to provide the suction stabilization. For this purpose an unquestionably constant power source will be employed; namely, gravity. By comparing the sinking speed at any given forward speed of a sailplane without boundary layer control with that of the same sailplane with the laminar boundary layer stabilized by suction, provided by a windmill driven blower, the economy of the particular system will be immediately determined. The use of sailplanes in this research provide many advantages.

The data were taken between an altitude of 12,000 feet and sea level with speeds from 40 to 80 m.p.h. (flight Reynolds numbers of 2 to 4 × 10^6).

Author

Availability:
N78-78556
N-23958

515. Head, M. R.: The Boundary Layer With Distributed Suction. R. & M. No. 2783, British A.R.C., 1955. (Available from DDC as AD B029 704.)

Experiments performed in flight at Reynolds numbers in the region of 3 × 10^6 have clearly demonstrated the stabilising effect of small amounts of distributed suction on the laminar boundary layer. In the absence of a pressure gradient and in adverse gradients similar to those occurring on a normal aerofoil, transition of the boundary layer to the turbulent form has been prevented by the use of such suction quantities as may be expected to lead to very considerable reductions in effective drag. It appears, however, that for extensive laminar flow to be achieved in this way, the surface must be free from such excrescences as would cause transition in the absence of suction. Laminar boundary-layer velocity-profiles obtained with suction in the absence of a pressure gradient are found to be in good agreement with those calculated for the flat plate, and the suction quantities required to maintain laminar flow are similar to those suggested by stability theory.

Author

Availability:
N78-78483
N-38620
AD B029 704

516. Pfenninger, W.; Groth, E. E.; Whites, R. C.; Carmichael, Bruce H.; and Atkinson, J. M.: Note About Low Drag Boundary Layer Suction Experiments in Flight on a Wing Glove of a F94-A Airplane. Rep. No. NAI-54-849 (BLC-69), Northrop Aircraft, Inc., Dec. 1954.

Low drag flight suction experiments were conducted on the upper surface of a 13%-thick cambered glove section mounted on the wing of an F94-A. Suction was applied through 12 slots located between 0.415 c and 0.94 c.

Completely laminar flow was observed from $R_c = 12x10^6$ to $30x10^6$ glove chord Reynolds number, and for Mach numbers up to 0.726 at 24,000 ft altitude ($R_c = 20x10^6$). With increasing Reynolds number, the profile drag first decreased in a manner similar to the friction drag of a laminar flat plate. The minimum profile drag coefficient for the upper surface was 0.000577 (including the equivalent drag due to the suction power) at $R_c = 22x10^6$. The corresponding suction weight flow coefficient was $c_w = 0.00034$.

No difficulties were generally experienced with surface roughness up to $R_c = 28x10^6$, corresponding to a Reynolds number per unit length of $3.73x10^6$/ft.

Twenty-one out of twenty-three consecutive flights showed 100% laminar flow, and only two flights were unsuccessful due to damage of the glove leading edge from bugs and sand.

Author

Availability:
NAI-54-849 (BLC-69)

517. Carmichael, B. H.; and Whites, R. C.: Low Drag Boundary Layer Suction Experiments in Flight on the Wing Glove of an F94A Airplane - Phase III: Laminar Suction Airfoil Tolerances. Rep. No. NAI-57-1163 (Contract AF33(616)-3168), BLC-101, Northrop Aircraft, Inc., Aug. 1957.

This report deals with investigations of: allowable suction variation, effect of slot blockage, allowable surface waviness and allowable surface roughness. An attempt was made to determine the suction and drag penalty for small disturbances as well as the minimum size of disturbance which would result in turbulent flow at the trailing edge for all conditions. The purpose of the experiments was to check the validity of prediction methods from the above references when applied to a wing with suction over the rear 60% chord and operating at high Reynolds numbers.

Author

Availability:
SN-24021, Sept. 1957
NAI-57-1163
BLC-101
N79-75700

518. Carmichael, B. H.; Whites, R. C., and Wisma, R. E.: Low Drag Boundary Layer Suction Experiments in Flight on the Wing Glove of an F94-A Airplane - Phase IV: Suction Through 81 Slots. Rep. No. BLC-102, NAI-57-1025 (Contract AF33(616)-3168), Northrop Aircraft, Inc., Aug. 1957. (Available from DDC as AD 150 529.)

Flight experiments were conducted on a wing glove section mounted on the upper surface of the wing of an F94-A aircraft. Boundary layer suction was applied through 81 slots from 8% c to 95% c. The total drag coefficient for the upper surface (including the equivalent drag due to the suction power) varied linearly from 5.1×10^{-4} at $C_{L_A} = 0.1$ to 8.5×10^{-4} at $C_{L_A} = 0.46$. The lowest total drag values were obtained by decreasing suction until a transition type profile occurred at the trailing edge. The required suction quantities over the new forward portion of the glove averaged $V_o^* = 0.6$ for the entire C_{L_A} range.

Laminar flow was maintained to the trailing edge at a maximum airplane lift coefficient of 0.51 as compared to a value of 0.32 for the 69-slot glove (where the suction started at 41% chord). The lift coefficient range for laminar flow at constant altitude has increased sixfold over the 69-slot suction glove.

The total drag coefficients at given lift coefficients were reduced by increasing the Reynolds number through steady turning flight at normal load factors of 1.4 to 2.0.

No problems of a practical nature were encountered with the 81-slot glove. This result is significant in that thin and/or swept wings will necessitate suction quite far forward.

Author

Availability:
N78-74849
SN-24021, Aug. 1957
BLC-102
NAI-57-1025
AD 150 529
N79-75728

519. Pfenninger, W.; and Groth, E.: Low Drag Boundary Layer Suction Experiments in Flight on a Wing Glove of an F-94A Airplane With Suction Through a Large Number of Fine Slots. Boundary Layer and Flow Control, Principles and Applications, Volume 2, G. V. Lachmann, ed., Pergamon Press, 1961, pp. 981-997.

This chapter describes the experimental setup and gives measurements and observations. The data are evaluated and results discussed. The F-94A flight experiments verified full-chord laminar flow with boundary layer suction at higher Reynolds numbers than in previous work, confirming the results of transition data on the King Cobra laminar wing.

520. Burrows, F. M.: Characteristics of the Flow Field Over the Mid-Upper Fuselage of Lancaster P.A. 474. Note No. 36, Coll. of Aeronaut., Cranfield (England), Jan. 1956.

This note describes a series of tests conducted to determine the characteristics of the flow field over the mid-upper fuselage. The range of the tests includes a determination of the distributions of total head, static pressure and velocity together with the flow directional characteristics in the pitching plane for a number of aircraft flight configurations. Curves are presented showing the flow directional characteristics and the distributions of static pressure and velocity in the region of investigation.

Availability:
N79-70014
CN-48016

521. Burrows, F. M.: Equipment Used for Boundary Layer Measurements in Flight. Note No. 49, Coll. of Aeronaut., Cranfield (England), July 1956.

Some notes are presented relating to the design and construction of a large multitube manometer and to two 'fixed head' type boundary layer combs to be used for the measurement in flight of the boundary layer characteristics of a swept back wing. Although the equipment described was designed with a particular object in view, there is no reason why the designs should not be modified as and where necessary for the construction of similar equipment.

Availability:
N79-70015
N-46427

522. Allen, L. D.; and Burrows, F. M.: Flight Experiments on the Boundary Layer Characteristics of a Swept Back Wing. Rep. No. 104, Coll. of Aeronaut., Cranfield (England), July 1956.

This work considers the measurement in flight of the boundary layer characteristics of an untapered, untwisted, 45° swept back half wing of thin symmetrical section, mounted vertically on top of the fuselage of an Anson Mark I aircraft. The primary aim was to study the transition mechanism on swept back wings, and an account is presented of the experiments so far performed with this object in view. Attention is also given to the design, development and construction of a suitable boundary layer traversing gear. For an incidence range of 0° to 10°, and Reynolds numbers of 4, 4½, 5, 6, 7, and 8 million the static pressure distributions were determined and also the locations of transition for both surfaces using the creeping surface pitot technique. For both upper and lower wing surfaces transition was found to move towards the leading edge with increase of either incidence or Reynolds number. This is in agreement with the results obtained by Butler.

Author

Availability:
N-48017
N78-79429

523. Burrows, F. M.: A Theoretical and Experimental Study of the Boundary Layer Flow on a 45° Swept Back Wing. Rep. No. 109, Coll. of Aeronaut., Cranfield (England), Oct. 1956.

Particular attention is given to the onset of boundary layer instability and its association with critical values of secondary flow Reynolds numbers as defined by Owen and Randall. Several aspects of the problem are considered, each in some detail, and some interesting results both theoretical and experimental are presented. To satisfy the need for tests at Reynolds numbers compatible with full scale, the experiments were performed, in flight, on a large untapered, untwisted, 45° swept back half wing mounted as a dorsal fin upon the mid upper fuselage of an Avro Lancaster, the Reynolds number range thus achieved being $0.88 \times 10^6 - 1.92 \times 10^6$ per foot. Curves are presented giving details of the measured distributions of static pressure, chordwise loadings, and the boundary layer flow, the latter in extensive detail, for wing geometric incidences in the range 0° - 10°, upper and lower surfaces, and for test Reynolds numbers in the range defined above. No laminar flow was found to exist on either the upper or lower surface of the wing for Reynolds numbers at, and in excess of 1.55 x 10^6 per foot thus showing the need for some form of boundary layer control to suppress the effects of sweep instability.

Author

Availability:
N78-79430
N-48300

524. Walton, J.: Addendum to a Theoretical and Experimental Study of the Boundary Layer Flow on a 45° Swept Back Wing. Rep. No. 109 Addendum, Coll. of Aeronaut., Cranfield (England), Nov. 1957.

College of Aeronautics Report 109 describes Flight Tests carried out on a swept back half wing of double elliptic section to investigate the nature of the boundary layer flow, with particular reference to Boundary Layer Instability and subsequent transition.

The wing, which had a chord of 7ft.2" was mounted as a dorsal fin on the mid upper fuselage of an Avro Lancaster, which enabled a Reynolds Number range of 0.88 x 10^6 - 1.92 x 10^6 per foot to be achieved. There was some doubt about the validity of applying the results of these tests to wings of orthodox section because of the possible occurrence of wake instability associated with the bluff trailing edge. This Addendum gives the results of a few check tests on the same wing with a short trailing edge extension having a trailing edge angle of approximately 12°. Unfortunately wing surface deterioration near the L.E. from mid semi span to the tip prevented conclusive results being obtained but some evidence is presented to show that the results are not invalidated by the choice of section.

Author

Availability:
N79-70016
N-48300 addendum

525. Landeryou, R. R.; and Porter, P. G.: Further Tests of a Laminar Flow Swept Wing With Boundary Layer Control by Suction. Rep. Aero. No. 192, Coll. of Aeronaut., Cranfield (England), May 1966.

Further flight tests have been performed on the Handley Page swept fin having slitted suction surfaces for laminar flow control.

The main object of the tests was to achieve full chord laminar flow at and slightly above a unit Reynolds number of 1.5 x 10^6 per foot.

Laminar flow was obtained, at the instrumentation position (90% chord) up to a unit Reynolds number of 1.87 x 10^6 per foot. It was also demonstrated that it was possible to achieve 99% laminarisation of the laminarisable area forward of 90% chord at a unit Reynolds number of 1.58 x 10^6 per foot.

Complete suppression of leading edge contamination has been demonstrated up to 1.47 times the theoretical critical Reynolds number based on the attachment line momentum thickness.

Investigations have been carried out into the effect of changes in incidence, suction quantity and unit Reynolds number on the chordwise position of transition.

Experimental and calculated boundary layer profiles at the same conditions have been compared and a good correlation between them has been obtained.

A qualitative assessment of environmental and production difficulties likely to be encountered on an aircraft using this system, has also been made.

Author

Availability:
N67-10475

526. Citation intentionally removed.

527. Groth, E. E.: Boundary Layer Transition on Bodies of Revolution. Rep. No. NAI-57-1162 (Contract AF33(616)-3168), BLC-100, Northrop Aircraft, Inc., July 1957. (Available from DDC as AD 150 527.)

Boundary layer transition measurements on bodies of revolution at zero incidence have been made in two wind tunnels and in flight at subsonic speeds. The results of these experiments demonstrate the importance of the potential flow pressure distribution along the body on transition. A theoretical analysis comparing the experimental data with two-dimensional transition values indicates that the slope of the body contour has a major influence on transition of bodies of revolution. Increasing radius along the body axis moves transition forward, decreasing radius moves it aft of the station computed for two-dimensional flow. Since the ratio of the momentum thickness Reynolds numbers at transition for axially symmetrical and two-dimensional flow depends primarily on the local slope of the body, the results of this analysis might be used for an estimate of boundary layer transition on any body of revolution at zero degree angle of attack and incompressible flow.

Author

Availability:
SN-24021, Sept. 1957
NAI-57-1162
N63-82639
AD 150 527

528. Groth, E. E.: Low Speed Wind Tunnel Measurements on a Body of Revolution of Fineness Ratio 8. Rep. No. BLC-6, Northrop Aircraft, Inc., Aug. 1953. (Available from DDC as AD 20 076.)

A 7-ft model of an ellipsoid of fineness ratio 8 with modified rear end was tested at the Northrop low speed wind tunnel for length Reynolds numbers between 1 and 7 · 10^6. The drag coefficient of the body was 1.4 times the laminar friction drag of a flat plate up to a Reynolds number of 4 · 10^6. Boundary layer observations showed a laminar separation without a well defined turbulent reattachment in the rear part of the body at Reynolds numbers below 1.8 · 10^6, a slow forward shift of transition from 92% at 2 · 10^6 to 78% of the length at a Reynolds number of 4 · 10^6, and then a rapid forward shift due to the turbulence of the wind tunnel.

Author

Availability:
SN-24021, Aug. 1953
BLC-6
AD 20 076

529. Groth, E. E.: Boundary Layer Transition on Bodies of Revolution of Different Shape. Summary of Laminar Boundary Layer Control Research. WADC Tech. Rep. 56-111, U.S. Air Force, Apr. 1957, pp. 182-183. (Available from DDC as AD 130 579.)

The application of boundary layer suction to bodies of revolution for maintaining full laminar flow over the body leads to the question as to where transition occurs without suction in order to determine the location of the first slot. The literature available on this subject is very limited. Preliminary experiments on an 8:1 ellipsoid (see Northrop Report BLC-6) indicated a maximum transition Reynolds number $R_T = X_T/L\ R_L$ of the order of 3.1 x 10^6 where X_T is the location of transition and L the length of the body. High speed tunnel measurements by Göthert in Germany gave maximum values of R_T of about 4 x 10^6 at Mach numbers beyond 0.7. Since it is expected that the shape of the body, i.e. the pressure distribution along the surface, has an effect on the extent of the laminar boundary layer, three different body shapes were investigated at the Northrop low speed wind tunnel.

Author

Availability:
N78-76390
N-53889
AD 130 579

530. Banner, Richard D.; McTigue, John G.; and Petty, Gilbert, Jr.: Boundary-Layer-Transition Measurements in Full-Scale Flight. NACA RM H58E28, 1958.

This paper shows the results obtained in the early flight tests which determined the extent of laminar flow that could be obtained with practical wing-surface conditions.

Chemical sublimation was employed for boundary-layer-flow visualization on the wings of a supersonic fighter airplane in level flight at speeds near a Mach number of 2.0. The tests showed that laminar flow can be obtained over extensive areas of the wing with practical wing-surface conditions.

In addition to the flow visualization tests, a method of continuously monitoring the conditions of the boundary layer was applied to flight testing, using heated temperature resistance gages installed in a Fiberglas "glove" installation on one wing. Tests were conducted at speeds from a Mach number of 1.2 to a Mach number of 2.0, at altitudes from 35,000 feet to 56,000 feet.

Data obtained at all angles of attack, from near 0° to near 10°, showed that the maximum transition Reynolds number on the upper surface of the wing varied from about 2.5×10^6 at a Mach number of 1.2 to about 4×10^6 at a Mach number of 2.0. On the lower surface, the maximum transition Reynolds number varied from about 2×10^6 at a Mach number of 1.2 to about 8×10^6 at a Mach number of 2.0.

Author

Availability:
N78-78570

531. McTigue, John G.; Overton, John D.; and Petty, Gilbert, Jr.: Two Techniques for Detecting Boundary-Layer Transition in Flight at Supersonic Speeds and at Altitudes Above 20,000 Feet. NASA TN D-18, 1959.

The location of transition was measured on a supersonic fighter-type airplane by resistance-thermometer and sublimation techniques. Application of these techniques required the use of only the external surface without disturbing the internal structure. Agreement between the two methods as achieved throughout this program is discussed. Also presented are possible extensions of the program to higher Mach numbers.

Author

Availability:
N78-78571

532. Raspet, August; and Gyorgyfalvy, Dezso: Boundary Layer Studies on the Phoenix Sailplane. Mississippi State Univ. paper presented at VIII Congress of O.S.T.I.V. (Köln, Germany), June 1960.

It was felt by the authors that a critical examination of the Phoenix would provide much useful information and would contribute to further improvements of Eppler's method for designing airfoils.

In view of the excellent geometric stability of the sandwich construction on the Phoenix and the unique mathematical approach to the airfoil design for this sailplane, a concentrated flight research aimed at examining the boundary layer development on the Phoenix airfoil was conducted at Mississippi State University during the spring of 1959. It is the purpose of this paper to report on the research conducted on the Phoenix airfoil. In general, the airfoil was found to fulfill the design conditions laid down by Eppler. In one particular, it even exceeded all expectations in that it attained a maximum lift coefficient of 1.75, considerably higher than classical laminar airfoils.

Author

Availability:
N66-84971
N-87601

533. Russell, W. R.: Analysis of Low-Speed Wind Tunnel Tests of a 30° Swept, Laminar, Suction Wing. NOR-61-233 (Contract AF33(600)-42052), Northrop Corp., Sept. 1961.

Wind tunnel tests were conducted in August 1961 in the Norair low-speed wind tunnel on a symmetrical, 30° swept, 12%-thick, laminar suction wing of constant chord. The objectives of the test were to obtain;

1. experimental data on suction wing stall characteristics with outflow from the leading edge slots,
2. suction requirements for maintaining laminar flow in the presence of a spanwise pressure gradient,
3. strip-tube pressure measurement accuracy at finite angles of attack,
4. low-lift drag of a slotted wing surface without suction, and
5. the effect on the aircraft's moment equilibrium, longitudinally and laterally, or complete loss of suction.

Comparison has been made between measured suction requirements due to spanwise pressure gradients and suction requirements due to spanwise pressure gradients obtained from an empirical method for prediction of such requirements.

Author

Availability:
NOR-61-233

534. Pfenninger, W.; Gross, L. W.; Bacon, J. W., Jr.; and Tucker, V. L.: Experimental Investigation of a 30° Swept 12%-Thick Laminar Suction Wing in the NASA Ames 12-Foot Pressure Wind Tunnel. Rep. No. NOR-60-108 (BLC-129), Northrop Corp., Oct. 1961.

The purpose of the present experiments is the verification of full chord laminar flow on the 30° swept 12%-thick symmetrical low drag suction wing which had previously been tested in the Michigan 5' × 7' tunnel and in the Norair 7' × 10' tunnel, at further increased Reynolds numbers in the Ames 12-foot pressure tunnel.

Low drag boundary layer suction experiments were conducted at high Reynolds numbers on the Norair wing at $\alpha = 0, \pm 1, \pm 1.5$ and -2° angles of attack. At five atmospheres tunnel pressure full chord laminar flow was maintained up to a wing chord Reynolds number $R_c = 29 \times 10^6$ within an angle of attack range of $\alpha = \pm 1^\circ$, with a minimum wing profile drag coefficient at $R_c = 27 \times 10^6$ of $C_{D_{\infty min}} = .00097$ for both wing surfaces (including equivalent suction drag) and a corresponding optimum suction quantity coefficient $C_{Q_{opt}} = .00070$. At $\alpha = \pm 1.5^\circ$ full chord laminar flow was maintained up to $R_c = 22 \times 10^6$ and 24×10^6, respectively.

Author

Availability:
N79-70658
CN-142,351
NOR-60-108 (BLC-129)

535. Gault, Donald E.: An Experimental Investigation of Boundary-Layer Control for Drag Reduction of a Swept-Wing Section at Low Speed and High Reynolds Numbers. NASA TN D-320, 1960.

The model was a 72.96-inch-chord wing panel, swept back 30°, which was installed between end plates to approximate a wing of infinite span. The airfoil section employed was a modified NACA 66-012 in the streamwise direction. Tests were limited to controlling the flow over only the upper surface of the model. Seventeen individually controllable suction chambers were provided below the surface to induce flow through 93 spanwise slots in the surface between the 0.0052- and 0.97-chord stations.

Tests were made at angles of attack of 0°, ±1.0°, ±1.5°, and -2.0° for Reynolds numbers from approximately 1.5×10^6 to 4.0×10^6 per foot. In general, essentially full-chord laminar flow was obtained for all conditions with small suction quantities. Minimum profile-drag coefficients of about 0.0005 to 0.0006 were obtained for the slotted surface at maximum values of the Reynolds number; these values include the power required to induce suction as an equivalent drag.

Author

Availability:
N62-70894

536. Gross, L. W.; Bacon, J. W., Jr.; and Tucker, V. L.: Experimental Investigation and Theoretical Analysis of Laminar Boundary Layer Suction on a 30° Swept, 12-Percent-Thick Wing in the NASA Ames 12-Foot Pressure Wind Tunnel. Summary of Laminar Boundary Layer Control Research, Volume I, ASD-TDR-63-554, U.S. Air Force, Mar. 1964, pp. 96-110. (Available from DDC as AD 605 185.)

Low drag boundary layer suction experiments were conducted at high Reynolds numbers in the Ames 12-foot pressure tunnel on the Norair 30° swept, 12-percent-thick, symmetrical laminar suction wing at $\alpha = 0, \pm 1, \pm 1.5$ and -2° angles of attack. At five atmospheres tunnel pressure full chord laminar flow was maintained up to a wing chord Reynolds number $R_c = 29 \times 10^6$ within an angle of attack range of $\alpha = \pm 1$, with a minimum equivalent total drag coefficient at $R_c = 27 \times 10^6$ of $C_{D_{t_{min}}} = .00097$ for both wing surfaces (including equivalent suction drag) and a corresponding optimum suction quantity coefficient $C_{Q_{opt}} = .00070$. At $\alpha = \pm 1.5^{\circ}$ full chord laminar flow was maintained up to $R_c = 22 \times 10^6$ and 24×10^6, respectively. Calculation of the boundary layer development for several test points at angles of attack $\alpha = 1^{\circ}, 0^{\circ}, +1^{\circ}$ indicate that the laminar boundary layer on a swept laminar suction wing is affected by both the stability of the tangential flow and the crossflow in the boundary layer.

Author

Availability:
N65-25555
AD 605 185

537. Gross, Lloyd W.; and Tucker, Virginia L.: Analysis of the Boundary Layer Development on a 30-Degree Swept Laminar Suction Wing. Rep. No. NOR-61-244 (BLC-134), Northrop Corp., June 1962.

In order to correlate the actual crossflow Reynolds number of the tests on the 30-degree swept laminar suction wing with the theoretical stability limit Reynolds number for the boundary layer crossflow, the boundary layer development over the model was calculated at several test points. The results of these calculations are presented in this report.

The model was designed for operation at a length Reynolds number $R_c = 10^7$. During the experiments, length Reynolds numbers of 28×10^6 were attained with full chord laminar flow. In order to ascertain the effects of operating so far from the design point, calculations were made to determine the inflow of each slot near the trailing edge at the highest length Reynolds numbers attained. The results of these calculations are also included in this report.

Author

Availability:
N78-78476
NOR-61-244 (BLC-134)

538. Boltz, Frederick W.; Kenyon, George C.; and Allen, Clyde Q.: The Boundary-Layer Transition Characteristics of Two Bodies of Revolution, a Flat Plate, and an Unswept Wing in a Low-Turbulence Wind Tunnel. NASA TN D-309, 1960.

An investigation was conducted in the Ames 12-foot low-turbulence pressure tunnel to determine the boundary-layer transition characteristics of two bodies of revolution (fineness ratios 7.5 and 9.0), a flat plate, and an unswept wing (NACA 64_2A015 section) at subsonic speeds. Included in the investigation was a survey of the tunnel turbulence and sound levels using a hot-wire anemometer and a condenser microphone. In all cases it was found that the pressure distribution was a primary factor in determining the level of transition Reynolds number. Adverse effects of increasing Mach number on the transition Reynolds numbers obtained at the lower speeds were found to be attributable to changes in both the frequency and intensity of sound waves in the tunnel.

Author

Availability:
N78-78521

539. Boltz, Frederick W.; Kenyon, George C.; and Allen, Clyde Q.: Effects of Sweep Angle on the Boundary-Layer Stability Characteristics of an Untapered Wing at Low Speeds. NASA TN D-338, 1960.

An investigation was conducted in the Ames 12-Foot Low-Turbulence Pressure Tunnel to determine the effects of sweep on the boundary-layer stability characteristics of an untapered variable-sweep wing having an NACA 64_2A015 section normal to the leading edge. Pressure distribution and transition were measured on the wing at low speeds at sweep angles of 0°, 10°, 20°, 30°, 40°, and 50° and at angles of attack from -3° to 3°. The investigation also included flow-visualization studies on the surface at sweep angles from 0° to 50° and total pressure surveys in the boundary layer at a sweep angle of 30° for angles of attack from -12° to 0°.

It was found that sweep caused premature transition on the wing under certain conditions.

A method is presented for the rapid computation of crossflow Reynolds number on any swept surface for which the pressure distribution is known.

Author

Availability:
N62-70912

540. Hyde, D.: Pressure and Boundary Layer Measurements on a Tapered Swept Wing in Flight. C.P. No. 560, British A.R.C., 1961.

Pressure and boundary-layer measurements were made in flight on a full scale swept half-wing mounted as a dorsal fin on the mid fuselage of an Avro Lancaster aircraft. A Reynolds number range of 0.88×10^6 to 1.86×10^6 per foot was available. The tapered wing had a semi-span of 102.5 in. and an aspect ratio of 2.87; the quarter chord sweep was 40° and the symmetrical section was RAE 102, of 8% thickness/chord ratio along wing.

Comprehensive static pressure measurements were recorded over a nominal incidence range of 0° to 10°. At mid semi-span and zero incidence, the measured chordwise pressure distribution compared well with theory. The nondimensional chordwise and spanwise loadings were in close agreement with Küchemann's predictions, but the experimental lift curve slope was 6% greater than the theoretical value.

From the boundary-layer results the positions of the transition fronts were deduced. No laminar flow was obtained on either surface at the highest Reynolds number of 1.86×10^6 and greater at all test Reynolds numbers.

The secondary flow Reynolds number corresponding to the onset of sweep instability was found to be in the range $80<N<133$; Owen's predicted critical value is 125.

Availability:
N62-10182

541. Pindar, A. C. S.; and Collingbourne, J. R.: Pressure Plotting and Balance Measurements in the High Speed Wind Tunnel on a Half-Model of a 90-deg-Apex Delta Wing With Fuselage. R. & M. No. 2844, British A.R.C., 1954.

Tests were made at a Reynolds number of 1.8×10^6 and Mach numbers up to 0.93. The wing tip was cropped to a taper of 1/7 and the wing section was RAE 102, symmetrical, 10 per cent thickness/chord at 35 per cent chord.

Form drag is highly localised near the root at low speed. Above $M = 0.88$, rearward movement of the strong shock causes a rapid rise of drag at all sections.

Spanwise loading at low incidence is close to potential theory for wing without body up to $M = 0.9$. A tip stall occurs at $M \geqslant 0.9$ for $\alpha = 3.65$ deg and at $M \geqslant 0.8$ for $\alpha = 7.7$ deg, and causes a nose-down moment. Overall lift slope at low C_L's increases to a maximum at about $M = 0.89$, then falls off with signs of a recovery at $M = 0.92$.

Local aerodynamic centres at low C_L agree with potential theory for wing alone at low speeds, but move backwards beyond $M = 0.8$. The overall aerodynamic centre for the wing moves back about 10 per cent mean chord by $M = 0.92$.

There is a loss of elevon power for angles up to -5 deg above $M = 0.92$, as found on a complete model at lower Reynolds number.

Author

Availability:
N78-78485
N-36094

542. Carlson, J. C.: Investigation of the Laminar Flow Control Characteristics of a 33° Swept Suction Wing at High Reynolds Numbers in the NASA Ames 12-Foot Pressure Wind Tunnel in August 1965. NOR-66-58, Northrop Corp., Jan. 1966.

Availability:
X67-81720
NOR-66-58

543. Whites, R. C.; Sudderth, R. W.; and Wheldon, W. G.: Laminar Flow Control on the X-21. Astronaut. & Aeronaut., vol. 4, no. 7, July 1966, pp. 38-43.

Discussion of results from flight-testing the laminar flow control (LFC) system on the X-21 aircraft. It is concluded that (1) the attainment of low drag at length Reynolds numbers to the order of 47 million demonstrates the technical feasibility of laminar flow for aircraft as large as any of the presently planned logistic types, (2) repeated flight demonstrations of predicted performance indicate satisfactory LFC design and analysis techniques, (3) LFC causes no adverse or unusual handling characteristics and requires no new pilot skills, (4) an LFC aircraft can maneuver as normally required for large transports under air traffic control without loss of laminar area, (5) proximity to or entry into clouds or atmospheric turbulence degrades laminar performance, (6) laminar flow tolerates normal variations in chordwise suction distribution, altitude, airspeed, and lift coefficient, and (7) practical manufacturing techniques meet design criteria covering surface irregularities.

Availability:
A66-34949

544. Zozulya, V. B.; and Cheranovskiy, O. R.: Control of Laminar Flow Past a Wing in Free Flight. Fluid Mech. - Soviet Res., vol. 2, no. 5, Sept.-Oct. 1973, pp. 16-20.

It is shown as a result of investigating characteristics of the laminar velocity distribution in free flight that, due to smallness of the disturbances acting in free flight as compared with a wind tunnel, the laminar part of the boundary layer is larger and, as a result, the form drag is smaller. Hence the use of suction in free flight requires a smaller suction rate for obtaining the same size of the laminar zone.

Author

Availability:
A74-15567

545. Frick, Charles W., Jr.; and McCullough, George B.: Tests of a Heated Low-Drag Airfoil. NACA ACR, 1942.

The results of an experimental investigation of an NACA 65,2-016 heated wing are presented. The test data show the following:

1. The chordwise distribution of high skin temperatures normal for heat de-icing can be obtained with negligible effect either on the drag coefficients in the low-drag Reynolds-number range or on the maximum Reynolds number at which low drag is obtained.

2. Distribution of heat along the chord resulting in high temperatures near the minimum pressure position will result in both an increase in the minimum drag coefficients and a marked reduction in the Reynolds-number range over which low drag occurs. This marked reduction of the critical Reynolds number occurs because the decrease in the stability of the laminar boundary layer promotes earlier transition to turbulent flow.

The tests were made primarily to find what changes would be experienced in the minimum drag characteristics of the wing with heat de-icing, and to compare these effects with the results of tests of a low-drag wing equipped with rubber de-icing boots.

Author

Availability:
N79-70280

546. Bussmann: Experimentelle und Theoretische Untersuchungen an Laminarprofilen. TPA 3/TIB Transl. No. GDC 10/1751 T, British Min. Supply, 1942.

Measurements of the lift, drag, pressure distribution and point of conversion of the laminar into turbulent flow were carried out on six laminar profiles of 1 and 2 m. wing chord. The highest Reynolds number reached was $\frac{vl}{\nu} = 6,\ 8.10^6$. The measurements were carried out in the wind tunnel of the Aerodynamical Institute of the Brunswick Technical College (1,2 m. jet diameter) and in the wind tunnel A.1 of the Hermann Göring Aeronautical Laboratory (2,5 m. jet diameter); in particular comparative measurements of the same profiles were also carried out in the two wind tunnels. Some of the profiles under investigation were American laminar profiles, some of our own profiles with the position of maximum thickness extremely far back. The purpose of the investigations was partly to investigate the American profiles more closely, and partly to establish whether the rise in the drag coefficients c_{wp} over Re at high Reynolds numbers, known from earlier measurements and calculations, may be avoided by placing the position of maximum thickness very far back. Running parallel with the measurements, theoretical calculations were carried out for the velocity distribution, the boundary layer and the beginning of the conversion from the laminar to the turbulent state. One of the profiles was investigated also with interference wire and showed the high sensitivity of the laminar profiles to roughnesses of the surface.

Part of the investigations dealt with in the present report were described in a paper read by H. Schlichting at the Conference of the Lilienthal Gesellschaft, - Airscrew Section - in Göttingen on 19.3.1942.

Author

Availability:
N79-73457

547. Richards, E. J.; Walker, W. S.; and Taylor, C. R.: Wind-Tunnel Tests on a 30 Per Cent. Suction Wing. R. & M. No. 2149, British A.R.C., 1945.

Tests carried out on a 16 per cent. suction wing have shown that it is impossible to maintain laminar flow aft of the suction slot at high Reynolds numbers, because of the dynamic instability of the laminar layer over the concave surface. As a result of this finding it was concluded that compared with a normal low-drag wing very little was to be gained by this means on wings of normal thickness-chord ratio except at very high Reynolds numbers. Since however the maximum thickness-chord ratio allowable on low-drag wings is of the order of 18 to 20 per cent., it was realised at once that a considerable gain could be obtained from the new designs by virtue of the fact that there appeared to be no limit to the thickness-chord ratios allowable on this type of wing and that wing thickness-chord ratios of 30-40 per cent. could be used which would give low drags and high maximum lifts.

It was further shown in the 16 per cent. tests that the amount of suction necessary if transition could not be delayed to the slot, and the quantity of air that needed removal from the boundary layer were not changed to any great extent; thus the scheme appeared promising even in the absence of extensive laminar flow because of the structural and storage gains obtained thereby.

The present paper describes tests carried out in the National Physical Laboratory 13 ft. × 9 ft. Wind Tunnel at Reynolds numbers between 0.8 and 3 millions on such a 30 per cent. suction wing to determine whether the suction principle is satisfactory and to investigate the general characteristics of the wing. Ordinates are given in Table 1, while Figure 1 gives the aerofoil profile.
Author

Availability:
N78-78499

548. Gregory, N.; and Walker, W. S.: Further Wind Tunnel Tests on a 30 Per Cent. Symmetrical Suction Aerofoil With a Movable Flap. R. & M. No. 2287, British A.R.C., 1950.

The present work was undertaken in order to extend the existing experimental information on the 30 per cent. Griffith suction aerofoil obtained by Richards, Walker and Taylor (1945), in particular:

(a) to investigate the behaviour of the wing when the flap was deflected,

(b) to test a wider slot and improved internal ducting system,

(c) to investigate further the variation of suction quantity with speed, and

(d) to find the variation of C_D with suction quantity and with different surface conditions.

Tests with zero suction were carried out at a Reynolds number of 2.88×10^6 for a range of incidence of 0-20 deg. and for flap angles of 0-14 deg. With boundary layer suction applied, tests were carried out at this Reynolds number to 6 deg. incidence only, owing to insufficient suction head. At a Reynolds number of 0.96×10^6 the pump power was sufficient to prevent separation up to an incidence of 16 deg.

The flap is effective as a high-lift device. There is considerable scale effect present between the two speeds at which tests were made, and it is desirable to test the wing in the Compressed Air Tunnel in order to estimate flight performance, particularly in the event of suction failure. The suction quantity is high at $R = 0.96 \times 10^6$ but now shows a continuous decrease with increase of

Reynolds number in contrast to the irregular variation found by Richards. With no suction and with laminar flow to the slot, the C_D has the low value, for the thickness of the aerofoil, of 0.010.

Author

Availability:
N78-78500

549. Richards, E. J.; and Burge, C. H.: An Aerofoil Designed To Give Laminar Flow Over the Whole Surface With Boundary-Layer Suction. R. & M. No. 2263, British A.R.C., 1949.

A new type of aerofoil is described over the whole of which it is possible to maintain laminar flow by means of a small amount of boundary-layer suction. Preliminary small scale experiments at Reynolds numbers of about 0.37×10^6 show that the mass flow it is necessary to remove by suction is less than that in the laminar boundary layer at the slot.

On the basis of these small-scale experiments the effective drag of this aerofoil at a Reynolds number R is estimated to be approximately $6.0R^{-1/2}$. Thus at the Reynolds numbers reached in present day flight (say 25×10^6) an effective drag coefficient of 0.0012 may be expected. These figures are all subject to experimental confirmation at higher Reynolds numbers. (This airfoil was designed from a suggestion by Dr. A. A. Griffiths.)

Author

Availability:
N78-78501

550. Fage, A.; and Walker, W. S.: Experiments on Laminar-Flow Aerofoil EQH 1260 in the William Froude National Tank and the 13 ft. × 9 ft. and the 9 ft. × 7 ft. Wind Tunnels at the National Physical Laboratory. R. & M. No. 2165, British A.R.C., 1948.

The purpose was to determine whether the flow conditions in the William Froude National Tank and the new 13 ft. × 9 ft. and 9 ft. × 7 ft. tunnels at the National Physical Laboratory are sufficiently steady to allow the properties of laminar-flow aerofoils to be investigated at high Reynolds numbers: and to obtain information on the behaviour of laminar-flow aerofoil section EQH 1260.

Author

Availability:
N78-78502

551. Transition and Drag Measurements on the Boulton Paul Sample of Laminar-Flow Wing Construction. R. & M. No. 2499, British A.R.C., 1952.

Preston, J. H.; and Gregory, N.: Part I - Measurements in the 13 × 9ft Tunnel at the N.P.L.
Kember, K. W.: Part II - Measurements in the No. 2, 11-1/2-ft Tunnel at the R.A.E.
Preston, J. H.: Part III - Discussion of Results, and Note.

At small incidences lying between ±2 deg and at Reynolds numbers up to 9×10^6, the agreement between measurements made in both tunnels is good. At incidences of ±3 and ±4 deg the transition moves forward with increase of speed more rapidly in the R.A.E. tunnel than in the N.P.L. tunnel, and the transition front is considerably more irregular in the R.A.E. tunnel. This difference occurs in spite of the appreciably less measured turbulence of the R.A.E. tunnel, which may be expected to show up, on a wing with appreciable waviness, near the limit of the low-drag range.

In the N.P.L. tunnel the theoretical low-drag C_L range of ±0.35 is maintained up to about $R = 7 \times 10^6$ with transition back to beyond 0.4c (pressure minimum at 0.45c). In the R.A.E. tunnel, the corresponding R is slightly less. The low-drag range decreases as R is increased until, at $R = 15 \times 10^6$ in the R.A.E. tunnel, the low-drag range of incidence is only ±1 deg. This reduction is attributed to waviness of the model, exaggerated by the turbulence of the tunnel stream. Nevertheless the wing, considering its waviness, has performed remarkably well in both tunnels, especially when compared with previous models of lower waviness. This is put down to:

(a) Absence of any skin joint (except at the leading edge) in regions where laminar flow is expected.

(b) The greater thickness of the aerofoil (18 per cent) and the moderate amount (0.45c) of laminar flow aimed at, both of which contribute to the wide C_L range of ±0.35 and the very strong favourable pressure gradients at small C_L's.

(c) The new evaporation techniques for determining the transition 'front', which enable surface imperfections giving rise to turbulent wakes to be detected and removed, thus avoiding spuriously high drag readings.

The minimum drags as measured in the two tunnels are in good agreement with each other, and also with theoretical predictions using the measured transition points over a range of Reynolds number of 2.5 to 15 millions.

A tunnel-flight comparison on a wing of this thickness designed for a moderate amount of laminar flow would be very valuable. If, as the present results in the R.A.E. tunnel suggest, some relaxation of the waviness requirements may be possible on such wings, then there is a hope of present standards of construction attaining laminar flow on such sections without resort to filling.

Transition phenomena need to be studied further in relation to waviness, and more attention needs to be paid to the form and number of waves in addition to the amplitude when considering means of reducing the curvature gauge readings.

Author

Availability:
N78-78506
N-21802

552. Preston, J. H.; Walker, W. S.; and Taylor, C. R.: The Effect on Drag of the Ejection of Air From Backward-Facing Slots on a 16.2 Per Cent. Griffith Aerofoil. R. & M. No. 2108, British A.R.C., 1946.

Drag measurements were made for three conditions of wing surface and various values of $C_Q \equiv Q$ per ft. run/$U_0 \cdot c$, for air ejected from two sizes of backward-facing slots (0.14 in. and 0.08 in.) located at the position of the discontinuities. The Reynolds number of the tests was $R = 2.3 \times 10^6$ and the incidence was 0 deg.

To prevent separation by blowing, about 2½ times the air necessary to prevent separation by suction is required. When separation is prevented, no comparable drop in C_D occurs. In order to obtain the same C_D as was obtained when separation was just prevented by suction, about seven times as much air must be ejected. Hence, as regards quantity, the suction scheme is by far the better. On a power basis, the merits of the two systems are more difficult to assess, since theoretically a large proportion of the air ejected to prevent separation requires no power. From a purely aerodynamic point of view suction is to be preferred, as potential-flow conditions over the rear of the wing are closely attained. With blowing this is not so likely to be the case and considerable form drag may result.

Author

Availability:
N78-78503

553. Braslow, Albert L.; and Visconti, Fioravante: Investigation of Boundary-Layer Reynolds Number for Transition on an NACA $65_{(215)}$-114 Airfoil in the Langley Two-Dimensional Low-Turbulence Pressure Tunnel. NACA TN 1704, 1948.

A low-turbulence wind-tunnel investigation was made of an aerodynamically smooth NACA $65_{(215)}$-114 airfoil having faired surfaces back to 37 percent chord to determine the magnitude of the boundary-layer Reynolds number at various positions of transition from laminar to turbulent flow along both airfoil surfaces. In addition to boundary-layer measurements, values of the section drag coefficient were obtained by means of the wake-survey method.

The boundary-layer Reynolds number $\left(R_{\delta_{cr}}\right)$ was found to vary in magnitude from approximately 6700 to 8000 at positions of transition ranging from 50 percent chord to 25 percent chord; the values of $R_{\delta_{cr}}$ were based on the boundary-layer thickness δ, which is defined as the distance from the airfoil surface to a point within the boundary layer where the velocity is equal to 0.707 of the velocity at the outer edge of the boundary layer. The results indicated, however, that for a smooth and faired low-drag-type airfoil operating in the low-drag range in an air stream of low turbulence, transition points and drag coefficients may be estimated within approximately 7 percent chord and 0.0003, respectively, of the actual values by assuming a constant value of $R_{\delta_{cr}}$ of 8000.

Author

Availability:
N78-78539

554. Glauert, M. B.; Walker, W. S.; and Raymer, W. G.: Wind Tunnel Tests on a Thick Suction Aerofoil With a Single Slot. Rep. No. F.M. 1150, British N.P.L., Sept. 8, 1947.

This report describes the preliminary two-dimensional wind tunnel tests carried out in the N.P.L. 13 ft. x 9 ft. wind tunnel on a 31.5% thick suction aerofoil, GLAS II, which has a single slot on the upper surface at 69% chord. A backward-facing slot was fitted so that both suction and blowing could be used to prevent separation. Lift, drag, pitching moment, and the flow through the slot were measured. Tests without suction were made at Reynolds numbers of 0.96 and 2.88 millions. The results at the two Reynolds numbers were markedly different, and at the higher speed widely varying values of the drag-coefficient were recorded in the same conditions, there apparently being several possible régimes of flow. With suction, the pump power available only enabled tests to be made at the lower Reynolds number, and with the boundary layer on the upper surface laminar to the slot. At low incidences suction quantities agreeing well with theoretical estimates sufficed to maintain unseparated flow, but at higher incidences the flow tended to break down. Three or four times as much suction was required at all incidences to make the separated flow readhere. With blowing, still larger quantities were necessary, but the spanwise distribution of the flow from the slot was unsatisfactory.

It is planned to modify the internal ducting to reduce the losses, and also to fit a slot with a rounded entry instead of a sharp beak to the front lip. It is hoped that these changes will cure or at least reduce the instability and hysteresis observed when sucking, and will also enable the tests to be extended to cover the cases in which there is a turbulent boundary layer on the upper surface in front of the slot. (This report includes the Ordinates for the GLAS II aerofoil.)

Author

Availability:
N79-70024
N-16820A

555. Wallis, R. A.: On Transition Along a Glass Plate With an Approximate Glas II Pressure Distribution. Aerodyn. Tech. Memo. 78, Aeronaut. Res. Labs., Dep. Supply and Develop. (Melbourne), Dec. 1949.

In connection with the development of the Glas II aerofoil for flight testing Stüper carried out tests on transition along a glass plate. The pressure distribution corresponded to the Glas II distribution except near the leading edge. The object of the tests was to determine, for laminar layers, the effect of a favourable pressure gradient in damping out disturbances created by waviness, flies, etc. Results obtained, however, were very disappointing and as a consequence Williams continued the investigations, noting that the position of the stagnation point affected the results to a large extent and suggesting that the location of the transition point was probably influenced by the shape of the leading edge and tunnel turbulence. The object of the present investigation was to determine the cause of transition.

It was from a stability point of view that the present tests were carried out. The existing test set-up proved very unsuitable for the task for which it was intended. Tunnel modifications will be carried out to clarify the position further.

Author

Availability:
N-3613
N78-79434

556. Salter, C.; Miles, C. J. W.; and Owen, R.: Tests on a Glas II Wing Without Suction in the Compressed Air Wind Tunnel. R. & M. No. 2540, British A.R.C., 1951.

Results are given of an investigation, without the application of suction, into the lift, drag and pitching moment of an aerofoil of 31.5 per cent thickness/chord ratio designed specifically for use with a single suction slot at 0.69c from the leading edge.

The object of the tests was primarily the estimation of the behaviour of the wing at high Reynolds numbers in the event of the failure of the suction, but it was also hoped to obtain information concerning some reasonable method of countering any serious effects that might arise.

Consequently, the tail of the aerofoil was hinged to form an unslotted main flap and fitted with a detachable split flap. Tests were also made with a slotted main flap. The Reynolds number range extended from 0.3×10^6 to 7.3×10^6.

Critical regions were observed and the scale effects were found to be large.

The influence of the flaps was generally more or less normal, although the increase in $C_{L\ max.}$ was less than half that for a conventional aerofoil of similar thickness/chord ratio, the NACA 0030.

The effect of the slot between the main flap and the forward portion of the wing was found to be comparatively small.

Author

Availability:
N78-78504
N-14308

557. Atkins, P. B.; and Keeble, T. S.: Wind Tunnel Tests of a 3'-Chord Two-Dimensional Glas II Aerofoil for Comparison With Flight Tests. Aero. Note 105, Aeronaut. Res. Labs., Dep. Supply (Melbourne), Oct. 1951.

Boundary layer conditions similar to those found in flight on an 8'-chord wing have been reproduced on a 3'-chord wind tunnel model; the local separation just ahead of the front slot observed on the glider occurred on the model, together with laminar flow right into the front slot. The internal slot loss coefficients were also of the same order as those found in flight. The slot loss depends upon the Reynolds No. in the slot throat in much the same way as the friction coefficient does in pipe flow, there being a transition from laminar to turbulent flow at values of Reynolds No. (based on twice the slot width) between 1000 and 2000 depending on flow conditions at entry to the slot.

Alterations made to the slot lip profiles caused no significant reduction in pumping effort to stabilise flow over the rear of the aerofoil; the placing of a transition cord at 50%c had a greater effect than could be found in flight. It is possible that had the cord been placed in a region of adverse gradient a more complete transition of the flow would have resulted.

An interesting change in slot flow can be made by placing a wire near the slot mouth but not on the surface of the model.

All tests were made at zero lift incidence, $R_c = 2.1 \times 10^6$ and a wind speed of 110 f.p.s.

Author

Availability:
N79-70023
N-11838

558. Dengate, R.; and Keeble, T. S.: The Use of an Auxiliary Aerofoil To Stabilise the Flow on Glas II in the Event of Suction Failure. Aero. Note 104, Aeronaut. Res. Labs., Dep. Supply (Melbourne), Aug. 1951.

It has been found possible to maintain orderly flow over the rear of the modified Williams Glas II profile without suction by placing a small auxiliary aerofoil close to the surface near 0.70 C.

The pressure distribution over the main aerofoil, with suction off, can be made to approximate to that obtained normally with minimum suction applied; the wake drag of the combination without suction is less than the minimum "total" drag of main aerofoil alone.

The auxiliary aerofoil incorporated a slat to obtain high lift at low Reynolds Numbers; no serious development of simpler forms was attempted.

This device might well be used to maintain orderly flow over the ailerons in emergency.

Author

Availability:
N79-70022
N-11619

559. Atkins, P. B.; and Keeble, T. S.: Tests on a 3' Chord Two-Dimensional Model With a Modified GLAS II Profile. Aero. Note 102, Aeronaut. Res. Labs., Dep. Supply (Melbourne), May 1951.

Very substantial reductions in pump drag have resulted from the modification of a theoretical profile developed by Williams; the sudden stall of the theoretical shape can also be avoided. With a single slot at 70%c the minimum suction pressure coefficient for stable flow is -0.65 and the corresponding flow coefficient is 0.0015 ($C_L = 0$, $R_C = 1.7 \times 10^6$).

The modification to the profile has induced an unfavourable pressure gradient in the neighborhood of the slot which has (a) reduced the pressure discontinuity at the slot and (b) caused transition just ahead of the slot, which results in a great improvement in slot flow. The experiments on this profile have indicated the main reason for the discrepancy between suction requirements found in pre-flight wind tunnel tests and those in flight.

The conditions controlling separation and transition of the laminar layer near the slot on the present empirical GLAS II section require investigation so that transition may be fixed at a suitable point ahead of the slot independently of changes in model scale or free stream speed.

Author

Availability:
N79-70021
N-11618

560. Atkins, P. B.: Preliminary Wind Tunnel Tests on a Modified Glas II Section Swept Back Wing. Aerodyn. Note 111, Aeronaut. Res. Labs., Dep. Supply (Melbourne), Sept. 1952.

Preliminary low speed wind tunnel tests on a 1/10th scale model of a projected glider with swept back suction wings have led to a considerable modification of the section to produce straight flow over the profile at incidence and to eliminate laminar separation which occurred at the low Reynolds number of the test.

In the course of the development it was found that 1/16" diameter suction holes cause turbulence which decays quickly in a favourable pressure gradient, but persists for 7 or 8 diameters in an unfavourable gradient.

The model is now being altered to the new profile in preparation for the measurement of the aerodynamic characteristics in the 9' x 7' tunnel.

The present tests were made at a wind speed of 85 ft/sec. ($R_{\bar{C}} = 5.4 \times 10^4$) and at 0^o and 7^o incidence.

Author

Availability:
N79-70020
N-21732

561. Gregory, N.; Walker, W. S.; and Raymer, W. G.: Wind-Tunnel Tests on the 30 Per Cent. Symmetrical Griffith Aerofoil With Ejection of Air at the Slots. R. & M. No. 2475, British A.R.C., 1952.

It has been shown by Preston (1946) that ejection of air at the point of velocity discontinuity on a 16.2 per cent. thick Griffith suction aerofoil prevents separation, and that if sufficient air is ejected, the drag is reduced. The present tests were undertaken to apply this principle to the 30 per cent. Griffith aerofoil and to investigate the effect on lift by pressure-plotting the aerofoil.

Ejection of air was found to prevent separation, but about 66 per cent. more air was required than with suction. Three times the suction quantity of air, when ejected, reduced the drag to the low values associated with suction.

At R = 0.96 millions, the range of the tests was 0-18 deg. incidence and 0-14 deg. flap angle. At 18 deg. incidence and 14 deg. flap angle, a C_{NF} of 2.5 was obtained, giving approximately the same lift-curve slope as with suction. Above this angle of incidence, the pump capacity was not large enough for unseparated flow to be attained. With separation prevented, the pitching moments were the same as with suction, but the hinge moments were sensitive to small changes of blowing quantity.

At R = 2.88 millions, the pump capacity was insufficient to prevent a partial stall at 6 deg. incidence as occurred with suction.

Curves of C_{NF}, C_Q, C_M, C_H, C_D and velocity distribution when blowing are given, and comparisons are made with corresponding curves obtained with suction and with no suction. The same lift and pitching moments are obtained at any incidence with blowing and with suction, but the suction quantities are about 40 per cent. less than the blowing quantities. The hinge moments are greatly different with blowing, and increase with increase of the normal force.

Author

Availability:
N78-78505
N-16333

562. Pearcey, H. H.; and Rogers, E. W. E.: The Effect of Compressibility on the Performance of a Griffith Aerofoil. R. & M. No. 2511, British A.R.C., 1953.

Experiments have been made in the 20 in. × 8 in. High Speed Tunnel at the National Physical Laboratory on a 9-in. chord, 22 per cent thick, symmetrical Griffith section at 0 deg incidence. Drag was determined by the pitot traverse method. Information on the flow was obtained from the pitot tube traverses, from direct shadow photographs, and from normal pressure measurements. Three Mach numbers of the undisturbed stream were covered, namely 0.4, 0.6 which is just below the theoretical critical, 0.65, for the section, and 0.7 at which shock waves were present. Estimates of the power absorbed by the compressor, ignoring duct losses, are made from measurements of the mass of air sucked and the static pressure in the slots. Additional information was obtained on the adverse effect of a large radius of the forward lip of the slot, on the effect at $M_o = 0.4$ of an increase in slot width, and on the choke quantities for the slots.

Below the critical Mach number, at the Reynolds numbers of flight, there is likely to be a saving of power, the gain decreasing as the critical Mach number is approached. For Mach numbers above the critical the results obtained are incomplete, but they indicate that modifications in the design may be desirable for these speeds.

Author

Availability:
N78-78507
N-26535

563. Cumming, R. W.; Gregory, N.; and Walker, W. S.: An Investigation of the Use of an Auxiliary Slot to Re-Establish Laminar Flow on Low-Drag Aerofoils. R. & M. No. 2742, British A.R.C., 1953.

The use of an auxiliary slot on a laminar-flow aerofoil has been investigated to check whether laminar flow can be re-established by suction at the rear of the region of deposited dirt, flies, etc.

Results indicate that in the absence of unfavourable pressure gradients, it is possible to re-establish a laminar boundary layer by removing a little more than the whole turbulent layer reaching the slot, and preliminary estimates suggest that with efficient ducting it should be possible to achieve a reduction in overall effective drag coefficient by this means.

The auxiliary slot under investigation was cut in the surface of a symmetrical low-drag aerofoil 13 per cent thick with maximum thickness at 50 per cent chord. The model had a 5-ft chord and was mounted two-dimensionally in the N.P.L. 13 × 9 ft Wind Tunnel.

Author

Availability:
N78-78508
N-26859

564. Wilkinson, Stephen P.: An Experimental Investigation of a Turbulent Boundary Layer With Suction Through Closely Spaced Streamwise Slots. M.S. Thesis, Old Dominion Univ., 1978.

The object of this research was to experimentally evaluate a suction surface for use with incompressible turbulent boundary layers. The surface consisted of an array of closely spaced slots aligned in the direction of the free stream flow. Direct drag and mean boundary layer velocity profile measurements showed that the slotted surface had nominally the same suction characteristics as the porous surface.

Availability:
N78-78788

565. Gregory, N.; Walker, W. S.; and Devereux, A. N.: Wind-Tunnel Tests on the 30 Per Cent Symmetrical Griffith Aerofoil With Distributed Suction Over the Nose. R. & M. No. 2647, British A.R.C., 1953.

These experiments were devised to test the effect of distributed suction over the leading edge of the 30 per cent Griffith section. This report describes tests carried out on the 30 per cent Griffith symmetrical aerofoil with continuous suction applied through a porous capping fitted over the front 15 per cent of the upper surface. Throughout the range of incidence covered in the experiments, distributed suction was found to decrease the slot suction necessary to prevent separation, especially when the distributed suction caused rearward movement of the transition position.

The profile drag of the aerofoil was measured, and estimates were made of the equivalent drag coefficients for the work done by the suction pumps. Assuming no losses additional to those in the boundary layer, it was found that the effect of distributed suction was to reduce slightly the overall drag of the aerofoil.

Measurements of the velocity within the boundary layer were made at various chordwise positions on the porous surface; the profiles recorded were very close to the theoretical. Distributed suction was able to delay transition when this would otherwise be precipitated by a ridge on the surface, or by adverse pressure gradients, but a turbulent boundary layer remained turbulent when suction was applied. The characteristic spread of turbulent flow in the wake of a small particle on the surface was much reduced by distributed suction; under favourable conditions, the wake was entirely eliminated.

Author

Availability:
N78-78512
N-27233

566. Pfenninger, W.: Experiments With Laminar Flow in a Two-Inch-Diameter 40-Foot-Long Tube at High Reynolds Numbers. Rep. No. AM-128 (Contract AF33(038)-11386), Northrop Aircraft, Inc., Dec. 20, 1950.

Laminar flow experiments have been carried out at high Reynolds numbers in a two-inch-diameter 40-feet-long straight tube. External disturbances have been reduced by installing a sonic throat at the end of the tube. A honeycomb of small mesh size and thirteen damping screens have been installed ahead of the tube inlet.

Laminar flow was observed in the tube at high Reynolds numbers by means of a stethoscope, and by boundary layer and pressure distribution measurements along the tube. A maximum transition Reynolds number, $R_\theta \cong 2900$, (based on boundary layer momentum thickness) has been achieved, for a slightly accelerated flow, corresponding to a length Reynolds number at transition of $19 \cdot 10^6$.

Author

Availability:
N78-78549
N-11020

567. Pfenninger, W.: Further Laminar Flow Experiments in a 40-Foot-Long 2-Inch-Diameter Tube. Rep. No. AM-133 (Contract No. 33(038)-11386), Northrop Aircraft, Inc., Feb. 20, 1951.

This report gives results of further laminar flow experiments in a 40-foot-long 2-inch-diameter straight tube (see earlier Northrop Report AM-128). The test setup was improved by carefully aligning the 40-foot tube and the sonic throat at the end of the measuring tube. Furthermore, finer damping screens were used at the inlet (0.0045-inch wire diameter and 65% open area). The experiments were carried out in the same manner as those in Northrop Report AM-128.

Author

Availability:
N79-70019
N-11021

568. Pfenninger, W.: Boundary Layer Suction Experiments With Laminar Flow in a Tube at High Reynolds Numbers With One Suction Slot. Rep. No. AM-134 (Contract No. 33(038)-11386), Northrop Aircraft, Inc., Feb. 20, 1951.

Boundary layer suction experiments have been carried out in a laminar flow tube consisting of a 20-foot or 40-foot 2-inch-diameter straight tube followed by a slightly expanding tube with eight suction slots. Suction was applied only in one slot (slot 1 or 2). This research was carried out in order to answer the question: "Is it possible to maintain laminar flow through a region of a pressure rise at high Reynolds numbers by means of suction in several slots?"

Author

Availability:
N79-70018
N-11022

569. Pfenninger, W.: Experiments With Laminar Boundary Layer Suction in a Tube at High Reynolds Numbers With Eight Suction Slots. Rep. No. AM-141 (Contract No. 33(038)-11376), Northrop Aircraft, Inc., May 1951.

Boundary layer suction experiments have been carried out in a laminar flow tube consisting of a 20-foot, two-inch diameter, straight tube followed by a suction tube with eight slots, with suction in all slots. Laminar flow could be maintained by means of suction on the whole tube at length Reynolds numbers of up to $14.7 \cdot 10^6$ through a pressure rise of 30% to 60% of the pressure difference between stagnation pressure and pressure minimum. At lower Reynolds numbers ($12 \cdot 10^6$ length Reynolds number) a laminar pressure rise of 80% of the pressure difference between stagnation pressure and minimum pressure was observed.

Author

Availability:
N79-70017
N-12513

570. Pfenninger, W.; and Meyer, W. A.: Transition Experiments in the Inlet Length of Laminar Flow Tubes at High Reynolds Numbers and Small External Disturbances. Summary of Laminar Boundary Layer Control Research, WADC Tech. Rep. 56-111, U.S. Air Force, Apr. 1957, pp. 15-17. (Available from DDC as AD 130 759.)

During previous laminar flow experiments in 2-inch ID tubes, transition length Reynolds numbers had been measured. The purpose of the present investigation was to increase these values by further reducing external disturbances.

External disturbances were reduced by damping screens at the tube inlet and by an improved sonic throat at the end of the test tube ahead of the compressor.

Availability:
N78-76390
N-53889
AD 130 759

571. Pfenninger, W.; and Meyer, W. A.: Transition Experiments in the Inlet Length of a 1-Inch I.D. Tube at High Reynolds Numbers and Low Turbulence. Rep. No. BLC-24, Northrop Aircraft, Inc., Nov. 1953. (Available from DDC as AD 30 321(a).)

Laminar flow experiments were conducted in the inlet length of a 1.007" i.d. tube of 50 ft length at high Reynolds numbers and low turbulence level. The experimental setup was similar to that of Ref. 1. External disturbances were reduced by damping screens at the tube inlet and by an improved sonic throat at the end of the test tube ahead of the compressor.

Completely laminar flow through the whole tube was observed up to a length Reynolds number $\frac{\bar{U}x}{\nu} = 53.2 \cdot 10^6$, with accelerated flow (the local velocity U at the edge of the boundary layer at the downstream end of the tube was 1.50 times the mean velocity $\bar{U}$). Intermittent laminar and turbulent flow was observed at $54.5 \cdot 10^6$ length Reynolds number.

Author

Availability:
SN-24021, Dec. 1953
BLC-24
AD 30 321(a)
N79-75684

572. Goldsmith, John; and Meyer, W. A.: Laminar Flow Experiments in the Inlet Length of a 2-Inch Tube at High Reynolds Numbers and Small External Disturbances With Boundary Layer Suction Through Holes. Summary of Laminar Boundary Layer Control Research, WADC Tech. Rep. 56-111, U.S. Air Force, Apr. 1957, pp. 8-10, 18-19, and 32-38. (Available from DDC as AD 130 759.)

In September 1953, experiments were begun to determine whether or not extensive laminar flow could be maintained at high Reynolds numbers by means of suction through holes. In the first experiments, suction was applied to a single hole to determine if disturbances would arise as a result of the three-dimensional flow field in the vicinity of the single hole.

Experiments were next conducted to determine whether or not there is interference between adjacent holes in a row. It remained to be determined whether or not there is interference between holes in adjacent rows of holes. To summarize, the critical suction quantity per row of holes for wide- and intermediate-spaced holes is generally reduced as additional rows are added in the tube.

Finally, laminar suction experiments were conducted in a 2-inch diameter low turbulence tube with 80 rows of closely spaced suction holes (110 holes row) at the downstream end of the tube. Laminar flow was observed for these experiments for tube length Reynolds numbers from 8.5 to 18.8 million, and pressure rises in the suction region from 36% to 69% of the maximum dynamic pressure.

Profile drag coefficients of equivalent symmetrical suction airfoils having the same pressure distribution as the tube, were estimated from the results of these experiments.

The results of these experiments with 80 rows of holes are given. Similar experiments were previously conducted for 80 slots and a comparison was made between the performance of the slots and rows of holes. It was found that the slots are generally more efficient than the rows of holes, but not so much more efficient as to eliminate the use of rows of holes where other considerations may favor them.

Author

Availability:
N78-76390
N-53889
AD 130 759

573. Meyer, W. A.: Smoke Observations of the Laminar Flow in an 8-Inch Tube With Suction Through Holes. Summary of Laminar Boundary Layer Control Research, WADC Tech. Rep. 56-111, U.S. Air Force, Apr. 1957, pp. 10-12, 18-19, and 39-41. (Available from DDC as AD 130 759.)

In order to better understand the results obtained with low drag suction through holes in the 2-inch tube and to obtain a clearer insight of the flow phenomena involved, laminar suction experiments were conducted in an 8-inch tube at low speeds and with thick boundary layers. The flow in the boundary layer was observed with smoke.

The first test section configuration consisted of a row of ten 1/8-inch diameter holes drilled 1/2-inch apart in the transparent tube at right angles to the tube flow. These holes were used singly and in pairs to produce the various flow fields. Suction through one hole was the first configuration tested, then suction through two adjacent holes, and finally through one row of twenty-four holes.

Availability:
N78-76390
N-53889
AD 130 759

574. Pfenninger, W.; Meyer, W. A.; Moness, E.; and Sipe, O. E.: Laminar Flow Experiments in the Inlet Length of a 2-Inch Tube at High Reynolds Numbers and Small External Disturbances With Boundary Layer Suction Through 80 Slots. Summary of Laminar Boundary Layer Control Research, WADC Tech. Rep. 56-111, U.S. Air Force, Apr. 1957, pp. 2-8, 18, and 20-29. (Available from DDC as AD 130 759.)

Laminar flow was observed in a tube with 80 suction slots through a pressure rise of 14% to 89% of the pressure difference between stagnation pressure and pressure minimum at length Reynolds numbers up to 20 x 10^6 and at a low turbulence level. A maximum Reynolds number of 21.2 x 10^6 with 40% laminar pressure rise was observed. The minimum suction quantities for complete laminar flow were approximately 27% smaller than with suction through eight slots with the same test setup.

Author

Availability:
N78-76390
N-53889
AD 130 759

575. Pfenninger, W.; Moness, E.; and Sipe, O. E., Jr.: Investigation of Laminar Flow in a Tube at High Reynolds Numbers and Low Turbulence With Boundary Layer Suction Through 80 Slots. Rep. No. BLC-53, Rep. No. NAI-54-488, Northrop Aircraft, Inc., July 1954. (Available from DDC as AD 54 971.)

Practically completely laminar flow was observed in a low turbulence tube with 80 suction slots through a pressure rise of 14% to 71% of the pressure difference between stagnation pressure and pressure minimum at high length Reynolds numbers. Data have been presented for length Reynolds numbers $\frac{\bar{U} \cdot x}{\nu}$ up to 17.5 x 10^6. The highest length Reynolds numbers observed with completely laminar flow were around 18.7 x 10^6, however external disturbances easily caused transition in these cases.

The profile drag coefficient of an equivalent suction airfoil having the same chordwise pressure distribution as the tube has been estimated from the

tube test data (from the measured boundary layer profile at the end of the tube, suction quantities and static pressures in the individual suction chambers).
Author

Availability:
SN-24021, July 1954
BLC-53
NAI-54-488
AD 54 971

576. Meyer, W. A.; and Pfenninger, W.: Preliminary Investigations of Laminar Flow in a Tube at High Reynolds Numbers and Low Turbulence With Boundary Layer Suction Through 80 Slots. Rep. No. BLC-7, Northrop Aircraft, Inc., Aug. 1953. (Available from DDC as AD 20 076(a).)

Laminar flow was observed in a tube with 80 suction slots through a pressure rise of 30% to 89% of the pressure difference between stagnation pressure and pressure minimum at length Reynolds numbers up to $20 \cdot 10^6$ and at a low turbulence level. A maximum Reynolds number of $21.2 \cdot 10^6$ with 40% laminar pressure rise was observed. The minimum suction quantities for completely laminar flow were approximately 20% smaller than with suction through 8 slots with the same test setup.

Availability:
SN-24021, Aug. 1953
BLC-7
AD 20 076(a)

577. Holstein, H.: Messungen zur Laminarhaltung der Grenzschicht durch Absaugung an einem Tragflügel. Bericht S10, L.G.L., Preisausschreiben, 1940, pp. 17-27.

Availability:
N78-78551

578. Pfenninger, W.: Experiments on a Laminar Suction Airfoil of 17 Per Cent Thickness. J. Aeronaut. Sci., vol. 16, no. 4, Apr. 1949, pp. 227-236.

Boundary-layer suction experiments have been carried out on a 17 per cent thick laminar airfoil in the 7- by 10-ft. wind tunnel of the Institute for Aerodynamics at the Federal Institute of Technology, Zürich. With small suction quantities ($c_{Q_t} = 0.0014$ to 0.0018), the boundary layer could be kept completely laminar on both sides of the airfoil within a considerable range of lift coefficients. The profile drag was reduced to one-half: $c_{d_{\infty_{min.}}} = 0.0023$ at $Re = 2.4 \times 10^6$ with suction (including the power absorbed for suction) as against $c_{d_{\infty_{min.}}} = 0.0048$ at $Re = 2 \times 10^6$ without suction. The range of c_l-values with low drag coefficients was more than doubled, and an optimum gliding angle of the airfoil $\varepsilon_{\infty_{\text{opt.}}} = 1/200$ was obtained. With moderate deflections of a small trailing-edge flap ($c_F = 0.108c$) a favorable envelope of the polars, as well as an optimim gliding angle of the airfoil $\varepsilon_{\infty_{\text{opt.}}} = 1/250$, was reached.

Author

579. Braslow, Albert L.; Visconti, Fioravante; and Burrows, Dale L.: Preliminary Wind-Tunnel Investigation of the Effect of Area Suction on the Laminar Boundary Layer Over an NACA 64A010 Airfoil. NACA RM L7L15, 1948.

A preliminary investigation was made in the Langley two-dimensional low-turbulence tunnel on an NACA 64A010 airfoil with permeable surfaces to obtain an indication of the stabilizing effect of area suction on the laminar boundary layer. Boundary-layer velocity profiles were measured at Reynolds numbers of 2.0×10^6, 4.0×10^6, and 6.0×10^6 and at various chordwise stations for values of the flow coefficient up to 0.012.

Although the surfaces of the airfoil model that was tested had many waves and irregularities of contour, the data corroborated qualitatively the theoretically predicted stabilizing effect of area suction on a smooth flat plate. The suction quantity required for the wavy airfoil tested, however, was much greater than the theoretical value for a smooth flat plate.

Author

Availability:
N78-78540

580. Loftin, Laurence K., Jr.; and Horton, Elmer A.: Experimental Investigation of Boundary-Layer Suction Through Slots To Obtain Extensive Laminar Boundary Layers on a 15-Percent-Thick Airfoil Section at High Reynolds Numbers. NACA RM L52D02, 1952.

The results presented indicate that essentially full-chord laminar flow with large net drag savings can be obtained through the use of multiple suction slots for Reynolds numbers as high as 16.0×10^6 to 17.0×10^6. These results, however, could be obtained only after a very high degree of surface excellence had been achieved on the model.

Author

Availability:
N78-78541

581. Pfenninger, W.: Experiments With a 15%-Thick Slotted Laminar Suction Wing Model in the NACA, Langley Field, Low Turbulence Wind Tunnel. Tech. Rep. 5982, U.S. Air Force, Apr. 1953.

Boundary layer suction experiments have been conducted on a 15%-thick slotted laminar-suction wing of 5-foot chord in the Low Turbulence Pressure Tunnel at the NACA, Langley Field, Virginia. Completely laminar flow was achieved on both wing surfaces up to $17 \cdot 10^6$ chord Reynolds number by means of suction in slots. With increasing Reynolds number, the drag at first decreased in a manner similar to that of friction drag on a laminar flat plate. At the design lift coefficient the minimum drag at 16.3 · 10^6 chord Reynolds number was $c_{D_{oo}}$ = 0.0011 including the equivalent drag due to the suction power. At still higher Reynolds numbers the drag increased again, very probably due to the combined effects of tunnel turbulence and noise and surface waviness. A high surface standard (small waviness and roughness) was necessary to achieve completely laminar flow at high Reynolds numbers.

Author

Availability:
N79-70281
N-22183

582. Burrows, Dale L.; and Schwartzberg, Milton A.: Experimental Investigation of an NACA 64A010 Airfoil Section With 41 Suction Slots on Each Surface for Control of Laminar Boundary Layer. NACA TN 2644, 1952.

The 3-foot-chord model was designed according to an analysis presented herein to maintain nearly full-chord laminar flow at Reynolds numbers up to 25 × 10^6 with the use of 41 suction slots on each surface.

Laminar flow was maintained over at least 0.91 chord on one surface up to a Reynolds number of 10 × 10^6. A like extent of laminar flow on the other surface would have resulted in a net drag saving of about 50 percent over the plain smooth airfoil at Reynolds numbers as high as 10 × 10^6. This result was obtained only after the expenditure of a great amount of effort in forming slot-entry contours that would not cause transition and in maintaining the surfaces of the model and the edges of the slots sufficiently smooth. Extensive laminar flow was not obtained at higher Reynolds numbers because of the increasing sensitivity of the flow to minute surface irregularities and slight inaccuracies of slot-entry contour.

Author

Availability:
N78-78547

583. Smith, A. M. O.; and Brazier, J. G.: Wind-Tunnel Tests on a Six-Foot Chord Model of the DESA-2 Laminar Suction Airfoil. Rep. No. ES 17129 (Contract No. NOa(s) 9027), Douglas Aircraft Co., Inc., Mar. 9, 1953.

Two series of tests have been performed on the DESA-2 airfoil, a 6.6 percent thick, 16-slot suction airfoil having a sawtooth pressure distribution. One series took place in the GALCIT TDT; the other in the Langley NACA TDPT. By means of the sawtooth distribution, much more rapidly accelerating velocities were possible than on conventional airfoils of about the same thickness, and, as a consequence, the airfoil had a very high stability with respect to Tollmien-Schlichting waves. Because of this feature, there was considerable hope that 100 percent laminar flow could be maintained to very high Reynolds numbers, or conversely, that the model would show reduced sensitivity to roughness at moderate Reynolds numbers.

The tests failed completely to bear out the expectation, for the model was no different from previous models, either boundary layer control or otherwise.

Extensive hot wire surveys of an exploratory nature were made to diagnose the causes of difficulty.

Author

Availability:
N78-78552
N-24513

584. Brazier, J. G.: Instrumentation for Tests on a Laminar-Boundary Layer Control Airfoil. Rep. No. ES 17126 (Contract NOa(s) 9027), Douglas Aircraft Co., Inc., Dec. 30, 1952.

Instrumentation which was used during wind tunnel tests of a laminar-boundary layer control airfoil model is discussed. It includes measurements of airflow rate and measurements of boundary-layer properties. For the first, orifice plates were designed and calibrated. For the second, hot-wire anemometer equipment, hot-wire anemometers, actuators and small total-head tubes were purchased, or designed and fabricated, and calibrated.

Author

Availability:
N79-70029
N-22822

585. Loftin, Laurence K., Jr.; and Horton, Elmer A.: Experimental Investigation of Laminar-Boundary-Layer Control on an Airfoil Section Equipped With Suction Slots Located at Discontinuities in the Surface Pressure Distribution. NACA RM L53J14, 1953.

An experimental investigation has been made of a two-dimensional 6.6-percent-thick, 6-foot-chord airfoil section equipped with suction slots for laminar-boundary-layer control. The airfoil section was designed to have favorable pressure gradients between the suction slots which were located at discontinuities in the airfoil surface pressure distribution. The upper surface contained nine slots, whereas the lower surface contained seven slots. The investigation indicated that the laminar boundary layer on this airfoil had the same extreme sensitivity to minute details of the model surface condition as has been found in other investigations of laminar-boundary-layer control.

Author

Availability:
N78-78542

586. Kay, J. M.: Boundary-Layer Flow Along a Flat Plate With Uniform Suction. R. & M. No. 2628, British A.R.C., 1953.

Experiments have been carried out in the closed-circuit wind-tunnel at Cambridge University to determine the effectiveness of distributed suction as a means of controlling and stabilizing the flow in a boundary layer. These experiments have shown that the laminar exponential suction profile can be established and retained, provided the boundary layer is in an undisturbed laminar condition at the start of the suction region. Good agreement has been obtained between the measured velocity profiles and the theoretical exponential form. It has also been shown that the laminar suction profile, when once established, is able to surmount small disturbances which would normally be sufficient to promote transition in the absence of suction. There is, however, no evidence whatever to suggest that laminar flow can be re-established if transition once occurs.

The variation with rate of suction of the total effective drag of a flat plate has been investigated. It has been established that, from the point of view of drag reduction, the optimim rate of suction is the minimum rate which is sufficient to maintain laminar flow under the prevailing conditions of stream turbulence and surface finish. A suction velocity ratio of approximately 0.0010 has proved necessary in order to ensure the preservation of laminar flow with the conditions prevailing in the wind-tunnel at Cambridge, although a lower figure may be adequate under the steadier air conditions of free flight.

As far as turbulent flow is concerned, it has been shown that distributed suction provides an effective method of thinning a turbulent boundary layer. Some evidence has also been accumulated to show that an asymptotic turbulent suction profile may be closely approached at sufficient values of suction velocity. A theoretical basis has been suggested for this type of boundary-layer flow, using the vorticity transfer theory, which has given good agreement with the experimental results.

Author

Availability:
N78-78509
N-26846

587. Groth, Eric E.: Low Speed Wind Tunnel Experiments on a Body of Revolution With Low Drag Boundary Layer Suction. Rep. No. NAI-58-335 (BLC-107) (Contract AF33(616)-3168), Northrop Aircraft, Inc., May 1958.

Full laminar flow and low drag coefficients at zero incidence were obtained on a 142 inch long elliptic body of revolution of fineness ratio 9 in low speed wind tunnel experiments up to length Reynolds numbers of the order of $14 \cdot 10^6$. The optimum total drag coefficient (including suction drag) was 1.24 times the friction coefficient of a laminar flat plate for Reynolds numbers below $11 \cdot 10^6$. A few measurements at angles of attack up to 3° showed that laminar flow could be maintained at slightly higher suction quantities and drag coefficients.

Author

Availability:
SN-24021, May 1958
NAI-58-335 (BLC-107)

588. Groth, E. E.: Calculation of the Boundary Layer With Continuous Suction Around a Body of Revolution of Fineness Ratio 8. Rep. No. BLC-5, Northrop Aircraft, Inc., Aug. 1953. (Available from DDC as AD 20 076(b).)

The development of the laminar boundary layer on an ellipsoid of fineness ratio 8 with modified rear end is computed for various amounts of continuous suction in the rear half of the body. The problem for the body of revolution is transformed to a two-dimensional problem by means of Mangler's transformation, and then the boundary layer equations are solved by Görtler's difference method. An estimation of the drag of the body shows that drag coefficients of the order of 1.26 times the laminar friction drag of a flat plate might be possible for moderate suction quantities. This value includes the power needed for the acceleration of the sucked air to the free stream velocity.

It is intended to test the same body in a wind tunnel at high Reynolds numbers (up to $30 \cdot 10^6$) and compare the theory with the test results.

Theoretical studies indicated that it is possible to maintain laminar flow over a body of revolution by sucking away part of the laminar boundary layer. The calculations made for an ellipsoid of fineness ratio 8 (see Northrop Report BLC-5) were used to design and build such a body with a small number of suction slots for wind tunnel and flight experiments to confirm the theoretical predictions concerning drag coefficients and necessary suction quantities.

The design of the body was started in the summer of 1953, and the first experiments took place at the Northrop low speed wind tunnel in April 1956.

Author

Availability:
SN-24021, Aug. 1953
BLC-5
AD 20 076(b)

589. Sipe, O. E., Jr.: Note on the Turbulence Level of the Northrop Wind Tunnel. NAI-55-946, Rep. No. BLC-82, Northrop Aircraft, Inc., Oct. 1955. (Available from DDC as AD 89 596(b).)

Drag and transition investigations of a 96-inch modified ellipsoid in the 12-Ft. Ames Low Turbulence Wind Tunnel and the Northrop Wind Tunnel showed low transition Reynolds numbers nearly equal in value. This suggested that the Northrop Wind Tunnel had a relatively low turbulence level, thus permitting future tests of laminar suction bodies of revolution and low drag suction wings at moderately high Reynolds numbers.

Transition experiments were conducted in the Northrop Wind Tunnel on a 96-inch chord flat plate to investigate the turbulence level, and also to better understand the reason for the low transition Reynolds numbers observed on the 96-inch body.

The value of 3.75×10^6 transition Reynolds number for practically zero pressure gradient compares reasonably well with the transition Reynolds number of 4.5×10^6 observed on a flat plate with a circular arc leading edge in the 12-ft low turbulence tunnel at the NACA Ames Laboratory. Transition experiments in the small R.A.E. low turbulence tunnel gave a somewhat higher value of 6×10^6 transition Reynolds number on a flat plate.

The relatively low turbulence level of the NAI Wind Tunnel will permit many preliminary laminar suction experiments to be conducted in this tunnel, for example, swept laminar suction wings, laminar suction bodies and wing root junctures.

Author

Availability:
SN-24021, Oct. 1955
NAI-55-946
BLC-82
AD 89 596(b)
N79-75745

590. Pfenninger, W.; Gross, Lloyd; and Bacon, John W., Jr.: Experiments on a 30^o Swept 12%-Thick Symmetrical Laminar Suction Wing in the 5-Ft. by 7-Ft. Michigan Tunnel. Rep. No. BLC-93, Rep. No. NAI-57-317, Northrop Aircraft, Inc., Feb. 1957.

Low drag boundary layer suction experiments were conducted in the 5' × 7' Michigan wind tunnel on a 2-dimensional, 12%-thick symmetrical laminar suction wing model of 30^o sweep at $\alpha = 0^o$, 1^o and -1^o angle of attack. Suction was applied through 86 fine slots from 25% chord to 95% chord. At $\alpha = 0^o$, 100% laminar flow and low profile drags were observed up to a wing chord Reynolds number $R_c = 11.8 \times 10^6$. The minimum profile drag was $c_{D_t} = .00125$ at $R_c \cong 11.8 \times 10^6$ and $\alpha = 0^o$ (drag for both wing surfaces, including the equivalent drag due to the suction power). With increasing wing chord Reynolds number, the optimim profile drag decreased at a slower rate than the laminar friction drag of a flat plate due to increasing values of $c_{Q_t} R_c$ with R_c. The minimum suction quantities c_{Q_t} required for 100% laminar flow were somewhat larger than for an equivalent straight laminar suction wing. The measured drag values agreed closely with theoretical values. The measured critical minimum suction quantities for 100% laminar flow were slightly smaller than the theoretical ones. This experiment proves the feasibility of 100% laminar flow and very low profile drags on swept laminar suction wings, at least for moderately large wing chord Reynolds numbers.

Author

Availability:
SN-24021, Nov. 1958
BLC-93
NAI-57-317
N79-75695

591. Bacon, J. W., Jr.; Tucker, V. L.; and Pfenninger, W.: Experiments on a 30^o Swept, 12% Thick Symmetrical Laminar Suction Wing in the 5- by 7-Foot University of Michigan Tunnel. Rep. No. NOR-59-328 (BLC-119), Northrop Aircraft, Inc., Aug. 1959.

The first series of tests on this wing (NAI-57-317, BLC-93), proved that full chord laminar flow can be maintained on a swept wing with adequate suction throughout the strong crossflow region in the aft portion of the wing at chord Reynolds numbers of at least 12×10^6. In addition, the leading edge crossflow instability was not critical at 0° and +1°, but was critical at a chord Reynolds number above 7×10^6 for -1° angle of attack. In the present series of tests, the swept wing laminar suction model has been modified by the installation of slots forward to achieve laminar flow at higher R.N. where the less severe leading edge crossflow becomes critical at 0° angle of attack. Full chord laminar flow low friction drags were observed up to the tunnel-limited wing chord R.N. The measured drags at 0° were slightly lower than those from the first series of tests and there were no indications that the forward slots caused any disturbances with or without suction applied. This suggests that laminar flow on swept wings is possible to much higher wing chord Reynolds numbers.

Availability:
NOR-59-328 (BLC-119)
N79-77132

592. McCormick, Barnes W., Jr.: An Experimental Study of Drag Reduction by Suction Through Circumferential Slots on a Buoyantly-Propelled, Axi-Symmetric Body. Naval Hydrodynamics - Ship Motions and Drag Reduction, ACR-112, Office of Naval Res., Dep. of Navy, 1964, pp. 1001-1015.

This paper presents the analysis, design, and results of testing performed to date on TRI-B, a buoyantly-propelled body incorporating boundary layer control by suction through circumferential slots. This body is designed to maintain a nearly, full-length laminar boundary layer at a length Reynolds number of 39×10^6. Although the expected performance has not yet been achieved in the field with the free-running body, nearly full-length laminar flow has been measured in wind tunnel tests at lower Reynolds numbers. From the results of an analysis based on the Karman-Pohlhausen method, it is believed that transition is occurring ahead of the first suction slot at the higher Reynolds number.
Author

Availability:
N-61721 (1964)

593. Summary of Additional Studies Leading to the Development of a Laminar Flow Torpedo. Rep. No. NOR 65-230 (BLC-164) (Contract NOw 64-0390-C), Northrop Corp., Dec. 1965. (Available from DDC as AD 373 647.)

Availability:
NOR 65-230 (BLC-164)
AD 373 647

594. Gross, L. W.: Investigation of a Laminar Suction Body of Revolution Having a Cylindrical Centersection in the Norair 7- × 10-Foot Wind Tunnel. Rep. No. NOR-64-116 (BLC-159), Northrop Corp., May 1964. (Available from DDC as AD 594 990.)

A 9:1 fineness ratio laminar suction body of revolution having a blunt nose and a cylindrical centersection was tested in the Norair 7- by 10-foot wind tunnel. Full length laminar flow with low friction and equivalent total drags was maintained on the 12-foot long model up to a Reynolds number $R_L = 20.63 \times 10^6$

by means of boundary layer suction through 102 fine slots. The coefficient of equivalent total drag (based on wetted area and including the equivalent suction drag) at an angle of attack $\alpha = 0^o$ was 1.4 times the laminar flat plate friction coefficient up to $R_L = 20 \times 10^6$. The lowest equivalent total drag coefficient that was measured was $C_{D_{t_{min}}} = 4.18 \times 10^{-4}$ at $R_L = 20.27 \times 10^6$ with a corresponding total suction quantity coefficient (based on wetted area) $C_{Q_{opt}} = 2.25 \times 10^{-4}$.

At an angle of attack $\alpha = -1^o$ a flow asymmetry that occurred at $\alpha = 0^o$ was compensated for and the minimum equivalent total drag coefficient was reduced to 1.37 times the laminar flat plate friction coefficient up to a length Reynolds number $R_L = 20 \times 10^6$. An equivalent total drag coefficient of $C_{D_{t_{min}}} = 3.96 \times 10^{-4}$ was measured at $R_L = 20.62 \times 10^6$, requiring a total suction quantity coefficient $C_{Q_{opt}} = 1.53 \times 10^{-4}$.

Author

Availability:
NOR-64-116 (BLC-159)
AD 594 990
N79-75711

595. Gregory, N.; and Love, E. M.: Some Problems of Flow Laminarization on a Slender Delta Wing. Recent Developments in Boundary Layer Research - Part I, AGARDograph 97, 1965, pp. 523-566. (Also available as NPL Aero. Rep. 1138, British A.R.C., Feb. 1965.)

The problems are discussed in the light of an experimental investigation made in a low-speed wind tunnel on the effect of distributed suction on the state of the boundary layer on a slender delta wing of aspect ratio 1 with sharp leading edges. Laminar flow at high Reynolds numbers can be maintained on the upper surface with suction at negative angles of incidence where the flow is attached throughout, and at high positive angles of incidence in areas between the secondary attachment lines and some way outboard of them. Secondary separation is preceded by strong cross flow and insufficient suction was available either to eliminate separation or to avoid transition. At other incidences wedges of turbulence appear and ways of eliminating them need to be found. The phenomenon of transverse turbulent contamination associated with any excrescences near the apex and midspan remains a difficulty.

Author

Availability:
N65-34652
X66-13336

596. Gross, Lloyd W.: Experimental Investigation of a 4%-Thick Straight Laminar Suction Wing of 17-Foot Chord in the Norair 7- by 10-Foot Wind Tunnel. Rep. No. NOR-62-045 (BLC-139), Norair Div., Northrop Corp., May 1962. (Also available in Summary of Laminar Boundary Layer Control Research - Volume I, ASD-TDR-63-554, U.S. Air Force, Mar. 1964, pp. 111-119. (Available from DDC as AD 605 185.)

Full chord laminar flow and very low wing equivalent total drags were maintained on a 4-percent-thick unswept suction wing of 17-foot chord up to a wing chord Reynolds number of 26 × 10^6 by means of suction through 100 fine slots. Without tunnel wall fairings, the minimum wing equivalent total drag coefficient for one wing surface (including the equivalent suction drag) was $C_{D_{t_{min}}} = .000375$ at $R_c \cong 25 \times 10^6$ and $\alpha = 0$ degree angle of attack; the corresponding suction quantity coefficient (based on wing projected area) was $C_{Q_{opt}} = .000130$. The maximum wing chord Reynolds number with full chord laminar flow was twice as large as that measured in the same tunnel on a 30-degree swept laminar suction wing of 7-foot chord and was probably limited by wind tunnel noise as well as by the number of suction slots used. The maximum attainable wing chord Reynolds number with full chord laminar flow was only slightly influenced by moderate changes of the external pressure distribution. These changes were obtained by varying the angle of attack and by putting fairings on the tunnel walls opposite the model. An increased overall flow acceleration along the wing chord resulted in somewhat higher wing chord Reynolds numbers with full chord laminar flow and, conversely, the maximum wing chord Reynolds number with 100 percent laminar flow was somewhat reduced when the flow was more strongly decelerated along the chord, as compared with the model at $\alpha = 0$ degree angle of attack without tunnel wall fairings present.

Author

Availability:
NOR-62-045 (BLC-139)
N65-25556
AD 605 185
N79-75706

597. Gross, L. W.: Investigation of a Laminar Suction Modified Sears-Haack Body of Revolution in the Norair 7- by 10-Foot Wind Tunnel. Summary of Laminar Boundary Layer Control Research - Volume I, ASD-TDR-63-554, U.S. Air Force, Mar. 1964, pp. 155-165. (Available from DDC as AD 605 185.)

Full length laminar flow with very low friction and equivalent total drags was maintained on a 9-to-1 fineness ratio laminar suction modified Sears-Haack body of revolution of 142-inch length up to a length Reynolds number $R_L = 20.1 \times 10^6$ by means of suction through 120 fine slots. The coefficient of equivalent total drag (based on wetted area and including the equivalent suction drag) at an angle of attack $\alpha = 0^o$ was 1.18 times the laminar flat plate friction coefficient up to $R_L = 19.6 \times 10^6$ with a corresponding suction quantity coefficient (based on wetted area) $C_{Q_t} = 1.75 \times 10^{-4}$. At an angle of attack $\alpha = 2^o$ the minimum equivalent total drag coefficient varied from 1.18 times the laminar flat plate friction coefficient C_f at a Reynolds number $R_L = 6.3 \times 10^6$ up to 1.45 C_f at $R_L = 16.19 \times 10^6$. An equivalent total drag coefficient $C_{D_t} = 4.8 \times 10^{-4}$ was measured at $R_L = 16.19 \times 10^6$ requiring

a total suction quantity coefficient $C_{Q_t} = 1.95 \times 10^{-4}$. Full length laminar flow at $\alpha = 2^{\circ}$ was observed up to a length Reynolds number $R_L = 18.55 \times 10^6$.
Author

Availability:
N65-25558
AD 605 185

598. Van Ingen, J. L.: Theoretical and Experimental Investigations of Incompressible Laminar Boundary Layers With and Without Suction. Rep. VTH-124, Dep. Aeronaut. Eng., Technol. Univ. Delft, Oct. 1965.

This dissertation describes some theoretical and experimental investigations of two-dimensional laminar boundary layers with and without suction. The primary purpose of the studies was the clarification of some points concerned with maintaining laminar flow in a boundary layer by means of suction through a porous surface, although some results were obtained which may be applicable to laminar boundary layers without suction. One theoretical study is concerned with the calculation of laminar boundary layers using approximate methods of the type introduced by Pohlhausen (1921). A new method is described which, through a special choice of the velocity profile, provides accurate results in those cases where the suction velocity is not too large. A second theoretical study deals with a phase-plane description of the laminar boundary layer flow between nonparallel plane walls. Here shear is plotted vs the velocity component parallel to the wall. The experimental part of the work consists of measurements on two airfoil sections in a low-speed wind tunnel. The first model is a 28% thick laminar-flow airfoil section with an impermeable surface and a chord length of 1 meter. A detailed survey of the velocity profiles in the laminar boundary layer was made with hot wires; the measurements were extended downstream far enough to include the laminar separation point. Results are compared with laminar boundary layer theory. The second model is a 15% thick laminar flow wing section with a chord length of 1.35 m and porous upper and lower surfaces between the 30% and 90% chord positions. The inside of the model is divided into 40 different compartments, each with its own suction line, flow-regulating valve, and flow-measuring device. Wake drag and transition position were measured for several suction distributions; for some of these positions, detailed boundary-layer surveys were made. From the transition measurements on the porous model a semiempirical method is derived which makes it possible to determine the transition position for two-dimensional incompressible laminar boundary layers with arbitrary pressure and suction distributions.

Availability:
N69-80548
A66-19355

599. Lespinard, Georges: Contribution à l'étude de la transition en couche limite: effet de l'aspiration pariétale. Ph. D. Thesis, Univ. of Grenoble, 1968.

The stabilizing influence of wall suction, which is well established for small perturbations, at all stages of the transition, is discussed. A method providing an effective means of varying the stability of the transition has been utilized and a mathematical model for laminar boundary layer has been developed. Details are given of the experimental design using a low turbulence wind tunnel and a multichannel ionized anemometer. Results of measurement in permanent boundary layers, and of the effect of suction at different rates are presented.

Availability:
N70-12306

600. Citation intentionally removed.

601. Kozlov, L. F.; and Tsyganyuk, A. I.: Drag on Bodies of Revolution With Boundary-Layer Suction. Fluid Mech. - Soviet Res., vol. 5, no. 1, Jan.-Feb. 1976, pp. 136-139.

Experimental results on the effect of distributed boundary-layer suction on the drag of a body of revolution moving at zero angle of attack in water are presented. The test data confirm that distributed suction of small amounts of liquid from the boundary layer is an effective means of boundary-layer control. The drag of the controlled section of the body of revolution (a cylinder) was reduced in half at Re = 1 to 3.5×10^6 at a suction flowrate of $c_Q = 6 \times 10^{-4}$. The experimental data are compared with theoretical results.

Author

602. Groth, E. E.: Low Drag Boundary Layer Suction Experiments on an Ogive Cylinder Body of Revolution at Supersonic Speeds. Rep. No. NAI-58-851 (BLC-115), Northrop Aircraft, Inc., Nov. 1958.

Low drag boundary layer suction experiments on an ogive cylinder body of revolution have been conducted at the AEDC tunnel E-1 at ARO, Inc., Tullahoma, Tennessee. Laminar flow and low drag coefficients were obtained at Mach numbers 2.5, 3.0 and 3.5. The maximum length Reynolds number with full laminar flow decreased from $10.6 \cdot 10^6$ at $M = 2.5$ to $4.7 \cdot 10^6$ at $M = 3.5$. The rather wide spacing between the suction slots and insufficient suction quantities due to excessive pressure losses in the ducts seemed to be the main reasons for the reduced Reynolds number range at the higher Mach numbers.

An approximate method for modifying the standard low speed pressure loss values in two- and three-dimensional ducts by a suitable density correction is presented which confirms the measured data with reasonable accuracy.

Author

Availability:
SN-24021, Nov. 1958
NAI-58-851 (BLC-115)
N79-75702

603. Strike, W. T.; and Donaldson, J. C.: Investigation of Suction Controlled Boundary Layer on a Northrop Model at Mach Numbers of 2.5, 3, and 3.5. AEDC-TN-59-80, U.S. Air Force, July 1959.

The application of suction-type boundary layer control on a body of revolution (20 caliber tangent ogive) was experimentally investigated at Mach numbers 2.5, 3, and 3.5 over a unit Reynolds number range of .074 to 1.0 x 10^6 per inch. As a result of the design limitations, only minor gains were attained with maximum suction. Without suction, good correlation was obtained between a theoretical laminar skin friction estimate and data obtained during this investigation.

Author

Availability:
N79-70028
N-73525

604. Groth, E. E.: Low Drag Boundary Layer Suction Experiments on a 5% Thick Biconvex Airfoil Section at M = 2.23 and 2.77. Rep. No. NAI-58-195, Rep. No. BLC-105 (Contract No. AF33(616)-3168), Northrop Aircraft, Inc., Mar. 1958. (Available from DDC as AD 162 060.)

Boundary layer suction was applied to a 20-inch chord 5% thick biconvex wing spanning the test section of the Convair OAL supersonic wind tunnel at Daingerfield, Texas. Laminar flow over the whole wing chord was produced at Mach numbers 2.23 and 2.77 and a chord Reynolds number of 12.5 x 10^6 over a wide range of suction quantities. The drag coefficients obtained, i.e., the sum of the wake drag and equivalent suction drag, were equal to about 1.5 times the laminar friction coefficient of a flat plate or about 27% of the turbulent friction coefficient of a flat plate at the same length Reynolds number.

Author

Availability:
SN-24021, Mar. 1958
N78-75633
NAI-58-195
BLC-105
AD 162 060

605. Groth, E. E.: Wind Tunnel Experiments on a 5%-Thick Biconvex Airfoil Section at M = 2.23 and 2.77. Rep. No. NAI-57-676, Rep. No. BLC-97, Northrop Aircraft, Inc., May 1957. (Available from DDC as AD 140 589(b).)

A 20-inch chord 5% biconvex wing spanning the test section of the Convair OAL supersonic wind tunnel at Daingerfield, Texas, was tested at $M = 2.23$ and 2.77 for boundary layer transition measurements. The measured boundary layer profiles at $M = 2.23$ indicated that transition occurred at 40% c, resulting in a transition Reynolds number R_T of 5.1×10^6. Surface spray observations at $M = 2.77$ showed transition at 30% c, or $R_T = 3.9 \times 10^6$.

Author

Availability:
SN-24021, Apr. 1957
NAI-57-676
BLC-97
AD 140 589(b)
N79-75699

606. Groth, E. E.: Low Drag Boundary Layer Suction Experiments at Supersonic Speeds on an Ogive Cylinder With 29 Closely Spaced Slots. Rep. No. NOR-61-162 (BLC-131), Northrop Corp., Aug. 1961. (Also available in Summary of Laminar Boundary Layer Control Research - Volume II, ASD-TDR-63-554, U.S. Air Force, Mar. 1964, pp. 449-463. (Available from DDC as AD 605 186.))

Low drag boundary layer suction experiments on an ogive cylinder were conducted at the Arnold Engineering Development Center supersonic Tunnel E-1 at Tullahoma, Tennessee, at Mach numbers 2.5, 3.0 and 3.5. The model had the same external dimensions as the one tested in 1958, but was equipped with an improved suction system. A larger number of closely spaced slots approached continuous suction to a better degree, and larger suction tubes permitted higher suction coefficients. Full laminar flow and drag coefficients were measured up to Reynolds numbers $R_L \sim 15 \times 10^6$ at $M = 2.5$, $R_L \sim 12 \times 10^6$ at $M = 3.0$ and $R_L \sim 7 \times 10^6$ at $M = 3.5$. The boundary layer development along the body was computed for several experimental suction and surface pressure distributions and the results were compared with the test data.

Author

Availability:
NOR-61-162 (BLC-131)
N65-25563
AD 605 186

607. Strike, W. T.; and Pate, S.: Investigation of Boundary-Layer Suction on a 20-Caliber Ogive Cylinder at Mach Numbers 2.5, 3.0, 3.5, and 4.0. AEDC-TN-61-66, U.S. Air Force, June 1961.

A second investigation was conducted in the 12-in., intermittent, supersonic wind tunnel of the von Kármán Gas Dynamics Facility to measure the effectiveness of boundary-layer suction on a 20-caliber ogive cylinder. The application of suction-type boundary-layer control on the ogive was investigated at Mach numbers 2.5, 3.0, 3.5, and 4.0 over a unit Reynolds number range from 0.07 to 1.03×10^6 per inch with the model at zero angle of attack. Some additional data were obtained at 2-deg angle of attack at Mach number 3. As a result of improving the design of the suction system a significant gain was made in reducing the net drag of the model at Mach number 3 by boundary-layer suction. The presence of the suction slots with no suction when compared with the sealed slot configuration (that is, smooth model) had some influence on the boundary-layer characteristics at all Mach numbers.

Author

Availability:
N78-78553
N-97467

608. Pate, S. R.: Investigation of Drag Reduction by Boundary-Layer Suction on a 50-Deg Swept Tapered Wing at $M_\infty = 2.5$ to 4. AEDC-TDR-64-221, U.S. Air Force, Oct. 1964. (Available from DDC as AD 450 195.)

Tests were conducted in the 40-in. supersonic Tunnel A of the von Kármán Gas Dynamics Facility to determine the effectiveness of boundary-layer suction for laminar flow control on a tapered, three-dimensional, 50-deg swept supersonic wing. Test Mach numbers were 2.5, 3, 3.5, and 4 with a Reynolds number range (based on boundary-layer rake location) from 4.3 to 19.5 million for angles of attack of zero and ±3 deg.

With suction, full-chord laminar flow was maintained for small angles of attack at $M_\infty = 2.5$, 3, and 3.5 up to length Reynolds numbers of 17, 12, and 9 million, respectively. Wake drag, suction drag, and total drag coefficients and the corresponding suction coefficients are presented, along with fully turbulent wake drag coefficients for the no-suction case.

Author

Availability:
N64-33951
AD 450 195

609. Groth, E. E.: Low Drag Boundary Layer Suction Experiments on a Flat Plate at Mach Numbers 2.5, 3.0, and 3.5. Summary of Laminar Boundary Layer Control Research - Volume II, ASD-TDR-63-554, U.S. Air Force, Mar. 1964, pp. 428-441. (Available from DDC as AD 605 186.)

Low drag boundary layer suction experiments on a 41-inch long flat plate were conducted at the 40- by 40-inch continuous supersonic Tunnel A of the Arnold Engineering Development Center at Tullahoma, Tennessee. The model was equipped with 76 closely spaced, fine slots arranged in eight suction chambers. Full length laminar flow was obtained at $M = 2.5$, 3.0 and 3.5 up to the highest possible tunnel pressures, resulting in length Reynolds numbers of 21.8×10^6, 25.7×10^6 and 21.4×10^6, respectively. The measured drag coefficients (sum of wake and suction drag) were of the order of 26 to 43 percent of the turbulent friction drag at the same Reynolds and Mach numbers. The results of calculations of the laminar boundary layer development along the plate at typical suction distributions are compared with the test data.

Author

Availability:
N65-25561
AD 605 186

610. Groth, Eric E.: Low Drag Boundary Layer Suction Experiments on a Flat Plate at Mach Numbers 3.0 and 3.5. Rep. No. NOR-61-251 (BLC-135), Norair Div., Northrop Corp., Oct. 1961.

Availability:
NOR-61-251 (BLC-135)
N79-77141

611. Jones, J. H.; and Pate, S. R.: Investigation of Boundary-Layer Suction on a Flat Plate at Mach Number 3. AEDC-TN-61-128, U.S. Air Force, Sept. 1961.

Tests were conducted in the 40 by 40-in. supersonic tunnel (Tunnel A) of the von Kármán Gas Dynamics Facility to determine the effects of boundary-layer suction on a flat plate at Mach number 3 over a Reynolds number range from 0.20 to 0.64 million per inch.

Boundary-layer characteristics are reported for the condition of no suction, and skin friction coefficients are presented for the conditions of suction and no-suction. By applying suction, a laminar boundary layer was maintained at Reynolds numbers up to 26 million, and a considerable reduction in the net drag resulted.

Author

Availability:
N78-78554
N-102,027

612. Groth, E. E.: Boundary Layer Suction Experiments on a Slotted Flat Plate Model With Interfering Shock Waves. Summary of Laminar Boundary Layer Control Research - Volume II, ASD-TDR-63-554, U.S. Air Force, Mar. 1964, pp. 442-448. (Available from DDC as AD 605 186.)

The interaction of an impinging shock wave with the laminar boundary layer was investigated at the AEDC Tunnel A on a 41-inch chord flat plate suction model by mounting a plate (shock generator) vertically on the suction model. The shock wave intersected the suction slots in the rear half of the model under an acute angle. The flat plate model and its suction system were the same ones which were used previously for shock-free low-drag measurements. Laminar flow was maintained aft of the shock wave up to certain intensities depending on Mach and Reynolds number. The increases in suction quantities and total drag as function of the shock intensity were measured at Mach numbers between 2.5 and 3.5 and Reynolds numbers up to 26×10^6.

Author

Availability:
N65-25562
AD 605 186

613. Pate, S. R.: The Use of Boundary-Layer Suction for Maintaining Laminar Flow Downstream of a Reflected Incidence Shock Wave on a Flat Plate at Free-Stream Mach Numbers 2.5, 3, and 3.5. AEDC-TR-65-81, U.S. Air Force, May 1965. (Available fron DDC as AD 462 130.)

Tests were conducted in the 40-in. supersonic tunnel of the von Kármán Gas Dynamics Facility to determine the effectiveness of boundary-layer suction for maintaining laminar flow downstream of a reflected incidence shock wave on a flat plate. Test Mach numbers were 2.5, 3, and 3.5, and the Reynolds number (based on the boundary-layer rake location) ranged from 2.3 to 26.2 million. With suction, laminar flow was maintained downstream of a two-dimensional reflected incidence shock wave for shock generator angles up to 5 deg for all test Mach numbers.

Author

Availability:
N65-24077
AD 462 130

614. Pate, S. R.; and Deitering, J. S.: Investigation of Drag Reduction by Boundary-Layer Suction on a Flat Plate and a 36-Deg Wing at Supersonic Speeds. AEDC-TDR-62-144, U.S. Air Force, Aug. 1962. (Available from DDC as AD 282 268.)

Tests were conducted in the 40-in. Supersonic Tunnel of the von Kármán Gas Dynamics Facility to determine the effectiveness of boundary-layer suction for laminar flow control on a two-dimensional, biconvex, 36-deg swept wing and on a flat plate with and without shock impingement. Test Mach numbers were 2.5, 3, 3.5, and 4 with a Reynolds-number-per-inch range from 0.17 to 0.66 x 10^6.

With suction, full chord laminar flow was maintained on the flat plate at $M_\infty = 2.5$ and 3 at length Reynolds numbers of 22 and 26.5 x 10^6, respectively, which resulted in a total drag reduction of 77 and 74 percent. With suction and shock impingement across the plate resulting from a one-degree shock generator angle, full chord laminar flow was maintained at $M_\infty = 2.5$, 3, and 3.5 at length Reynolds numbers of 19.7, 18.9, and 21.7 x 10^6, respectively. On the 36-deg swept wing, full chord laminar flow was maintained with suction up to a length Reynolds number of 11.3 x 10^6 at $M_\infty = 3$.

Author

Availability:
N78-74839
AD 282 268

615. Groth, E. E.: Low Drag Boundary Layer Suction Experiments on a 36° Swept Wing at Mach Numbers 2.5, 3.0, and 3.5. Summary of Laminar Boundary Layer Control Research - Volume II, ASD-TDR-63-554, U.S. Air Force, Mar. 1964, pp. 464-480. (Available from DDC as AD 605 186.)

A 36° swept suction wing of 3-percent-thick biconvex section was tested at AEDC Tunnel A at Mach numbers between 2.5 and 3.5. Laminar flow and low drag coefficients were maintained up to the highest tunnel pressures, resulting in length Reynolds numbers of 17, 25 and 20 × 10^6 at Mach numbers 2.5, 3.0 and 3.5, respectively. The computation of the laminar boundary layer development along the wing chord for typical test conditions provided numerical values of cross-flow Reynolds numbers with full laminar flow. Two separate tests were conducted. The first model with the original - relatively narrow - slots was successful at $M = 2.5$ and in the Reynolds number range up to $R = 13 \times 10^6$ at $M = 3.0$. The second model, with wider slots, provided satisfactory data at $M = 3.0$ and 3.5 at further increased chord Reynolds numbers. Both models were rather sensitive to the local suction quantities.

Author

Availability:
N65-25564
AD 605 186

616. Goldsmith, J.: Low Drag Boundary Layer Suction Experiments on a 72° Swept Wing Model at Mach Number 2.0 and 2.25. Summary of Laminar Boundary Layer Control Research - Volume II, ASD-TDR-63-554, U.S. Air Force, Mar. 1964, pp. 487-508. (Available from DDC as AD 605 186.)

An investigation was made to determine the effectiveness of combining the advantages of laminar suction with sweepback in excess of the Mach angle for the purpose of obtaining low drags on supersonic airfoils. This initial investigation was limited to that portion of a wing over which the flow could be considered two dimensional in nature, i.e., the region where the flow field was similar to that of an infinite swept airfoil. Calculation of the drags for such an airfoil indicated encouragingly low drags and a wind tunnel model simulating a long swept airfoil was designed for Mach 2.0 and tested at Mach 2.0 and 2.25 in order to confirm the results of the calculations. Although the measured total drags were somewhat higher than the calculated values, they were respectably low ($C_{D_t} < 1.4 \times 10^{-3}$ at $C_L \cong 0.068$) for upper wing surface only, and it is clear that laminar flow is possible for supersonic wings swept behind the Mach cone. The approximate lift coefficient of 0.068 was determined from measured pressures on the upper surface and an estimated lower surface pressure distribution. Its value was less than predicted, but there is no indication that it could not be increased to a $C_L = 0.09$ or better by increasing the angle of attack or design camber of the airfoil. Calculations indicated that the airfoil would be supercritical (supersonic velocity component perpendicular to the leading edge) at Mach 2.25, but because the lift coefficient was lower than predicted the measured flow was everywhere subcritical at this higher Mach Number, and the measured total drag coefficients ($C_{D_t} < 1.6 \times 10^{-3}$) indicated laminar flow.

Author

Availability:
N65-25566
AD 605 186

AUTHOR INDEX

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15. Supplementary Notes

16. Abstract

A survey has been conducted and a bibliography compiled on attainment of laminar flow in air through the use of favorable pressure gradient and suction. This report contains the survey, summaries of data for both ground and flight experiments, and abstracts of referenced reports. Much early information is also included which may be of some immediate use as background material for LFC applications.

17. Key Words (Suggested by Author(s))
Laminar flow control
Laminar boundary-layer suction
Favorable pressure gradient
Suction LFC
Boundary-layer transition

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