# AIRCRAFT LAMINAR FLOW CONTROL†

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ABSTRACT
Aircraft laminar flow control (LFC) from the 1930's through the 1990's is reviewed and the current status of the technology is assessed. Examples are provided to demonstrate the benefits of LFC for subsonic and supersonic aircraft. Early studies related to the laminar boundary-layer flow physics, manufacturing tolerances for laminar flow, and insect-contamination avoidance are discussed. LFC concept studies in wind-tunnel and flight experiments are the major focus of the paper. LFC design tools are briefly outlined for completeness.

## 1. INTRODUCTION

This overview will review the current state-of-the-art in laminar flow control (LFC). LFC research began in the 1930's and flourished through the 1960's when it was de-emphasized due to reprioritization of national priorities. During the 1970's when the OPEC embargo caused a fuel shortage and high-cost fuel, LFC research became important again because of the aerodynamic performance benefits it could potentially produce for commercial aircraft. The next 20 yrs of research had resulted in numerous significant achievements in both the wind tunnel and flight in the United States and Europe.

### 1.1. *What is Laminar Flow Control?*

What is LFC? LFC is an active boundary-layer flow control technique (usually steady suction) employed to maintain the laminar flow (LF) state at chord

Reynolds numbers beyond that which is normally characterized as being transitional or turbulent in the absence of control. Understanding this definition is an important first step toward understanding the goals of the technology. Often, one mistakenly assumes that LFC implies the re-laminarization of a turbulent flow. These are two different flow physics phenomena and although the same control system may be employed for both problems, the energy requirements for re-laminarization could typically be an order of magnitude greater than that required for LFC. Finally, LFC is a capability that is designed to benefit the aircraft during cruise.

A significant advancement made in the development of LFC technology is the concept of hybrid laminar flow control (HLFC). HLFC integrates the concepts of natural laminar flow (NLF) with LFC to reduce suction requirements and reduce system complexity (Figure 1). NLF employs favorable pressure gradient to delay the transition process, is sweep limited, and usually has poor off-design cruise aerodynamic performance. LFC is complex, involving suction (and ducts, flutes, and pump power) over the whole wing chord (or engine nacelle). The key features of HLFC are *(a)* suction is required only in the leading-edge region ahead of the front spar, *(b)* NLF is obtained over the wing (aft of front spar) through proper tailoring of the surface geometry (favorable pressure gradient), and *(c)* the HLFC wing design has good performance in the turbulent mode.

## 1.2. *What are the benefits of Laminar Flow Control?*

Thibert et al (1990) have shown that skin-friction drag could amount to about 50% of the total drag for a subsonic transport aircraft, which is a function of the aircraft size. Since laminar skin friction can be as much as 90% less than turbulent skin friction at the same Reynolds number, it is obvious that LF would be more desirable than turbulent flow for reducing the drag of aerodynamic vehicles (except in recovery regions where the pressure drag penalty of boundary-layer separation is severe). Unfortunately, achieving LF over the entire configuration is impractical because of the sensitivity of the LF to external and vehicle disturbances. However, drag reduction due to LF over select portions of a vehicle are achievable.

For an aircraft, the wings, engine nacelles, fuselage nose, and horizontal and vertical tail are candidates for achieving LF. Although the summation of the drag reduction from each individual component would indicate a benefit due to LF, the maximum/optimal benefits of LFC are achieved by utilizing the benefits of LF to reduce the size of the aircraft. These LF benefits include reductions in take-off gross weight (TOGW), operating empty weight (OEW), block fuel (BF) for a given mission and increase in cruise lift-to-drag ratio (L/D). Associated benefits may include reductions in both emissions (pollution) and noise.

For an advanced subsonic transport, Arcara et al (1991) projected 1995 technology improvements into a HLFC design. With 50% chord LF on the upper wing surfaces and horizontal and vertical tails and 40% on the engine nacelles, the LFC aircraft would have projected reductions in TOGW of 9.9%, OEW of 5.7%, and BF of 18.2% and an increase in L/D of 14.7% compared to the turbulent baseline. Robert (1992) discussed the potential benefits of HLFC applied to Airbus A320 and A340 subsonic transports. For the A320 with a range of 500 nm (nautical miles), cruise represented only 35% of the total fuel burn while for the A340 with a 3000 nm, cruise represented 80% of the total fuel burn.

Because LFC is a cruise technology, the A340 would benefit more from the application of LFC than the A320. Using HLFC over the first 15% to 20% chord for the A340, a potential drag reduction of 14% could be obtained using LF concepts on the wing, horizontal tail, vertical tail, and nacelles.

Boeing (1990) and McDonnell Douglas (Powell et al, 1989) assessed the benefits of using supersonic laminar flow control (SLFC) for an advanced supersonic transport designed to carry 247 passengers at Mach 2.4 over a distance of 5000 nm. With LF covering 40% of the wing wetted area and 20% of the empennage, reductions in TOGW, OEW, and BF of 8.5%, 6.2%, and 12.0%, respectively, were projected with the LFC transport compared to the turbulent supersonic aircraft (Boeing: NASA CR 181917, 1990).

Aerodynamic performance benefits bought by skin-friction drag reduction can translate into reduced operating costs of an aircraft. Arcara et al (1991) have briefly discussed the impact of fuel cost on the LFC benefits. Essentially, a projected reduction in direct operating cost of 5.8% was achieved with HLFC for fuel costing $0.65 per gallon, while HLFC led to an 8.8% reduction in operating cost for higher priced fuel at $2 per gallon. In addition to fuel savings and reduced emissions and noise, LFC leads to a reduced aircraft size because of the reduction in fuel; this should lead to reductions in the total aircraft operating costs.

## 1.3. *Content of This Paper*

The goal of this paper is to review the status of LFC technology. Early studies related to boundary-layer flow physics, manufacturing tolerances for LF, insect-contamination avoidance, and slot-, porous-, and perforated suction LFC studies in wind-tunnel and flight experiments are discussed. Tools for LFC aerodynamic design are included for completeness. More attention is given to recent wind-tunnel and flight tests that demonstrate multiple facets of LFC.

Because of the brevity of this article and the rich nearly 60-yr history of LFC and LFC-related research, the literature cited here is subjectively limited. For a thorough review of research related to LFC, refer to bibliographies by

Bushnell & Tuttle (1979) and Tuttle & Maddalon (1993), to overview papers by Hefner (1992), Wagner et al (1988), and Collier (1993) and to a historical perspective of LFC (Joslin 1998).

# 2. LAMINAR FLOW CONTROL DESIGN METHODOLOGY

For an LFC design (a wing for example), the analysis begins by defining an initial wing geometry. With wing geometry defined, the wing pressures and velocities can be obtained using transonic wing theory and/or computational fluid dynamics (CFD). The inverse approach of prescribing a target pressure distribution and solving for the wing geometry is then utilized. After obtaining the external flow-field for the final geometry, boundary-layer and stability theory calculations are used to determine the suction flow rates and distribution for the desired transition location. With the suction flow rate determined from boundary-layer stability considerations, the pressure drop through the skin must be set to obtain a reasonable sub-surface compartmentation scheme and perforation spacing distribution for the desired suction distribution. The process is iterative until an acceptable design is obtained. Finally, the suction system ducting and compressor specifications are prescribed.

Besides the design procedure, other key information that must be understood for LFC design include: *(a)* the physics associated with the laminar to turbulent boundary-layer transition process, *(b)* impact of surface tolerances–roughness, waviness, steps, and gaps–on LF extent (required for manufacturing), *(c)* slot suction, porous, and perforated suction and thermal LFC, and *(d)* issues relating to manufacturing LFC articles, and *(e)* the methodology and limitations of transition prediction (determining LF extent for projecting benefits to aircraft). These issues are covered in this section.

## 2.1. *Boundary-Layer Flow Physics*

A brief summary of the boundary-layer flow physics follows. For more comprehensive discussions of viscous flow physics refer to Bayly et al (1988), Reed & Saric (1989), and Kachanov (1994).

The first major theoretical contributions to the study of boundary-layer transition were made in the late 1800s and early 1900s. After these early contributions, Tollmien (1926) and Schlichting (1932) discovered convective traveling-wave instabilities now termed Tollmien-Schlichting (TS) instabilities, and Liepmann (1943) and Schubauer & Skramstad (1947) experimentally confirmed the existence of these TS waves.

In addition to TS-disturbance dominated transition, LFC applications must account for a dynamic instability, termed the crossflow (CF) disturbance.

The flow becomes unstable due to an inflection point in the spanwise velocity component. As shown by Anscombe & Illingworth (1952), CF-disturbances are characterized by corotating vortices. At a critical speed (or Reynolds number), "striations" in the surface flow visualizations appear and as the speed of the free-stream continues to increase the transition location moves forward.

The presence of TS and CF disturbances in the boundary-layer flow is dependent on the pressure gradient and on the wing sweep angle. Based on numerous investigations (e.g., Anscombe & Illingworth, 1952), our understanding of the role of sweep and pressure gradient on transition indicates that TS disturbances dominate transition for wings with sweeps $0^o$ through about $25^o$. If the design pressure gradient is more favorable (accelerating flow), longer runs of LF can be realized because the growth of the TS disturbance is suppressed, while the opposite effect is realized with an adverse pressure gradient. For wing sweep angles greater than $25^o$, both TS and CF disturbances can dominate transition, and much of the flow physics associated with the nonlinear interaction of these modes is unknown. For greater than $30^o$ to $35^o$ wing sweeps, CF disturbances dominate transition–often very near the wing leading edge. Therefore, wing design should minimize the growth of these disturbances to enable long runs of LF.

In addition to TS and CF disturbances which lead to transition over the wing chord, attachment-line instabilities are possible and can cause transition in the leading-edge region. As the many flight experiments have shown, maintaining NLF on the attachment line is attainable by keeping the Reynolds number below some critical value; the Reynolds number can be lowered by reducing sweep, leading-edge radius, or unit Reynolds number. Decreasing the leading-edge radius has a compounded benefit of decreasing the chordwise extent of the crossflow region and providing a more rapid acceleration of the flow over the wing. Turbulence (or attachment-line contamination) from the fuselage turbulent boundary-layer flow can sweep out onto the attachment line and cause the entire wing to be engulfed in turbulent flow. However, a turbulence diverter such as Gaster's bump (1965) can be effectively used to establish a LF attachment line, allowing the potential for LF on the wing. As an alternative, strong suction can be used at the fuselage/wing juncture to re-laminarize the flow on the attachment line (Pfenninger 1965). Some of the major flight experiments have shown the necessity for one of these devices to achieve LF.

Additionally, a turbulent wedge, originating at the fuselage/wing leading-edge juncture, can sweep out over a portion of the wing root region to decrease the LF benefits. Clearly, one would attempt to optimize the fuselage/wing juncture point to cause this wedge to cling to the fuselage as much as possible, thereby enabling LF in a region close to the fuselage. No study which has investigated the potential instability of the interface between a turbulent wedge and LF over a wing could be found for this review.

## 2.2. *Manufacturing Tolerances*

As discussed by Jones (1938), investigations in the 1930s recognized that small roughness and waviness at high Reynolds numbers could reduce the LF extent. The stringent surface smoothness and waviness criteria (tolerances) for LF posed a major challenge for research in the 1950s and 1960s. A partial explanation for the de-scope of subsonic LFC in the 1950s was attributable to the severe surface manufacturing tolerances required to achieve LF. However the 1990s manufacturing technologies have matured to the point that surface-definition tolerances are readily achievable. A thorough review of the surface-tolerance issues is described by Carmichael (1979) and Holmes et al (1985); the current understanding is summarized in this section. For LFC design, Braslow et al (1990) gives formulae for manufacturing tolerances.

Flight and wind-tunnel tests have provided our current understanding of the mechanisms which cause transition to move forward due to surface imperfections. The impact of a surface imperfection (such as a rivet head) on the transition location can be viewed either by looking at the transition location as a function of imperfection size for a fixed unit Reynolds number or by keeping the size of the imperfection fixed and looking at transition location as a function of unit Reynolds number. In either case, the imperfection stimulates eigenmodes in the boundary layer; the linear stability of the flow dictates whether these modes will grow or decay as they evolve in the flow. However, as the height of the imperfection or unit Reynolds number increases, a point is reached when flow separation occurs due to the surface imperfection. At this point, inviscid instability arising from the inflectional velocity profile can grow and induce transition. Or if the imperfection is sufficiently large, linear instability amplification is "by-passed" and transition follows by-way-of a nonlinear process. Finally, our current understanding of imperfections suggest that larger critical step heights can be realized using rounded steps because a reduced region of separation and reduced inflectional instability growth are encountered in the experiments.

Based on our understanding of the flow physics associated a surface imperfection, we summarize that *(a)* a local separation region due to the surface imperfection can induce transition, *(b)* the local adverse pressure gradient due to the surface imperfection could cause amplification of TS disturbances and decrease the LF extent, *(c)* the beneficial stabilizing influence of compressibility on TS disturbances overcomes the the detrimental increase in the amplitude of the pressure disturbance caused by compressibility near the surface imperfection, *(d)* the critical wave height decreases with increased number of waves, waves, and *(e)* forward-facing rounded steps can increase the the critical step height compared with forward-facing square steps.

This section ends with a brief mention of innovative tools which are used to estimate the influence of a surface imperfection on LF extent. Masad (1996) has shown that interacting boundary-layer theory (which accounts for viscous-inviscid interaction) coupled with linear stability theory can be used to parameterize allowable surface imperfections for maximizing LF extent while minimizing constraints put on manufacturing.

## 2.3. *Suction and Thermal Laminar Flow Control*

Investigations to obtain LF with the slot-suction LFC concept began in the late 1930s and continued into the 1980s. Zalovcik et al (1944) with a B-18, Groth et al (1957) with a F-94, Whites et al (1966) and Fowell & Antonatos (1965) with the X-21 and Maddalon & Braslow (1990) with the Jetstar showed that large regions of LF could be realized in flight using slot-suction LFC. Pfenninger et al (1957) and Bobbitt et al (1992) showed that full-chord LF could be achieved in the wind-tunnel using slot-suction.

In the late 1950s and early 1960s, a series of supersonic LFC wind-tunnel experiments by Gross et al (1964) and Groth et al (1965) reported the achievement of full-chord LF up to chord Reynolds numbers of 20 to $29 \times 10^6$ using slot-suction. For example, Groth et al (1965) showed that full-chord LF on $36^o$ and $50^o$ swept wing slot-suction models led to skin-friction and drag reductions using LFC.

Finally, Gregory (1961) reviewed the status of suction surfaces for LFC applications and pointed out that as a wing was swept a loss of slot effectiveness occurred, especially near the leading edge region. The advantages of a wholly porous (or perforated) suction surface became pronounced for LFC applied to swept wings.

In the 1940s, full-chord LF was achieved using porous-suction on a wing model as described by Burrows et al (1949) and Braslow & Visconti (1950). Head et al (1955) obtained full-chord LF in flight using porous suction located from 6%-98% chord on a Vampire III aircraft wing. In these early wind-tunnel and flight tests, suction was achieved through a porous-material skin which covered the model.

As noted in the discussion of perforated-suction LFC by Saric (1985), threshold design parameters of size, spacing, geometry, and inclination of the holes and the suction level and distribution can introduce streamwise vorticity in a boundary layer, potentially inducing transition. Although there is no design tool available today which completely accounts for the impact of each parameter, progress is being made to understand the influence of each parameter on the flow.

One of first fundamental experimental studies on critical suction through isolated holes and a row of holes was reported by Goldsmith (1955, 1957). Minimum and maximum suction values were determined; below or above these critical values, the flow was turbulent. The critical suction was affected by the hole diameter, the hole spacing, and the boundary-layer thickness. In the later report it was noted that the action of vortices from holes in different rows could lead to horse-shoe vortices, which then led to turbulence. This undesirable flow phenomena can happen with lower suction compared with the isolated hole or row of holes.

Meitz & Fasel (1994) used a Navier-Stokes solver to study the unsteady flow field adjacent and downstream of suction holes. In agreement with the Goldsmith experiments, the simulations showed that low suction through the holes generated a pair of vortices which decayed with downstream distance. As the suction increased to some critical value, the vortices became unstable. Larger suction led to vortex shedding at the suction hole location.

MacManus & Eaton (1996) performed three-dimensional (3D) Navier-Stokes simulations of suction through holes to study single and multiple rows of holes. The simulations showed that *(a)* irregularities of the hole shape had minimal effect on the induced flow, *(b)* it was undesirable to have holes inclined to the surface, *(c)* the flow field at the hole inlet was highly 3D, *(d)* the pressure drop and mass-flow rate were insensitive to the hole inlet shape, and *(e)* significant inter-hole flow field effects existed for multiple rows of holes. In companion experiments, MacManus et al (1996) used LDV to show that the suction hole-induced flow was highly 3D and could lead to premature transition when large suction was used.

Besides the suppression of disturbance growth by suction, cooling (in air) can be used to suppress disturbances (Dunn & Lin, 1953). As shown by Boeing (1990) cooling has a larger impact on TS disturbances and only a subtle influence on CF disturbances; hence, cooling would not be used in the leading-edge region of swept wings for CF stabilization.

LFC concepts of the future must trade-off the benefits of various boundary-layer control concepts, including HLFC suction on the leading edge with either strips of perforated-suction control or thermal control on the wing roof-top region. Furthermore, reducing the costs associated with manufacturing (and maintaining) these systems will be a primary driver in the the acceptance of LFC on a future aircraft.

## 2.4. *Manufacturing Capabilities*

In the early years of airplanes, thin metal skins, multiple spanwise stringers, and countless fasteners (e.g., rivets) on the surface prevented achieving LF without hand-filling and sanding the surface. With the advent of bonded-sandwich construction methods, the production surface structure became sufficiently stiff that under loads adequate waviness criteria should be maintainable (in subsonic/transonic aircraft). Hence, the production capability in the 1990s has solved (in principle) the task of manufacturing LF-quality surfaces.

For the manufacturing process, Schwab (1992) discussed electron-beam drilling for creating holes in a surface for suction LFC. Using this method, some 3000 holes per second could be generated in stainless steel sheets 0.5 and 1.0 mm thick with hole diameters as small as 0.04 mm and 0.06 mm, respectively. Cross sections of the drilled holes indicated that the upper most part of the drilled holes were 2-2.5 times larger in diameter than the exit diameter, with the exit of the hole being absolutely burr-fee and round. The Jetstar (Powell 1987) used this technique for generating a perforated-suction surface.

Laser-drilled holes are an alternative to the electron-beam process. The B-757 (Collier, 1993) and F-16XL (Norris 1994) LFC flight test articles have been generated with lasers. The F-16XL SLFC glove had a titanium skin with laser-drilled holes; the laser produced holes with characteristics similar to the electron-beam (Norris 1994). However, Poll et al (1992) and Buxbaum & Höhne (1996) observed that laser-drilled holes had a random variety of shapes with no distinct characteristic diameter.

In summary, LFC slot-, porous-, and perforated-suction concepts have been demonstrated in wind-tunnels and flight experiments and thermal LFC was been shown effective in computations. State-of-the-art manufacturing processes (e.g., electron-beam or laser drilling) have been demonstrated for the fabrication of perforated-suction surfaces. With the exception of the Jetstar LFC flight test, little understanding of the potential degradation of the perforated structure with time is available in the literature. The Jetstar LFC flight experiment showed no degradation of the system after nearly four years of operations (Maddalon & Braslow 1990).

## 2.5. *Transition Prediction Design Tool Methodology*

The LFC design of an aircraft requires an accurate prediction of the amount of LF (the transition location) or the accurate prediction of suction distribution for a given target transition location. This section describes the conventional and advanced transition prediction tools, some of which include prediction of perturbations to the laminar boundary layer, the spectrum and amplitudes of these perturbations, and the linear and nonlinear propagation of these perturbations which ultimately leads to transition.

GRANVILLE CRITERION: Granville (1953) developed an empirical criterion for determining the transition location for 2D TS-dominated flows. Granville showed that a variety of flight and low-turbulence wind-tunnel data collapsed into criterion (curve) based on the difference between the momentum thickness Reynolds number at transition and at the neutral point correlated with an average pressure gradient parameter. As shown by Holmes et al (1983), this transition-prediction correlation is quite accurate for TS-dominated transition on a 2D NLF wing.

C1 AND C2 CRITERIA: Along the approach of the Granville criterion, Arnal et al (1984) developed transition criterion referred to as C1 and C2. The C1 criteria involves a correlation of transition onset integral values of the crossflow Reynolds number and the streamwise shape factor. The C2 criteria is a correlation of transition onset with a Reynolds number computed in the direction of the most unstable wave, the streamwise shape factor, and the free-stream turbulence level.

LINEAR STABILITY THEORY: The ability to predict transition based on the disturbance amplification came in the 1950s with the empirical method by Smith (1956), Smith & Gamberoni (1956), and van Ingen (1956). This transition-prediction method–called $e^N$ or N-factor method–correlates the predicted disturbance growth with the measured transition location. Hence, although the N-factor method is limited to the calibration of available experimental data, the method is the main tool in use through the 1990s. The use of linear stability theory is summarized in the recent review by Reed et al (1996) and additional discussion focusing on the theoretical and computational aspects of transition prediction and LFC are provided by Cousteix (1992) and Arnal (1994).

According to the conventional normal mode assumption used to derive the Orr-Sommerfeld equation, the eigensolutions take the form.

$$\Phi = \hat{\Phi}(y) e^{i(\alpha x + \beta z - \omega t)} \tag{1}$$

where $i = \sqrt{-1}$ and $\hat{\Phi}$ is the disturbance profile. With the mean flow available, a stability problem has to determine 6 unknowns: $\alpha_r, \alpha_i, \beta_r, \beta_i, \omega_r$, and $\omega_i$, which are the streamwise wavenumber and growth rate, spanwise wavenumber and growth rate, and wave frequency and temporal growth rate. Either spatial or temporal stability analysis may be performed, whereby the temporal analysis is less expensive and the spatial analysis is more physical. For the temporal formulation, $\alpha$ and $\beta$ are real numbers and $\omega$ is a complex number which is determined by solving the stability equations. The temporal approach was used by Srokowski & Orszag (1977) in the SALLY code and later by Malik (1982) in the COSAL code. The spatial formulation is more representative of the real boundary-layer flow; the frequency ($\omega_r$) is specified, $\omega_i = 0$, and $\{\alpha_r, \alpha_i, \beta_r, \beta_i\}$ are parameters to be determined. While an eigenvalue analysis will provide two of these values, additional criteria must be specified to determine the remaining two parameters. Arnal (1994) discussed approaches available to determine the two free parameters for 3D disturbances.

Upon solving the eigenvalue problem, integrations are made from the neutral point ($s_0$) to the transition point ($s_1$) where the N-factors are correlated with the experimental database. The N-factor parameter of interest is defined as

$$N = \int_{s_0}^{s_1} \gamma ds \tag{2}$$

where $\gamma$ is the characteristic growth rate of the disturbance. Hence, the methodology is critically dependent on the fidelity of the experimental database. By correlating this N-factor with many transition cases, the amplification factor for which transition is expected for similar flow situations can be inferred. This criteria is then used to determine the LF extent during LFC design.

In a discussion of the application of linear stability theory (and $e^N$ method) in LFC, Malik (1987) described both the incompressible and compressible methodology. Transition in the later portion of a wing was shown to correlate N-factors with 9-11. For transition near the leading edge of a wing, the stabilizing effects of curvature must be included to arrive at N-factors of 9-11.

Finally, Hefner and Bushnell (1980) looked at the status of linear stability theory and the N-factor methodology for predicting the transition location. They noted that a main feature lacking in the methodology was the inability of the method to account for the characterization of the instabilities perturbed in the boundary layer. This shortcoming in the N-factor methodology has inspired the development of more advanced transition prediction methods, which include additional boundary-layer flow physics.

PARABOLIZED STABILITY EQUATION THEORY: Herbert(1991) and Bertolotti (1992) proposed a new methodology based on a system of parabolized stability equations (PSE). The PSE method accounts for the influence of surface curvature and boundary-layer growth on the amplification of disturbances. Individual modal evolutions or the nonlinear interaction of modes can be computed with PSE theory. The PSE system assumes that the dependence of the convective disturbances on downstream development is negligible and that no rapid streamwise variations occur in the wavelength, growth rate, and mean velocity and disturbance profiles. Assuming periodicity in the spanwise direction and time, the PSE disturbance takes the form

$$\Phi = \sum_{m=-N_z}^{N_z} \sum_{n=-N_t}^{N_t} \hat{\Phi}_{m,n}(x,y) e^{i(\int_{x_o}^{x} \alpha_{m,n} dx + m\beta z - n\omega t)} \tag{3}$$

where $N_z$ and $N_t$ are the numbers of modes retained in the truncated Fourier series. The convective direction has been decomposed into a fast-oscillatory wave component and a slowly-varying shape-function component, $\hat{\Phi}$, which is a function of $x$ and $y$. Note, the disturbance profile in Equation 1 was a function of $y$ only and led to ordinary differential equation, while partial differential equations describe the shape function for PSE theory. After the initial values of $\alpha_{n,m}$ are selected, a sequence of iterations is required during the streamwise marching procedure to satisfy the shape-function equations at each streamwise location.

Joslin et al (1993) and Pruett & Chang (1995) have shown that PSE solutions agree with direct numerical simulation (DNS) results for the case of incompressible flat-plate boundary-layer transition and for compressible transition on a cone, respectively. Haynes & Reed (1996) showed that nonlinear PSE computations agree with swept-wing flow experiments (Reibert et al 1996) in that the stationary disturbances distort the mean velocity profiles and reach a saturation state (confirmed with DNS by Joslin & Streett 1994 and Joslin 1995), where as linear N-factor results suggest that the disturbances continue to grow.

Important to the methodology, a good initial disturbance $(\hat{\Phi}, \alpha_{n,m}, \omega, \beta)$ is required for convergence of the iterative solution procedure. Typically, linear stability theory can provide the initial disturbance information; however, the tools of the future will include more of the transition flow physics. Hence, the tools which predict the initiation process for a disturbance–receptivity theory–could provide the necessary input for PSE theory. This initial information could lead to either better correlation criterion for transition (linear use of PSE) or accurately compute the amplification of disturbances–amplitude-based transition prediction method.

RECEPTIVITY–THE INGESTION OF DISTURBANCES: Morkovin (1969) is usually given the credit for coining the phrase–receptivity. Receptivity is the process by which free-stream turbulence perturbs the boundary layer by pressure disturbances originating at the edge of the boundary layer; theories of receptivity have not been used for LFC design, yet. However, receptivity tools which provide the disturbance spectrum and initial amplitudes arising from a conversion of long-wavelength free-stream disturbances to short-wavelength boundary-layer instability modes for use by the linear and/or nonlinear evolution modules (e.g., linear stability theory, PSE theory) will inevitably be an invaluable portion of transition prediction and correlation for future NLF and LFC design tools. Such capability already exists for the simplest of disturbance initiation processes as described by Bertolotti & Crouch (1992).

# 3. LAMINAR FLOW CONTROL AIRCRAFT OPERATIONS

Crucial to maintaining LF in flight, the accumulation of ice, insects, or other debris must be prevented or minimized. Such accumulation would effectuate a surface imperfection and potentially degrade the amount of LF. Where as anti-icing systems have been operational for many years on the leading edge of wings and on nacelles, only limited research results for realistic insect-prevention systems are available.

## 3.1. *Insect Contamination*

The impact of insects on an aircraft is a function of the population density of insects (or insects per volume) and depends on temperature, moisture, humidity, local terrain, vegetation, climate, wind speed, altitude, and vehicle surface shape.

Glick (1939), Coleman (1961), and Croom & Holmes (1985) showed that the largest density of insects was measured at low altitudes (near the ground), with the number of insects decreasing rapidly with increased altitude. Recent flight results of Croom & Holmes (1985) indicated that the largest insect accumulation occurred near 75$^o$F in 4- to 8-mph winds and rapidly decreasing in cooler and hotter temperature ranges. These results are consistent with the early studies of Glick (1939) and Coleman (1961). Coleman (1961) noted that no consistent correlations for insect population density have been identified for barometric pressure, humidity, light intensity, precipitation, or the electrical state of the atmosphere.

Coleman (1961) discussed techniques to either eliminate or prevent insect contamination. These techniques included *(a)* mechanical scrapers which scrape the surface free of insects, *(b)* deflectors which either catch the insects or cause their paths to be deflected away from the surface, *(c)* paper covers which cover the surface until sufficient altitude is reached and the cover is either released or extracted into the aircraft (leaving a clean surface for cruise), *(d)* a cover which is dissolvable by fluid discharge, removed by a thermal process, or carried away in flight by the high shear, and *(e)* continuous liquid discharge. For each anti-insect device, a weight and system-complexity penalty arises.

Of the techniques tested, paper coverings, continuous liquid discharge, and deflectors have been demonstrated in flight to prevent the loss of LF due to insects. Gray & Davies (1947) with the King Cobra flight test, Head et al (1955) with the Vampire porous-suction flight test, Groth et al (1957) with the F-94 slot-suction flight test, and Runyan et al (1987) with the B-757 NLF flight test have successfully used the paper-cover concept to protect the test section from insect accumulation during take-off and climb. Peterson & Fisher (1978) and Maddalon & Braslow (1990) with the Jetstar aircraft and Croom & Holmes (1985) with a Cessna 206 showed that continuous spray could be effective in preventing insect accumulation. And Maddalon & Braslow (1990) with the Jetstar and Collier (1993) with the B-757 indicated the Krueger insect shield was effective in deflecting the insects from the LFC test region.

## 3.2. *Ice Accumulation and Atmospheric Effects*

The accumulation of ice on the leading-edge of wings can significantly alter the geometry of the wing and cause drag penalty and performance degradation. Additionally, atmospheric effects including gusts, rain, clouds, and pollution can potentially impact LFC aircraft.

Similar to the non-LFC aircraft, a LFC-type aircraft must account for potential ice-accumulation and prevent such a detrimental and dangerous encounter by the use of anti-icing techniques–either by applying heat or by dispelling anti-freeze agents. The icing issue for NLF and LFC is more of a system design problem than a technical obstacle to achieving LF.

Concerning atmospheric effects, loss of LF had been reported during cloud encounters for the X-21 (Hall 1964), the F-94 (Groth et al 1957), and the Jetstar (Maddalon & Braslow 1990) LFC flight tests. In a F-14 NLF flight experiment, Anderson & Meyer (1990) showed flight data for the that indicated that turbulent bursts were measured during cloud encounters. During these encounters and loss of LF, the charge patch indicated the presence of ice particles. In all of the above flight experiments, LF was soon re-gained after emerging from the cloud. Also, LF was maintained in moderately gusty weather; however, strong atmospheric turbulence levels led to a loss of LF.

Finally, Smith & Higton (1945) reported the impact of rain, dust, flies, and surface-finish polish on the flow were assessed in the King Cobra flight tests. Drag results from dust and water accumulation showed no deviation compared with smooth clean surface drag measurements.

## 3.3. *Operational Maintenance of Laminar Flow*

Laminar flow research in the 1940s through the 1960s had difficulty retaining surface smoothness specifications during the day-to-day operations of NLF and LFC flight test aircraft. However, manufacturing techniques have improved for aircraft in the 1990s and operational maintenance problems of the past are no longer a major concern.

Aside from surface-quality maintenance issues, Meifarth & Heinrich (1992) presented a list of operational issues related to achieving and maintaining NLF and LFC. Some of the issues included the need for additional spare parts and maintenance due to the suction system, uncertainties in the potential contamination due to pollution residue on the structural surface, and operational planning for suction-system failure. Clearly, the literature attests to the awareness that an operational plan for an LFC aircraft must account for many of these issues, and Robert (1992) stated that LFC brings benefits even after the penalties (system and operational) are factored into the costs.

# 4. PROGRESS IN THE UNITED STATES

Sections 4 and 5 discuss some of the most significant recent advancements in LFC technology made in the United States and Europe.

In the 1970s and 1980s, the LFC project (under the NASA Aircraft Energy Efficiency program) was formed to help improve aircraft cruise efficiency. The progression of major NLF projects in the US included various general aviation flight tests, F-111, F-14, and B-757 NLF flight experiments, LF nacelle demonstrator flight experiments, and advanced airfoil methodology development and validation. Results from the NLF flight tests showed that LF could be realized in flight to approximately 50% chord for wing sweeps near $10^o$ and to 20% chord for wing sweeps near $25^o$; however, the N-factor correlations using the flight data did not collapse to give a sufficiently good design criterion. Wind-tunnel and flight tests using LFC and HLFC technology ensued; some of the major projects are summarized below.

## 4.1. *Subsonic and Transonic LFC Wind-Tunnel Tests*

Toward demonstrating the benefits of supercritical wings and LFC, Brooks & Harris (1987) and Bobbitt et al (1992, 1996) discussed the results of a transonic slot- and perforated-suction LFC wind-tunnel experiment. Using wall liners, the infinite swept wing model had suction capability to 96% chord on the upper surface and to 85% chord on the lower surface. Brooks & Harris (1987) noted that, for the slot-suction LFC test, full-chord LF was obtained on the upper and lower surface for Mach 0.82 and a chord Reynolds number of $12 \times 10^6$.

Later in 1995, a NASA/Boeing team conducted a subsonic HLFC wind-tunnel experiment to determine the influence of hole size and spacing and suction level and distribution on LF extent. The set-up was similar to the early transonic test in that tunnel liners were used to simulate an infinite swept wing. Some 3000 infrared images and 6000 velocity profiles were gathered during the test. LF was easily obtained back to the pressure minimum with sufficient suction. More detailed results are not available for this article.

## 4.2. *Jetstar Leading-Edge Flight Test*

In the 1980s, the Jetstar flight experiment (Fischer et al 1983; Maddalon & Braslow 1990) was probably the most significant contribution to the advancement of LFC technology. The Jetstar LFC flight test article (illustrated in Figure 2) addressed LFC leading-edge system integration issues and determined the practicality of the LFC system in operational environments.

McDonnell Douglas and Lockheed designed and constructed leading-edge test sections for the right and left wings, respectively, of the Jetstar. Both test articles had $30^o$ leading-edge sweep, involved 20% of the spanwise extent of the wings, and had LFC back to the front spar (12% chord). From the end of the test article at the front spar,a fairing was used to continue the contours of the test articles back to 65% chord. The contours were designed to simulate a supercritical pressure distribution. flight conditions ranged from Mach 0.7 to 0.8 and altitudes of 32000 to 40000 ft.

As described by Etchberger (1983) and Lange (1984, 1987), the Lockheed concept involved the use of slot-suction for the LFC system with slots on both the lower and upper surface back to the front spar. At the leading-edge, 6 slots served to control the flow during cruise and to provide liquid discharge for the prevention of insect and ice accumulation. Reported by Pearce (1982), Pearce et al (1984), and Powell (1987), the Douglas concept involved an electron-beam perforated titanium skin. Suction was applied from just below the attachment-line back to the front spar. A Krueger device was used at the leading edge to deflect insects; a spray nozzle system was appended to the Krueger device to prevent both insects and ice accumulation. The backup system was never used during the flight test.

Using the Douglas LFC system and a Gaster bump on the leading-edge, LF was observed back to 83% of the article length for the design conditions. Shown in Figure 3, LF was realized back to 97% for an off-design condition. With a leading-edge bump, the Lockheed test article achieved comparable amounts of LF. Also, because the Krueger device prevented insect-accumulation on the test section, liquid discharge was not necessary for the Douglas system. Davis et al (1986, 1987) discussed the effect of cloud encounters on the LF extent in the flight test program. Shown in Figure 3, a degradation of the flow was observed during a cloud encounter; however, full LF was regained within a few seconds after the cloud encounter.

Finally, Powell (1987) discussed the LFC technological accomplishments resulting from the Jetstar program (for Douglas). Electron-beam perforated suction surface fabrication, simplified LFC suction panel construction, and a retractable leading-edge Krueger device and TKS insect/ice prevention system were devised and/or demonstrated on the Jetstar. The Jetstar program demonstrated that LFC could be operated in an airline-type environment without any special maintenance considerations (Maddalon & Braslow 1990).

### 4.3. *B-757 HLFC Flight Test*

Following the NASA Jetstar LFC flight test, the B-757 HLFC flight test (Figure 4) proceeded to increase the LFC technology readiness and increase the application Reynolds number. A spanwise segment of the leading-edge box outboard of the engine nacelle pylon and on the left wing was replaced with a perforated titanium HLFC leading-edge system. The leading-edge consisted of a fully integrated Krueger insect shield and a thermal de-icing system. Flights tested in 1990 and 1991 led to the achievement of LF using HLFC suction. Sample results shown in Figure 4 (Collier 1993) indicate that approximately 65% chord LF was measured in flight. Drag calculations yielded a local drag reduction on the order of 29% using HLFC and a projected overall drag reduction of 6% for the aircraft.

## 4.4. *HLFC Nacelle Demonstration Flight Test*

Bhutiani et al (1993) discussed a subsequent flight test to demonstrate LF benefits for HLFC nacelle applications. A production GEAE CF6-50C2 engine nacelle modified to incorporate two HLFC panels was installed on the starboard wing of an Airbus A300/B2 transport. As discussed by Collier (1993), the HLFC concept was extremely effective over the range of cruise altitudes and Mach numbers tested, resulting in LF to 43% of the nacelle length (the design objective) independent of altitude. In addition, significant LF was achieved at various altitudes with no suction.

## 4.5. *High-Speed Civil Transport*

Concerning the application of LFC to supersonic transport aircraft, two fundamental approaches were posed for the supersonic laminar wing. The first approach was a low-sweep wing which involved the design of a NLF leading-edge region. As discussed by Gottschalk (1996), such a concept proposed by Northrop-Grumman would have a sharp supersonic leading edge and result in a thin attachment-line boundary layer and very small momentum-thickness Reynolds number. Such a flow should be stable and avoid the turbulent attachment-line issue. Crossflow disturbances could be avoided with low sweep, and, with appropriate wing shaping, a partially NLF flow wing could potentially be achieved. LFC (suction or thermal) would be required on the roof-top of the wing to extend the region of LF to high chord Reynolds numbers. In contrast to the low-sweep concept, the second approach would involve a high-sweep wing. The highly swept wing would have a subsonic leading edge, a blunt nose, and higher momentum thickness Reynolds number and therefore require LFC in the leading-edge region and on the roof-top to control the CF disturbances and achieve a large LF extent. With the later approach, feasibility studies (Boeing 1990; Powell et al 1989) showed significant performance benefits of supersonic LFC applied to the HSCT configuration. Based on large potential benefits, quiet wind-tunnel research was initiated at NASA Langley and Ames Research Centers to advance the state-of-the-art in the wind-tunnel testing of SLFC and F-16XL SLFC flight tests were carried out to demonstrate the LFC concept in supersonic flight.

M3.5 AND M1.6 QUIET-TUNNEL TESTS: Conventional supersonic and hypersonic wind tunnels are dominated by acoustic disturbances radiated from the turbulent boundary layers on the tunnel walls. To study LF (i.e., transition, boundary-layer instability, and LFC), the test section in the tunnel must have very low disturbance levels (defined as free-stream pressure fluctuations below 0.1%). Wilkinson et al (1992) gave a review of low-disturbance (or quiet) tunnel technology.

Beckwith et al (1988) discussed a method to maintain a test section free from acoustic disturbances, which culminated in the Mach 3.5 supersonic low-disturbance tunnel (SLDT) at NASA Langley Research Center. The nozzle throat is highly polished to maximize the extent of LF on the nozzle walls. In the upstream converging section of the tunnel, suction was used to remove the turbulent boundary layer on the contraction wall upstream of the throat. The fresh laminar boundary layer evolves through the contoured nozzle until the boundary layer transitions to turbulence. The location of this transition point governs the length of the low-disturbance test-section rhombus and is directly influenced by the unit Reynolds number of the flow. As the unit Reynolds number increases, the size of the quiet test-section rhombus decreases; however, the Reynolds number based on the length of the quiet test core increases. Run times for the tunnel are on the order of 30 minutes.

In support of the F-16XL SLFC flight experiment, models were developed for the Langley quiet tunnel to calibrate the design tools for NLF and LFC and to study attachment-line transition. Cattafesta et al (1994, 1996) discussed temperature sensitive paint (TSP) transition measurements and the transition locations for the solid model. The calculated N-factors correlated well for N=14 over a range of free-stream unit Reynolds numbers and angle-of-attacks for the solid model. A SLFC perforated-suction model was built and tested for the quiet tunnel but the results are not available for this article.

At NASA Ames Research Center, a Mach 1.6 laminar-flow supersonic wind tunnel (LFSWT) has features which include a low-disturbance settling chamber, smooth nozzle and test section walls for LF, steady supersonic diffuser flow, and low structural vibration of nozzle and test section walls. Wolf et al (1994) presented results for flow quality and tunnel transition aspects of the Mach 1.6 quiet tunnel. No SLFC tests were performed as of this article; however, fundamental studies of attachment-line transition were performed in the tunnel (Coleman et al 1996).

F-16XL SLFC FLIGHT TESTS: Two General Dynamics F-16XL aircraft (XL has delta wings) served as test beds to demonstrate the first ever achievement of LF in supersonic flight using LFC. The F-16XL wings had inboard sweep of $70^o$ and outboard sweep of $50^o$, similar to the proposed HSCT wing configuration. NASA and Rockwell carried out flight tests using the F-16XL Ship 1, and NASA, Rockwell, Boeing, and McDonnell Douglas carried out flight tests using the F-16XL Ship 2.

The flight test program began in 1990. According to Woan et al (1991), Anderson & Bohn-Meyer (1992), and Norris (1994), the suction glove on the F-16XL Ship 1 was designed for a Mach number of 1.6, altitude of 44000 ft, angle of attack of $2^o$, momentum thickness Reynolds number on the attachment line of less than 114, and a unit Reynolds number of $2.53 \times 10^6$/ft. Suction was limited to the first 25% chord and attachment-line CF disturbances were the primary focus of the LFC experiment (Figure 5).

Although no LF was observed at the design conditions, LF was measured at other flight conditions. Anderson & Bohn-Meyer (1992) show in our Figure 5 the amount of LF with and without suction for a given flight test condition; hot-film data indicated LF to the outboard portion of the glove. Woan et al (1991) noted that the weakest area in the design procedure was estimating the attachment-line condition.

In 1991-92, flight measurements were obtained for the flow on the F-16XL Ship 2 leading-edge passive glove. The flight tests with the passive glove provided pressure and LF data valuable for the design of the Ship 2 suction glove.

The Ship 2 SLFC perforated-suction glove was constructed of inner and outer titanium (perforated) skin with aluminum stringers. According to Fischer & Vemuru (1991), the F-16XL-2 SLFC flight experiment had objectives of achieving 50%-60% chord LF on a highly swept wing, of delivering validated CFD codes and design methodology, and of establishing initial suction system design criteria for LFC at supersonic speeds. The suction glove was installed on the F-16XL Ship 2 and the first suction-on LFC supersonic flight test was accomplished in January 1996. Smith (1996) noted that the Ship 2 supersonic LFC flight experiment achieved about 70%-80% of the initial goals; however, more detailed results are not available for this article.

# 5. PROGRESS IN EUROPE

According to Bulgubure & Arnal (1992), NLF and LFC programs began in France in 1984. These NLF and LFC programs were sparked by the successful results demonstrated in the US. In 1989, a formal LF program–the European Laminar Flow Investigation (ELFIN) project– was initiated with participation by industry, government research laboratories, and universities. The ELFIN project concentrated on the development of LF technology for application to commercial transport aircraft.

## 5.1. *Dassault Falcon 50 HLFC Flight Tests*

Before the formation of ELFIN, the Falcon 50 (business-type) HLFC flight tests aimed to show the feasibility of HLFC in the 3D region near the fuselage and to show that LF could be realized for a $35^o$ swept wing ($30^o$ with slide slip) for flight Reynolds numbers ranging from $12 - 20 \times 10^6$ (Bulgubure & Arnal 1992; Courty et al 1993). The perforated stainless steel HLFC system had suction aft to 10% chord on the upper surface and TKS anti-icing/insect-contamination avoidance in the leading-edge of the wing. A Gaster (1965) bump was positioned at the wing/fuselage junction to prevent attachment-line contamination. With LFC suction and with the Gaster bump position at 300 mm from the wing root, significant LF was achieved in flight, while turbulent flow was measured with no suction.

## 5.2. *HLFC Transonic Wind-Tunnel Tests*

Reneaux & Blanchard (1992) discussed the design and testing of an Airbus transport HLFC swept wing model in the ONERA-CERT T2 wind tunnel. Suction was applied from the leading edge back to 20% chord and a favorable pressure gradient was maintained back to 60% chord on the upper surface and 55% chord on the lower surface. For transonic flow and at a maximum chord Reynolds number of $42 \times 10^6$, the computed LF extent ranged from 25% chord at the wing root to 55% chord at the wing tip using suction. The computed viscous (total) drag of the HLFC wing was 45% (10%) less than the turbulent wing, and suction on the upper surface alone led to a viscous (total) drag reduction of 29% (6.3%).

Based on the successful VFW-614 and Fokker 100 NLF flight tests, a 1/2-scale model of an HLFC VFW-614 wing was built in 1992 for the French S1MA transonic tunnel (Schmidt et al 1993). The titanium outer skin had perforated holes covering about 15% chord on both the upper and lower surface. The results showed that LF was achieved to 50% chord on the upper surface and to 30% chord on the lower surface.

## 5.3. *European HLFC Nacelle Demonstration Flight Test*

In 1992 and 1993, a program was initiated to investigate the prospects of achieving extensive LF on the engine nacelles (Barry et al 1994) using the VFW-614/ATTAS aircraft. The HLFC nacelle included a TKS anti-icing/anti-insect system (Humphreys 1992). The nacelle was designed to meet acceptable low-speed performance characteristics (not installed design) for takeoff and landing. The flight test demonstrated that LF flow was achievable over 60% of the nacelle length in the installed environment over a large range of flight conditions. The liquid insect-avoidance system was operated successfully during the course of the flight testing.

## 5.4. *A320 Laminar Fin Flight Test Program*

Airbus Industries in collaboration with ONERA and DLR formulated a plan to enable LFC capability for subsonic transport aircraft. The vertical fin of the A320 aircraft was chosen as the candidate for evaluation of the feasibility of HLFC because of the availability of an aircraft for flight testing, simple installation, no de-icing system, attainment of flight Reynolds number in a wind-tunnel facility (S1MA), and minimized cost (Robert 1992; Thibert et al 1990).

Analysis of a proposed HLFC A320 vertical tail indicated that LF was expected to about 50% chord. Further analysis of the computed results revealed that 1.0%-1.5% aircraft drag reduction was possible with LF on the vertical fin. The second phase of the program involved the testing of a 1/2-scale HLFC A320 vertical fin in the ONERA S1MA facility. According to Birch (1996), the development of the A3XX program at Airbus has allowed for the success of the A320 LFC fin program by requiring the power plants of the A3XX to be positioned closer to the wing and for suction LFC nacelles. No additional results are available for this article.

# 6. DISCUSSION

This article has reviewed some of the early foundational work on LFC and some of the more recent US and European projects which had goals of solving technical obstacles associated with the application of LFC to advanced transport aircraft.

The 1980s and 1990s brought the successful demonstration of an LFC aircraft (Jetstar) in airline operations and with insect-prevention systems, the achievement of LF at high Reynolds numbers (B-757 HLFC flight test), the achievement of LF on an HLFC engine nacelle (A300/GE test and VFW-614), and various successful LFC wind-tunnel tests. In the supersonic vehicle class, the 1990s brought the first flight demonstration of LF achieved by supersonic laminar flow control (SLFC).

The technology has the potential to offer breakthrough improvements in aircraft efficiency, leading to significant reductions in aircraft fuel consumption and take-off gross weight, extended range or increased payload, reductions in emissions and noise, and increased cruise lift/drag.

Much progress has been accomplished toward the goal of commercial incorporation of LFC (and NLF) on wings, tails, and engine nacelles. However, because the application of the technology has led to additional systems and some uncertainty in the maintenance requirements and long-term structural integrity due to the system, there are still questions which must be resolved relative to long-term operational and reliability characteristics of current HLFC concepts before the aircraft industry can guarantee the sustained performance of the LFC vehicle to the airline customers. Finally, significant additional benefits could be bought with LFC if new innovative suction-systems (reduced part-count and distributed arrays) could be developed and tested. Such futuristic concepts can be found in the embryonic technologies of active flow control.

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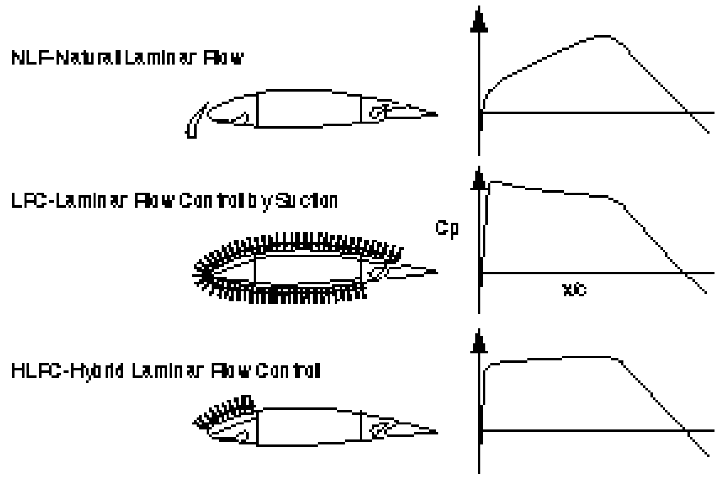


*Figure 1* Schematic of NLF, LFC, and HLFC concepts for wing (Collier 1993). Diagrams show suction locations and surface pressure coefficient ($C_p$) versus chordwise extent ($x/c$).

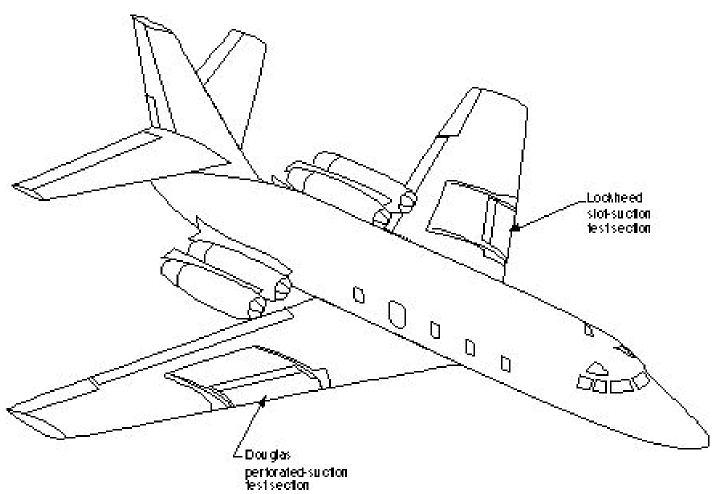


*Figure 2* NASA Jetstar leading-edge flight test aircraft (Fischer et al 1983).

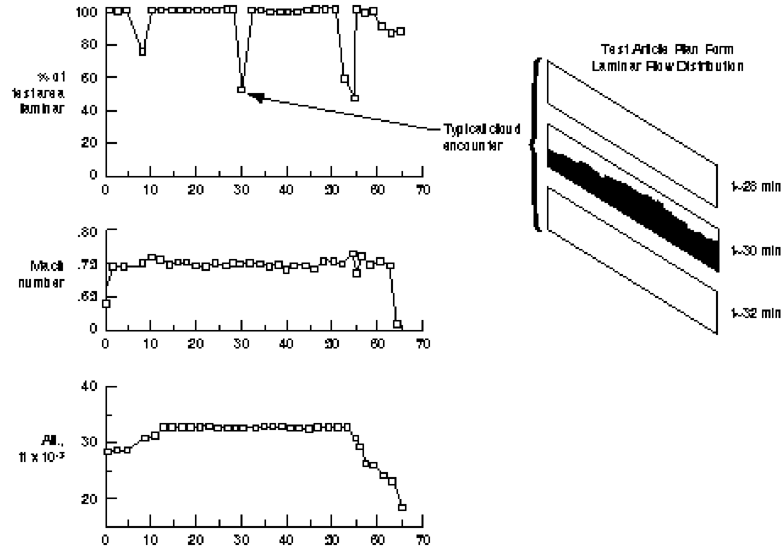


*Figure 3* Typical LF extent with time for Douglas perforated-suction test article (Wagner et al 1992).

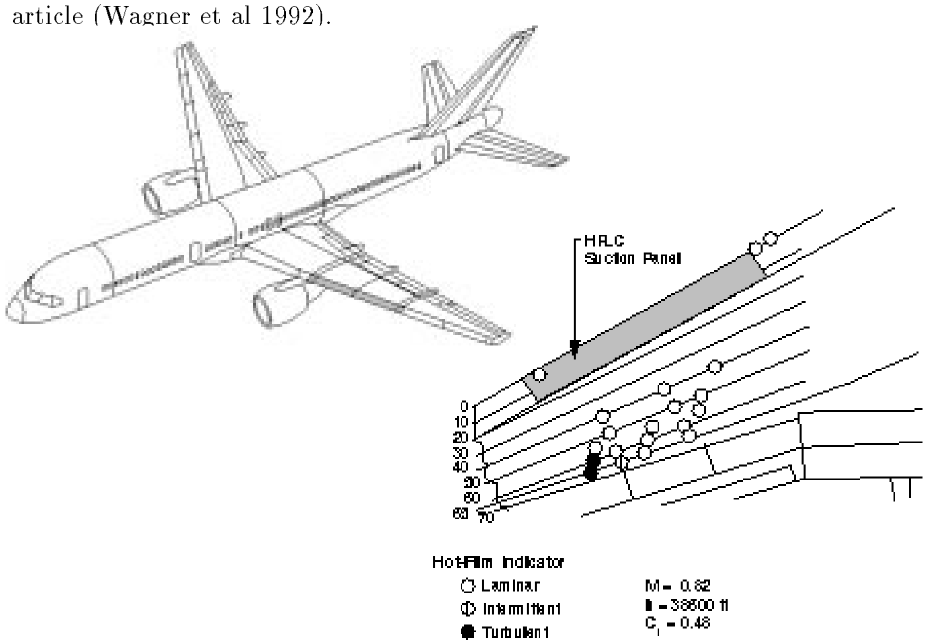


*Figure 4* B-757 hybrid laminar flow control (HLFC) test article and sample laminar flow results (Collier 1993).

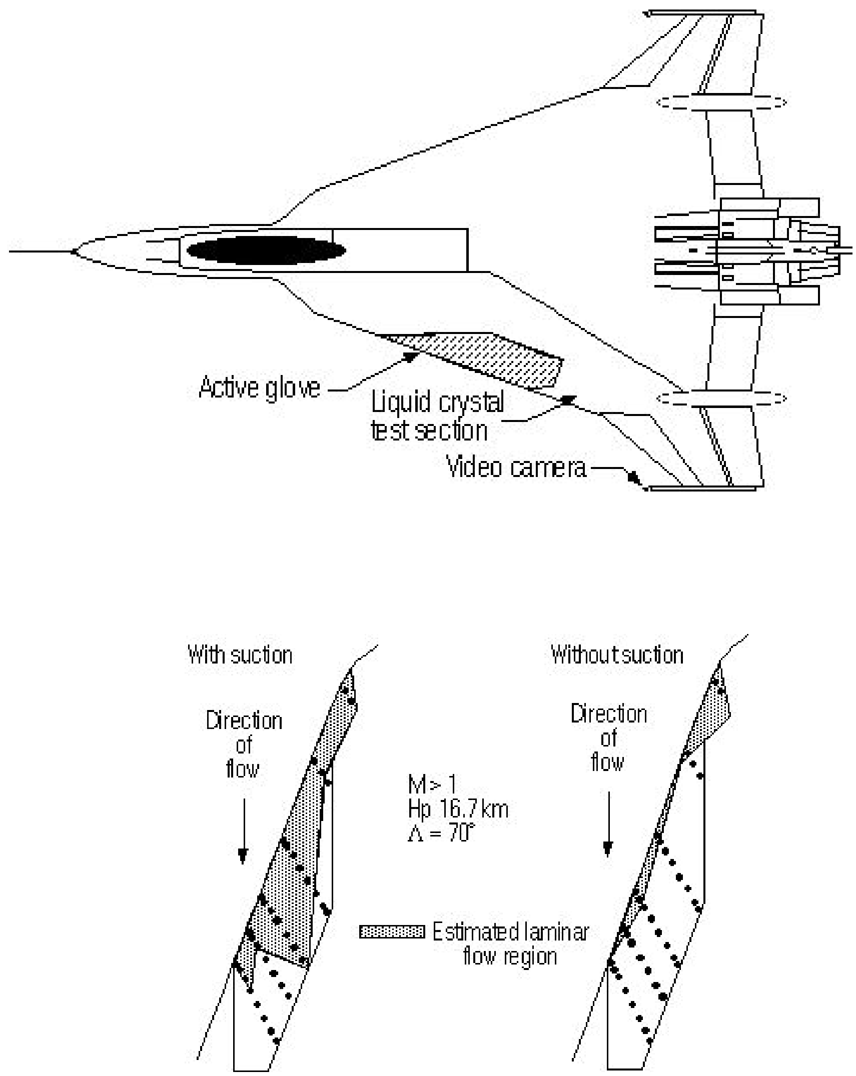


*Figure 5* F-16XL Ship 1 with perforated-suction glove and laminar flow extent with and without suction (Anderson & Bohn-Meyer 1992).