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ROUGHNESS AND WAVINESS REQUIREMENTS FOR LAMINAR FLOW SURFACES

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INTRODUCTION

Many modern metal and composite airframe manufacturing techniques can provide surface smoothness which is compatible with natural laminar flow (NLF) requirements. Specifically, this has been shown in flight investigations over a range of free-stream conditions including Mach numbers up to 0.7, chord Reynolds numbers up to about 30 million, and transition Reynolds numbers up to about 14 million. The recent flight experiments were conducted on flush-riveted thin aluminum skins, integrally stiffened milled thick aluminum skins, bonded thin aluminum skins, and composite surfaces. The most important conclusion concerning manufacturing to be drawn from these experiences is that the waviness of the surfaces in the tests met the NLF criterion for the free-stream conditions flown. However, in addition to waviness, an equally important consideration is manufacturing roughness of the surface in the form of steps and gaps perpendicular to the free stream. While much work has been done in the past, many unknowns still exist concerning the influences of wing sweep, compressibility, and shapes of steps or gaps on manufacturing tolerances for laminar flow surfaces. Even less information is available concerning NLF requirements related to practical three-dimensional roughness elements such as flush screw head slots and incorrectly installed flush rivets.

The principal challenge to the design and manufacture of laminar flow surfaces today appears to be in the installation of leading-edge panels on wing, nacelle, and empennage surfaces. Another similar challenge is in the installation of access panels, doors, windows, and the like on fuselage noses and engine nacelles where laminar flow may be desired. These surface discontinuities appear to be unavoidable for typical current aircraft; the challenge is, "Can laminar flow be maintained over these discontinuities?"

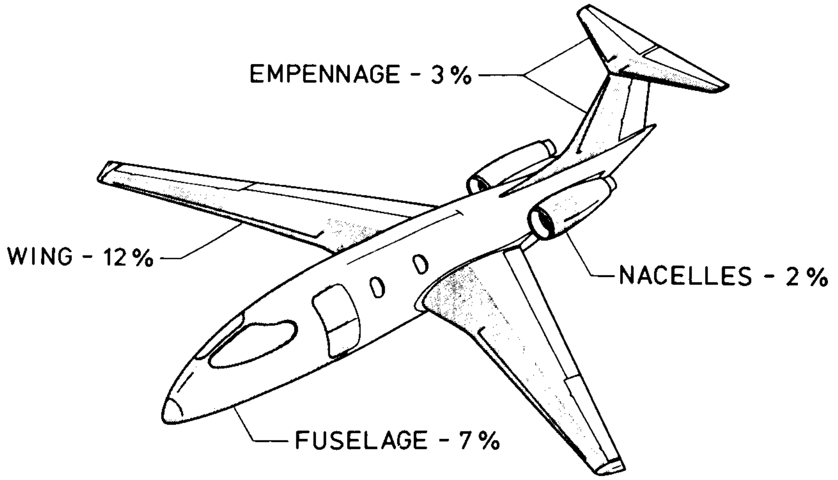
NLF APPLICATIONS

Applications of NLF can include all surfaces of an aircraft. Favorable pressure gradients can be designed onto fuselages, horizontal and vertical tails and nacelles as well as the wings. For a high performance business jet, the potential drag reduction with NLF ranges between about 12 percent (for NLF on the wing only) to about 24 percent (for NLF on the wing, fuselage, empennage, and engine nacelles). These values of drag reduction are calculated as a percent of total airframe drag at a cruise Mach number of 0.7. Individual component benefits are tabulated below:

Component	% of Body Length NLF	% of Drag Reduction
Wing	50	12
Horizontal tail	30	2
Vertical tail	30	1
Fuselage	30	7
Nacelles	30	2
TOTAL:		24

These benefits can amount to large savings in fuel cost as well as increased performance. These drag reductions are calculated for NLF added to an existing configuration; larger benefits would accrue for integrated design calculations.

DRAG REDUCTION AS PERCENT OF TOTAL
EXTENT OF NLF



TOTAL NLF DRAG BENEFIT - 24 %

NLF MANUFACTURING TOLERANCES

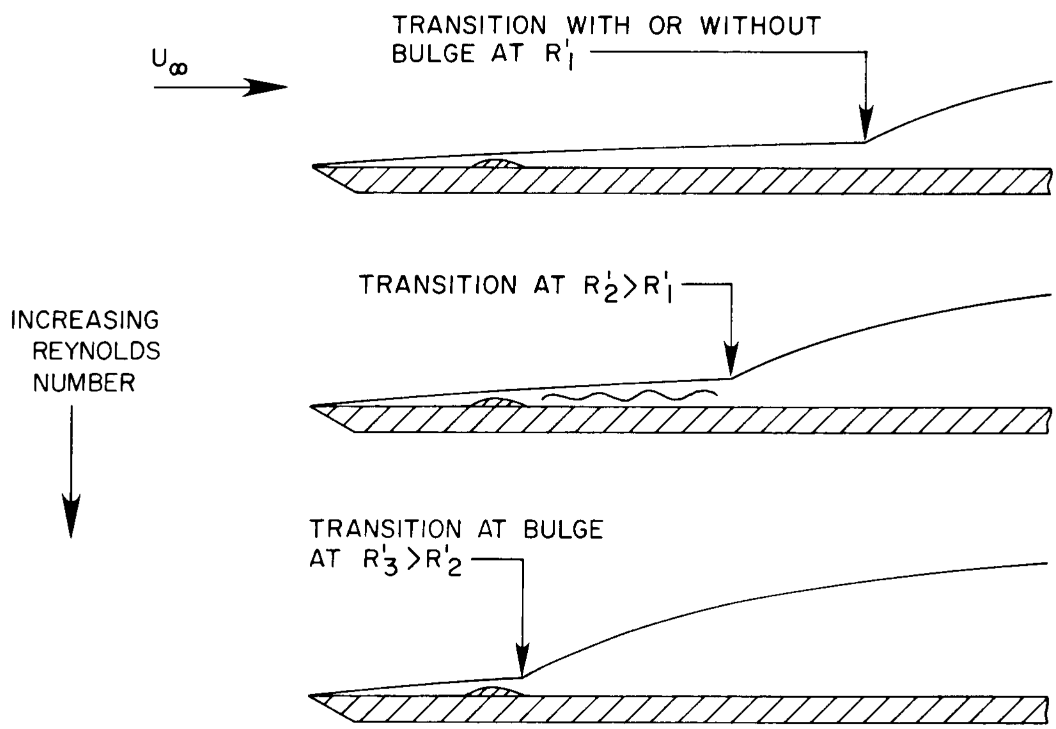
Existing criteria for NLF surfaces deal with waviness and with both two- and three-dimensional roughnesses. Each of these types of surface imperfections can cause transition by different mechanisms in the boundary layer. The definition of critical height for waviness or roughness is related to the mechanism by which transition is affected. The mechanisms of most practical interest include laminar separation, amplification of Tollmien-Schlichting (T-S) waves, amplification of crossflow vorticity, and interactions between any of these mechanisms. In addition, free-stream turbulence and acoustic disturbances may interact with these mechanisms to influence critical waviness and roughness heights. Criteria exist only for critical waviness and roughness which cause either laminar separation or amplification of T-S waves. No criteria exist which fully address surface-imperfection-induced transition related to crossflow amplification on swept wings or interactions between the various transition mechanisms and free-stream disturbances.

The following definitions appear in the literature and are useful for the present discussion. Critical waviness height-to-length ratio (h/λ) and critical step height or gap width can be defined as those which produce transition forward of the location where it would occur in the absence of the surface imperfection. Experimentally, premature transition was identified in past work as the first appearance of turbulent spots downstream of either a waviness or roughness surface imperfection. This is the definition used by Fage (ref. 1) and Carmichael (ref. 2) to establish critical conditions for surface imperfections.

- WAVINESS
  - CHORDWISE
  - SPANWISE
- ROUGHNESS
  - TWO-DIMENSIONAL
  - THREE-DIMENSIONAL
- COUPLING EFFECTS
  - SWEEP
  - ACOUSTICS
  - COMPRESSIBILITY

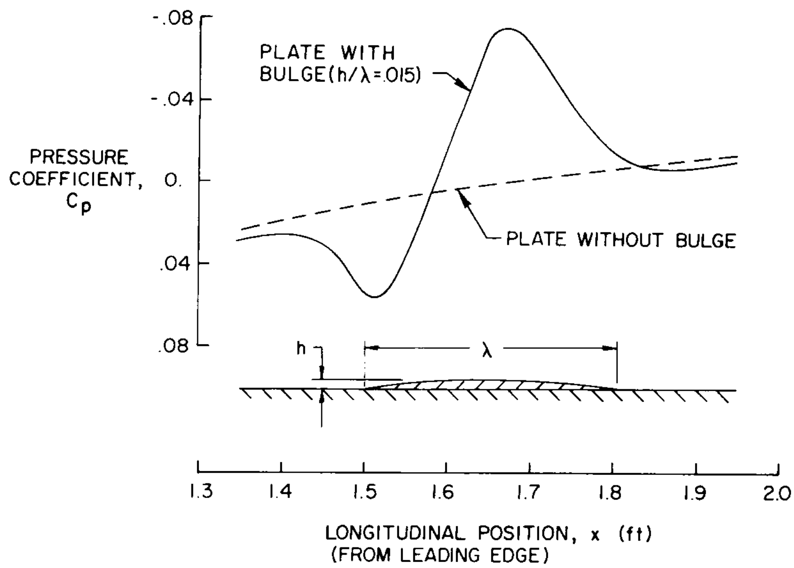
EFFECTS OF 2-D SURFACE IMPERFECTIONS ON LAMINAR FLOW

For most common applications in two-dimensional flows, the previous definition physically relates to the viscous amplification of T-S waves, or to (Rayleigh's) inflectional instability growth over a laminar separation bubble. This figure illustrates possible effects of a given two-dimensional surface imperfection on transition. A subcritical condition exists when transition is unaffected by the disturbance (top of figure). The middle of the diagram illustrates the critical condition at which transition just begins to be affected by the disturbance. In the extreme, a surface imperfection could cause sufficiently rapid T-S wave amplification for transition to occur very near the wave itself, as illustrated at the bottom of the figure. Another limiting condition of practical interest is the occurrence of transition at the surface imperfection caused by the inflectional instability in the free shear layer over the laminar separation bubble formed there.



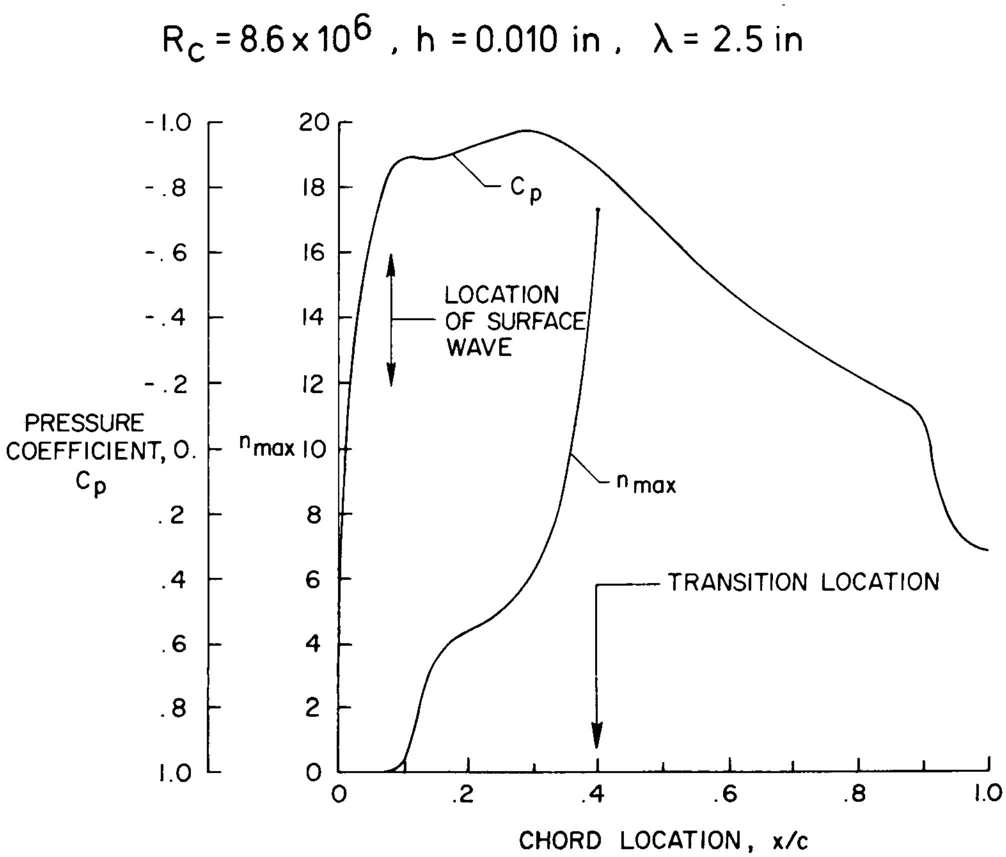
PRESSURE DISTRIBUTION OVER A BULGE

From Schlichting (ref. 3), the laminar boundary layer will separate for $(\theta^2/\nu)\ (du_e/dx) < -0.1567$ where θ is the boundary layer momentum thickness, ν is the local kinematic viscosity, and u_e is the local potential flow velocity. Calculation of values of $(\theta^2/\nu)\ (du_e/dx)$ for both Fage's (ref. 1) and Carmichael's (ref. 4) surface imperfections indicate that the critical value for laminar separation was exceeded at most of the test conditions for those studies. For example, at the conditions shown in the figure (from Fage), $(\theta^2/\nu)\ (du^e/dx) = -0.19$. Similar results occur for analysis of Carmichael's data (ref. 4). Apparently, for many of the critical surface imperfections tested by Fage and Carmichael, laminar separation at the imperfection was present. Thus, the mechanism for forward movement of transition due to a surface imperfection could involve both the effect of local adverse pressure gradient on T-S amplification and the effect of Rayleigh's inflectional instability.



TOLLMIEN-SCHLICHTING INSTABILITY GROWTH IN THE PRESENCE OF A WAVE

Using flight data from Obara and Holmes (ref. 5), this figure illustrates the predicted local increase in growth rate of T-S instability caused by a surface wave. The surface wave tested was 0.010 in. high and had a wave length of 2.5 in. The effects of this wave on the pressure distribution between 10 and 13 percent chord and on maximum T-S amplitude ratios are apparent in the figure. In the adverse pressure gradient of the wave, the logarithmic exponent of T-S wave growth is seen to grow from about 1 to near 4. Elsewhere, in favorable pressure gradients, the rate of growth of the T-S disturbance is damped. For the surface wave and flight conditions tested, the growth rate of T-S instability was not large enough to cause premature transition. The measured location of boundary layer transition was at 40 percent chord which corresponded to the predicted location of laminar separation.



WAVINESS CRITERION (CARMICHAEL)

The research of Carmichael (ref. 2) provided the basis for the existing criterion on allowable waviness for both swept and unswept wing surfaces. Carmichael's investigations at least partially included the influences of compressibility, boundary layer stabilization by suction and pressure gradient, multiple waves, and wing sweep. Compressibility favorably increases the damping of growth rates for T-S waves. A second, unfavorable effect results from the increased pressure peak amplitude over a wave due to compressibility. It is not clear which effect dominates. With wing sweep, Carmichael and Pfenninger (ref. 6) observed a slight reduction in allowable waviness. Furthermore, a slightly greater reduction in allowable wave height to wave length ratio (h/λ) was observed for multiple waves on a swept wing than for multiple waves on an unswept wing. This might be expected to result from the interaction between the T-S instability growth in the deceleration on the backside of the wave and the crossflow instability growth due to the spanwise pressure gradient. Carmichael (ref. 2) defined a critical wave as the minimum (h/λ) which prevents the attainment of laminar flow to the trailing edge under boundary layer stabilization using moderate suction. On a non-suction wing, the criterion applies for waves in regions of boundary layer stabilization using a favorable pressure gradient (flow acceleration). The criterion was based on experimental results for waves located more than 25-percent chord downstream of the leading edge. Thus for waves located in very highly accelerated flows closer to the leading edge, the criterion may under-predict allowable waviness. Conversely, the criterion would over-predict the allowable waviness in a region of unaccelerated flow. Carmichael's waviness criterion is given as:

$$\frac{h}{\lambda} = \left[\frac{59000\ c\ \cos^2 \Lambda}{\lambda R_c^{1.5}}\right]^{0.5}$$

where h is the double-amplitude wave height in inches, λ is the wavelength in in., c is the streamwise wing chord in in., Λ is the wing leading-edge sweep and R_c is the chord Reynolds number based on chord length and airspeed in the free-stream direction.

ON MODERN SUBSONIC WINGS WITH SMALL SWEEP, FAVORABLE PRESSURE GRADIENTS, USE CARMICHAEL'S (X-21) CRITERION FOR SINGLE WAVES

$$\frac{h}{\lambda} = \left(\frac{59{,}000 \cdot c \cdot \cos^2 \Lambda}{\lambda \cdot R_C^{\ 3/2}}\right)^{1/2}$$

WAVINESS CRITERION (FAGE)

The classical research by Fage (ref. 1) provided criteria for critical height of 2-D bulges, ridges and hollows in incompressible 2-D boundary layers. His shapes do not accurately represent many of the surface imperfections observed on modern airframe surfaces. However, the pressure disturbances over Fage's bulges and hollows do simulate those which will occur over sinusoidal waves. In spite of these limitations, Fage's experiments did provide an understanding of some of the mechanisms associated with transition over these imperfections. Fage's criterion is given by:

$$\frac{h'}{\lambda} = 9 \times 10^{6} \ \frac{u_e s_t}{\nu}^{-3/2} \ \frac{s_t}{\lambda}^{1/2}$$

where h' is the height of a bulge in ft above the nominal surface, λ is the length of the bulge in ft, s_t is the surface length to transition in ft, u_e is the boundary layer edge velocity in ft/sec at the location of the center of the bulge for the undistorted surface, and ν is the kinematic viscosity. Using local C_p and free-stream velocity, u_e can be determined directly for use in the equation. Fage's work covered a range of transition Reynolds numbers from 1×10^6 to 3.5×10^6, and did not include any effects of compressibility or sweep.

ON FLAT PLATES WITH

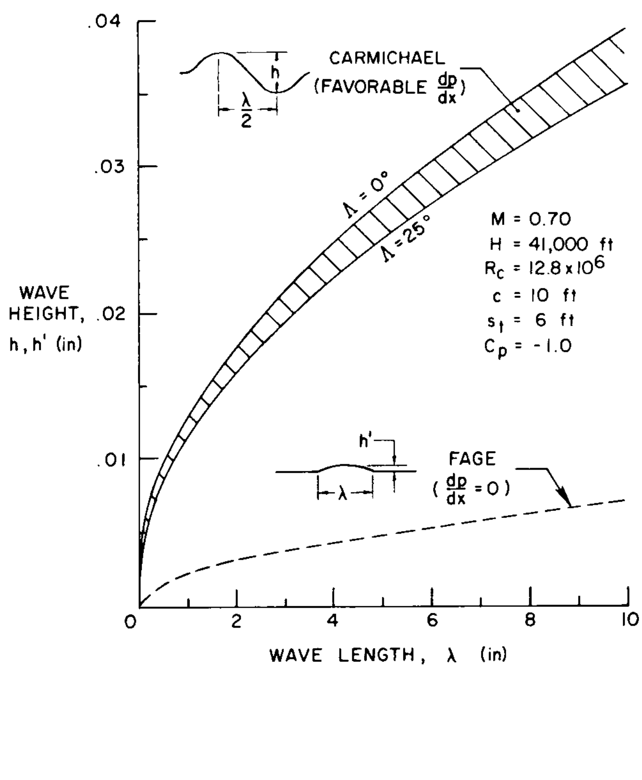
NO SWEEP, ZERO PRESSURE GRADIENT

AND INCOMPRESSIBLE FLOW

USE FAGE'S CRITERION

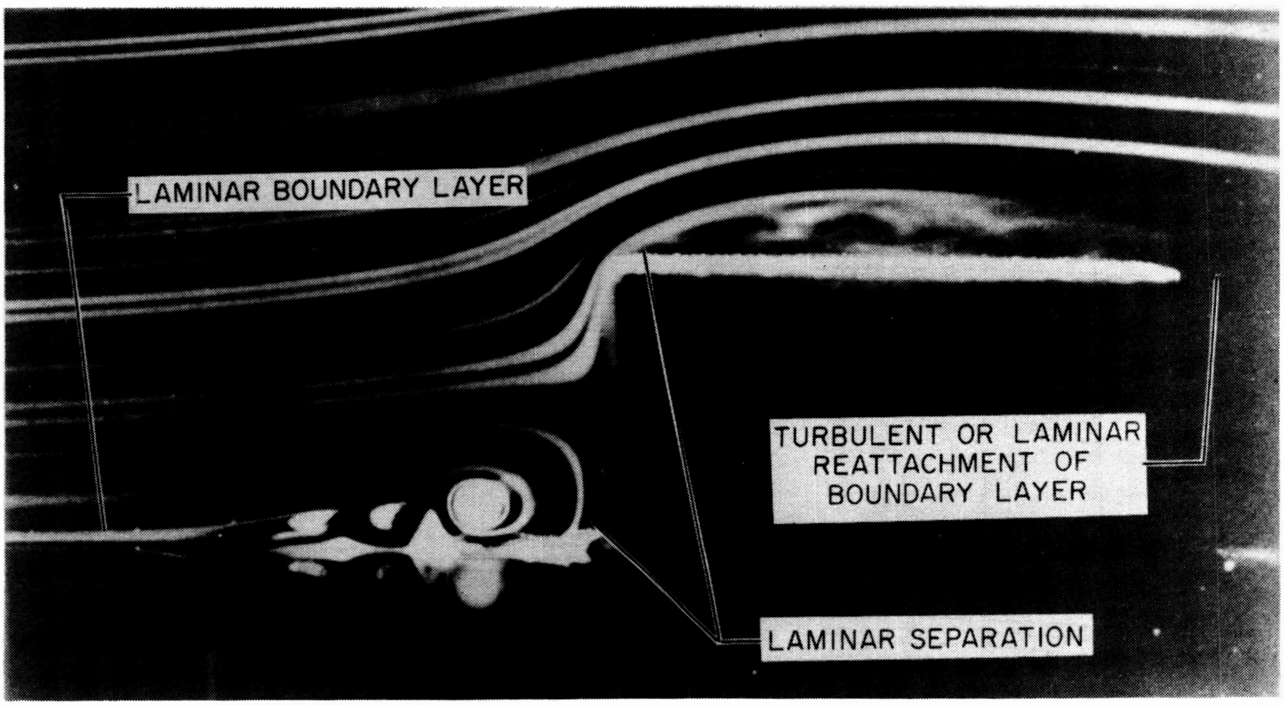
$$\frac{h}{\lambda} = 9 \times 10^{6} \cdot \left(\frac{u_e \cdot s_t}{\nu}\right)^{-3/2} \cdot \left(\frac{s_t}{\lambda}\right)^{1/2}$$

This figure presents examples of allowable waviness for free-stream conditions representative of a high-performance business airplane flying at Mach 0.7 at 41,000 ft. The chart shows allowable waviness using both Fage's (ref. 1) and Carmichael's (ref. 2) equations. Using Carmichael's criterion, the effect of sweep on allowable waviness is seen to be on the order of 10 percent. These calculations show that with a wavelength of 6 in., the allowable wave height is 0.025 in. on a 25° swept wing, with a favorable pressure gradient. Such a manufacturing tolerance for waviness is within the capabilities of modern airframe manufacturing methods. Were this same 6-in. wave in a region of unaccelerated flow, the allowable height would be about 0.010 in. This calculation assumes it is reasonable to relate Carmichael's wave height (h) to Fage's wave height (h') by a factor of 2; that is, an allowable double amplitude wave height may be estimated using 2 x h' in Fage's equation for comparisons with h in Carmichael's equation. The dashed line for Fage's criterion in the figure is presented with the caution that it has never been verified for compressible flows. The figure shows the effect of an unaccelerated flow (Fage's criterion) on reducing the allowable waviness significantly compared to allowable waviness in an accelerated flow (Carmichael's criterion). This result illustrates the dominant effect of pressure gradient on waviness tolerances. The reason for this effect is explained by the dominant effect of pressure gradient on boundary velocity profiles and, hence, on T-S stability.



CHARACTERISTICS OF LAMINAR SEPARATION OVER A STEP

A potentially misleading conclusion from Fage (ref. 1) was that shape did not affect the critical size of the surface imperfection. This conclusion resulted at least in part from the particular shapes tested by Fage. In the case of his ridges, each shape produced a laminar separation region at the front of the ridge and a second laminar separation at the aft facing step on the downstream edge of the ridge. Transition behind Fage's ridges could have been dominated by the inflectional instability growth over these two separated flow regions. For modern airframe surfaces, the simple forward-facing step, aft-facing step, or gap (perpendicular to the free stream) are of more practical interest. This figure shows the characteristics of laminar separation over such a step. Laminar separation bubbles form at the corner and at the top of the step. Depending on the step height Reynolds number, the boundary layer will reattach as turbulent or laminar behind the second separation bubble.

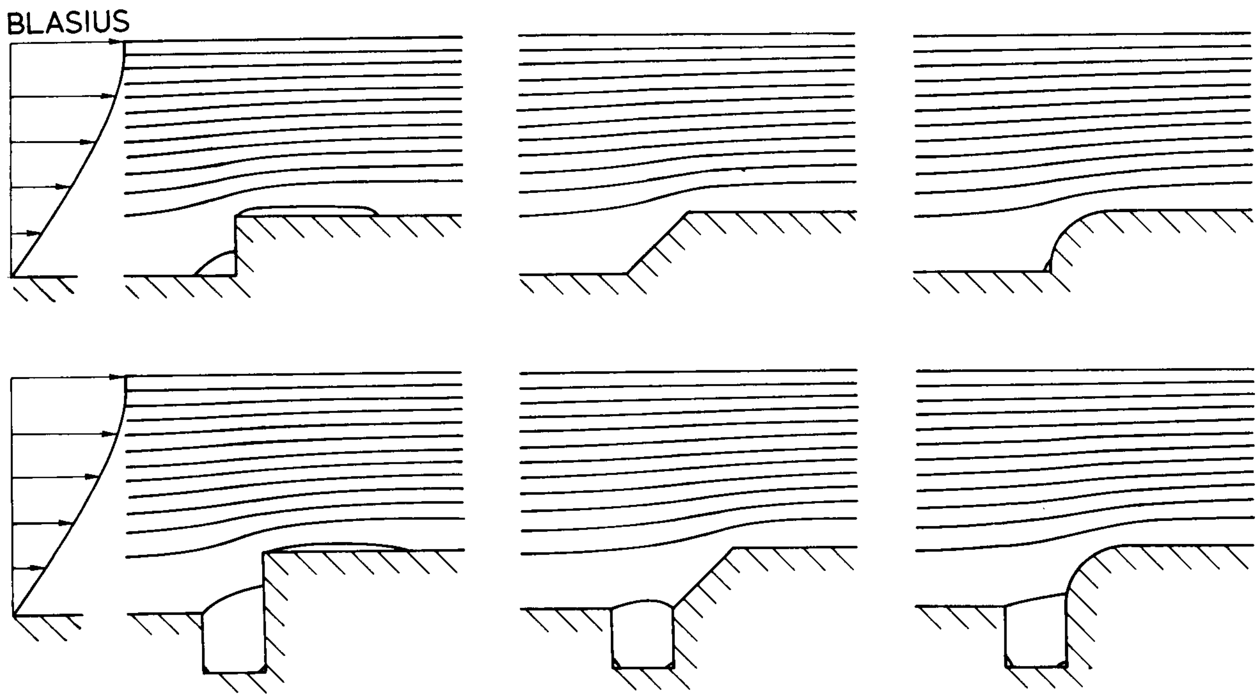


INFLUENCE OF SHAPED STEPS AND GAPS ON LAMINAR SEPARATION

The mechanism by which transition is affected by steps and/or gaps in a laminar surface involves both the viscous Tollmien-Schlichting (T-S) growth and the inflection (Rayleigh's) instability across the free shear layer over regions of laminar separation. Thus, the allowable height of a step or width of a gap will depend in part on the length of the region of laminar separation for a given Reynolds number.

The figure illustrates the significant influence of step and gap shapes on the presence and length of laminar separation regions associated with surface imperfections. The streamlines were calculated by M. D. Gunzburger, R. A. Nicolaides (Carnegie-Mellon, unpublished data), and C. H. Liu (NASA Langley, unpublished data) using a complete finite difference Navier-Stokes solution with a Blasius boundary layer input boundary condition. The streamlines illustrate the reduction in size of the laminar separation regions for the rounded or ramped steps in comparison to the orthogonal sharp steps. These differences in laminar separation explain the differences in flight-measured critical Reynolds numbers for the various shapes.

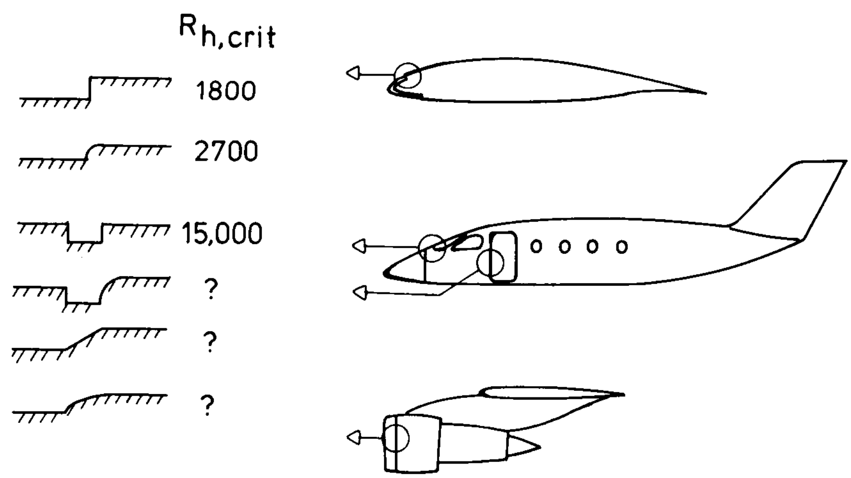
COMPLETE N-S SOLUTION AT $R_h = 600$
(GUNZBURGER, NICOLAIDES AND LIU)



NLF SURFACE IMPERFECTION TOLERANCES

The past work on criteria for step and gap tolerances came from the X-21 experiments (ref. 7). The literature does not state what definition was used to determine critical Reynolds numbers for these surface imperfections. However, according to Dr. Werner Pfenninger (ESCON, Grafton, VA, and C. J. Obara, PRC Kentron, Hampton, VA, private communication) who conducted wind tunnel experiments to develop these criteria, the critical step height Reynolds number was established based on the conditions where the first turbulent spots occurred far downstream from the surface imperfection. Thus, these criteria were developed in a manner consistent with those for the waviness criteria. The critical Reynolds number $R_{h,crit} = (Uh/\nu)$, h is determined based on free-stream airspeed U_∞ and kinematic viscosity and on the height of the step or length of the gap (h). The shapes and critical Reynolds numbers for which tolerances were established in the X-21 experiments are illustrated in the figure. In addition, the figure presents information from recent NASA investigations (ref. 8) on the influence of rounded steps on critical Reynolds numbers. For three of the illustrated surface imperfection shapes (indicated by question marks), no criteria exists.

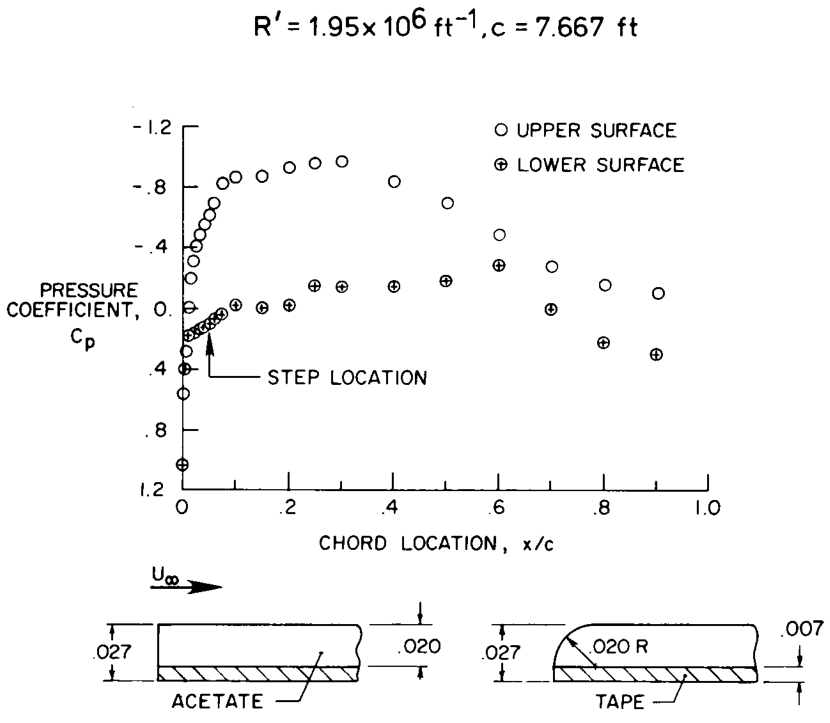
The NASA flight experiments on shaped steps were conducted on a NLF glove installed on a T-34C airplane. These experiments illustrate (in contrast to Fage's experiments) that shape of the surface imperfection influences the allowable height. The reason for the difference in Fage's conclusions and the recent experiments has to do with sensitivity of the laminar boundary layer to inflectional instability growth over a laminar separation region. In the case of the present experiments, the boundary layer was subjected to smaller regions of laminar separation than in Fage's experiments. This occurred because in the NASA experiments, the rounded shape of the step reduced the length of the region of laminar separation over the step, thus reducing the inflectional instability growth. Critical step heights may be larger for steps with shapes which reduce the length of the region of laminar separation.



T-34C NLF GLOVE STEP SHAPE FLIGHT EXPERIMENT

This figure illustrates the NASA flight experiments on shaped steps. Previous flight transition experiments on the T-34C NLF glove are described by Obara and Holmes (ref. 5). The steps were located on the lower surface of the NLF glove at the 5-percent chord location. The pressure distribution over the region of the steps was slightly favorable as shown.

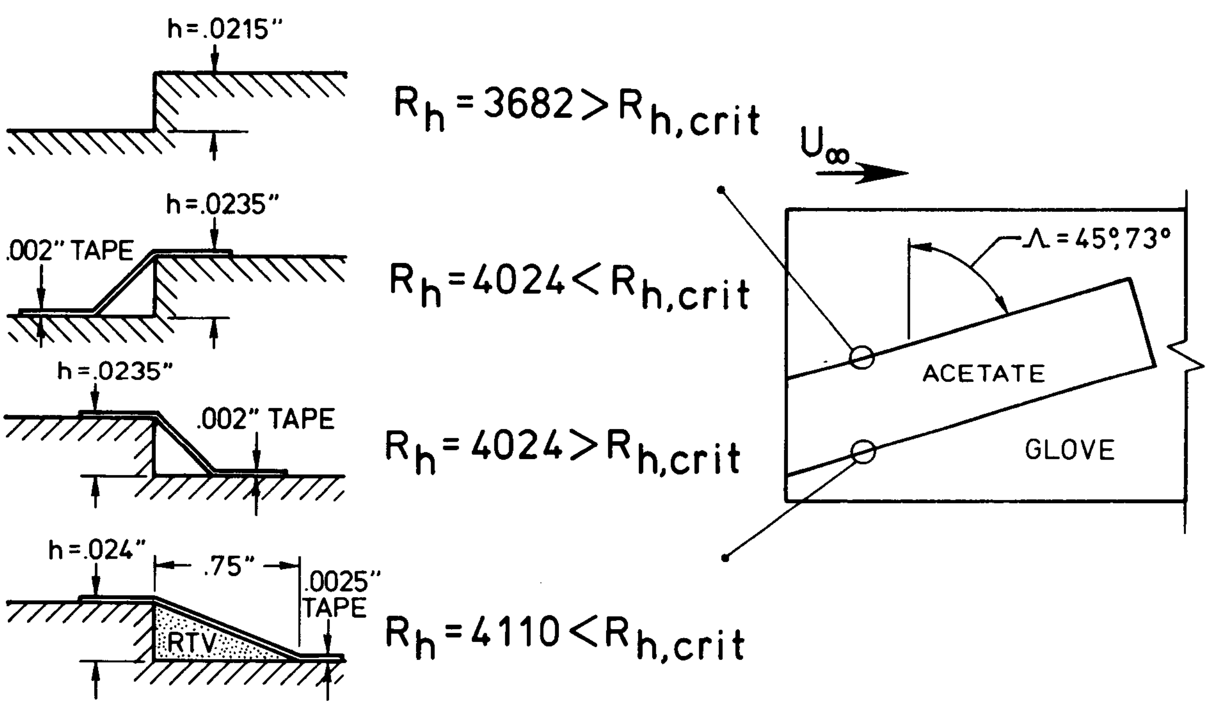
Determination of critical step height Reynolds number for the square and rounded steps was made by flying both step shapes of equal height on one flight using sublimating chemicals to detect transition. A flight condition was chosen to provide a step height Reynolds number which would significantly exceed the critical value of 1800 for a square forward-facing step. The condition flown resulted in an R_h of 2720, thus exceeding 1800 by more than 50 percent. At this condition, transition occurred at the square step as expected. For the round step, on the other hand, transition occurred far downstream from the step (about 2 ft downstream). These data establish a conservative value of $R_{h,crit}$ = 2700 for a rounded forward-facing step, close to the leading edge, on an unswept wing, with a radius approximately equal to the step height.



STEP SHAPES TESTED

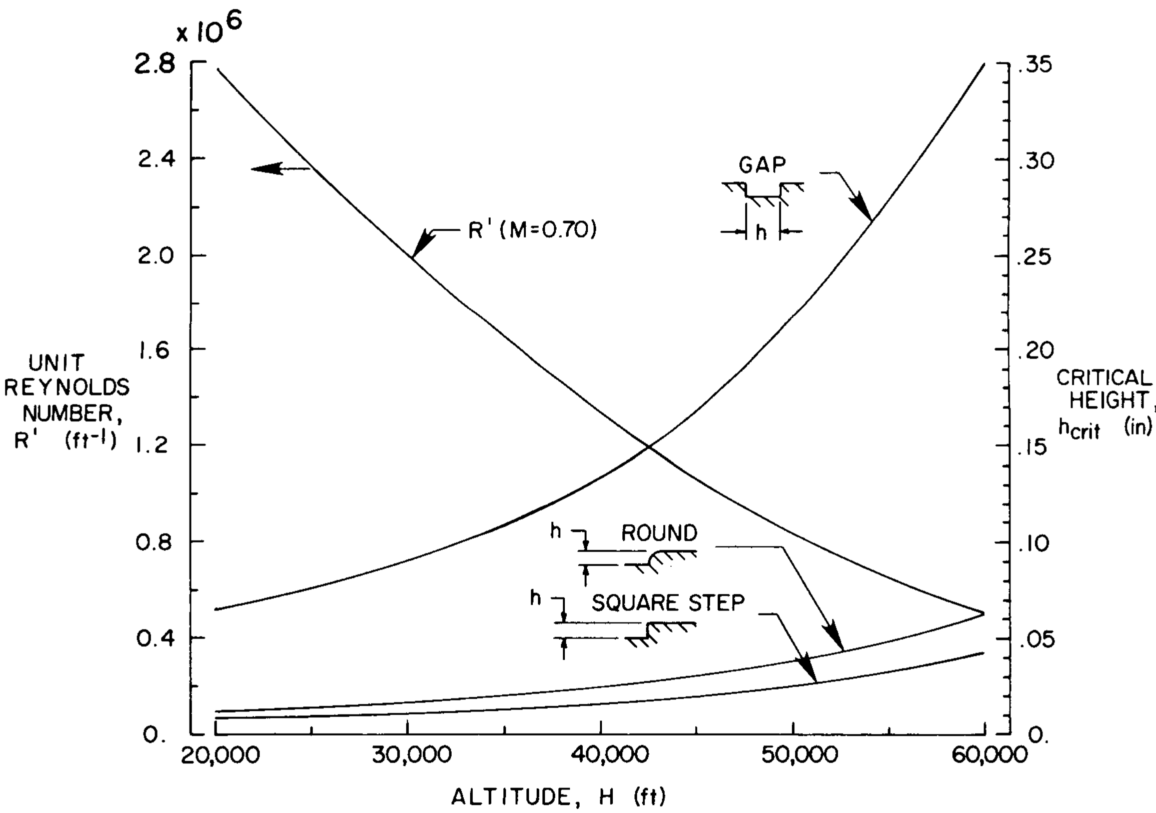
T-34C NLF GLOVE FLIGHT EXPERIMENTS

Additional flight experiments were conducted to simulate both forward and aft-facing steps at several sweep angles. The sweep angle in this context is the angle between the ridge of the step and the free stream. Acetate sheets were attached to the upper surface of the T-34C glove. The purpose of these experiments was to develop a technique for installation of large thin films carrying flush instrumentation (e.g. hot-film transition sensors) on swept airplane wings for NLF flight experiments. These experiments were designed to crudely simulate the flow which a spanwise facing step would see on a swept wing. On an actual swept lifting surface, the presence of crossflow vorticity would very likely produce smaller critical step sizes. The shape of the steps was varied until the step no longer caused boundary layer transition. At a step height of 0.0215 in. and a sweep angle of 73°, both the forward-facing square step and the aft-facing ramp step caused transition. The figure shows the modified step shapes that did not cause boundary layer transition at step sweep angles (Λ) of 73° and 45°. The step height Reynolds numbers for these two steps were R_h = 4024 and 4110, for the forward ramp step and the aft ramp step, respectively. These values of R_h can be used as a guide to size allowable forward and aft facing steps with up to 45° of step sweep in a region of accelerated two-dimensional flow, with steps shaped as shown in the figure.



ALLOWABLE STEP HEIGHTS AND GAP WIDTHS FOR NLF AT M = 0.7

For one set of free-stream conditions representative of a high performance business airplane, this figure illustrates allowable step heights and gap widths for a range of cruise altitudes. The strong beneficial effect of higher altitudes on allowable step heights and gap widths is readily apparent. The increases in tolerances with increased altitude results directly from the decrease in unit Reynolds number. As the unit Reynolds number decreases, the length of the laminar separation regions associated with the steps decreases, reducing the growth of the inflectional instability and increasing the allowable step height.



CONCLUSIONS

A review of past work on roughness and waviness manufacturing tolerances and comparisons with more recent experiments provided the following conclusions.

1. On modern airframe surfaces where large waves typically occur only at major structural joints, the assumption of multiple waves for use of Carmichael's waviness criterion (ref. 2) is too conservative. Based on recent flight experiences with modern airframes, it is recommended that Carmichael's criterion be used with the single wave assumption.

2. In contrast to Fage's (ref. 1) conclusion concerning the unimportance of the shape of a two dimensional step in a laminar boundary layer, it has been demonstrated experimentally that shape has a significant effect on critical Reynolds numbers. For a forward-facing rounded step, close to the leading edge, with a radius approximately equal to the step height, a conservative value for the critical step height Reynold's number of 2700 is indicated. This value is more than a 50-percent increase over the critical step height Reynolds number for a forward-facing square step.

3. For steps with up to 45° to 73° of sweep in two-dimensional flows, step height Reynolds numbers of 4000 and 4100 can be used as a guide to size foward- and aft-facing steps, respectively. These values apply to swept forward-facing ramp steps with rounded corners and to swept aft-facing ramp steps.

- USE SINGLE WAVE CRITERION

- SHAPED STEPS AND GAPS INCREASE 2-D ROUGHNESS TOLERANCES

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