LONG-RANGE LFC TRANSPORT

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A potential design for high-subsonic speed Laminar Flow Control (LFC) transport that can carry large payloads to any place on earth without refuelling is discussed (see Fig. 1). A cruise lift-to-drag ratio (L/D) of 39.4 appears feasible with 70% laminar flow on the wings, tails, nacelles, and struts, and a fully turbulent fuselage. Strut-braced wings with large span and aspect ratio are used to achieve lower induced drag-to-lift ratio. Additional performance gains appear possible with fuselage laminarization. An example of a 180,000 kg take-off gross weight LFC transport airplane with 50,000 kg payload (250 passengers plus cargo) and a cruising speed of $M_{cruise} = 0.83$ is described.

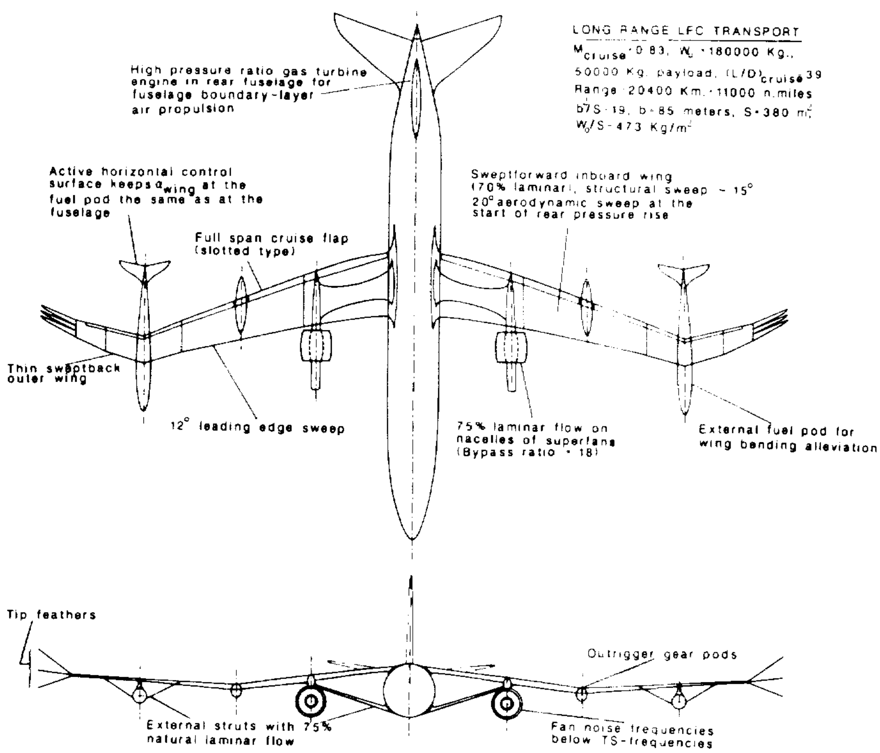
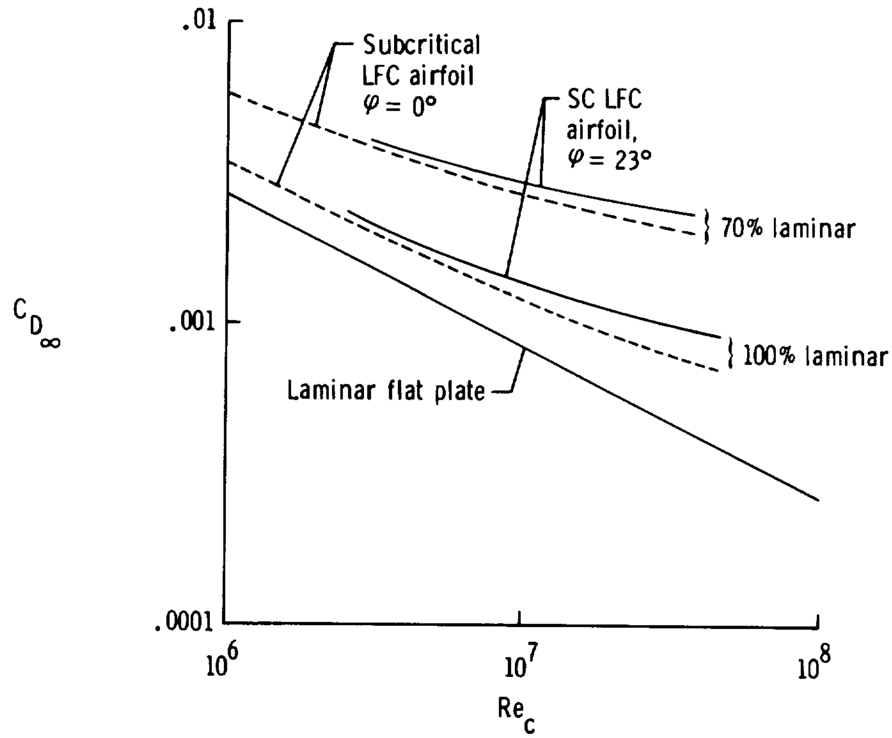


Figure 1

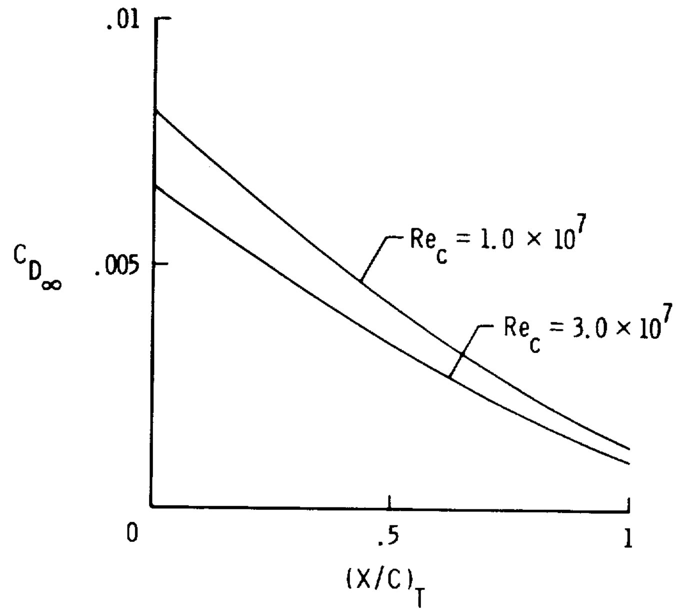
ORIGINAL PAGE IS OF POOR QUALITY

The variation of wing profile drag, C_{D_∞}, with chord Reynolds number, Re_c, is shown in Fig. 2 for various degrees of suction laminarization, as indicated by the transition location $(x/c)_T$. The wing profile drag coefficient at $Re_c = 30 \times 10^6$ is 0.0067 for a fully turbulent flow, 0.0024 with 70% laminarization, and 0.0010 with 100% laminar flow. These numbers include suction drag penalty. The additional drag due to sweep, especially at high Reynolds numbers, is primarily the result of higher suction rates required in the front and rear part of the wing to control sweep-induced boundary-layer crossflow instability.



(A)

Figure 2



(B)

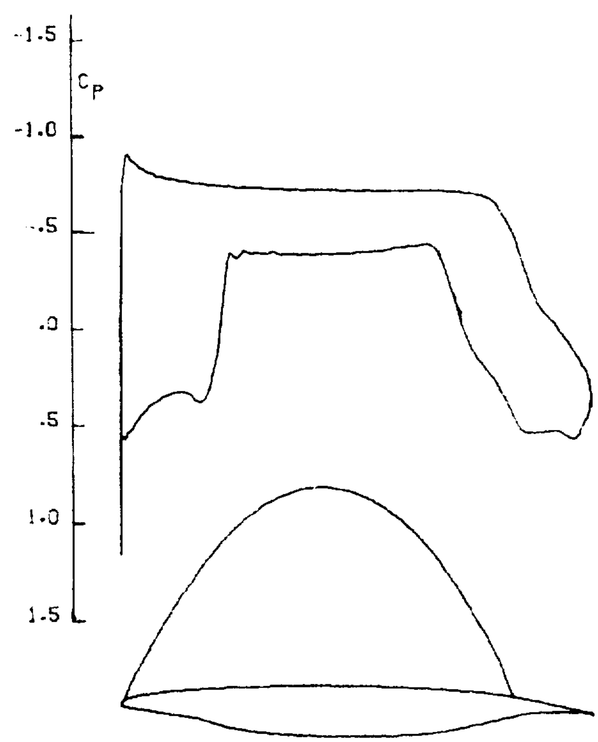
Figure 2

LAMINARIZATION OF SWEPT LFC WINGS

Boundary layer crossflow instability, as well as spanwise turbulent contamination along the wing attachment line, critically affect the design of strongly swept LFC wings at high Re_c. Swept LFC wings are inherently more sensitive to 3-D leading-edge roughness: in addition to higher local flow velocities in the leading-edge region of the swept wing, the streamwise disturbance vorticity induced by 3-D roughness is adversely superimposed on the sweep-induced streamwise vorticities to cause early transition. Indeed, leading-edge flyspecks often caused extensive loss of laminar flow in the X-21 LFC wing with its 33^0 swept leading edge at $M_\infty = 0.75$ and 12,000 meters altitude (Ref. 1) while full chord laminar flow was often observed on the F94 LFC wing glove with its 10^0 swept leading edge at $M_\infty = 0.65$ and altitudes above 6,000 - 7,000 meters (Ref. 2), despite the presence of leading-edge flyspecks. Similarly, atmospheric ice crystals apparently did not influence transition on the F94 LFC glove, while they often caused extensive loss of laminar flow on the X-21 wing. Therefore, to alleviate these sweep-induced problems, wing sweep should be reduced by raising the 2-D airfoil design Mach number $M_{\infty_{Design}}$, while maintaining satisfactory off-design characteristics. To simplify the wing design and minimize the LFC wing weight penalty, natural laminar flow should be maintained in the area of wing bending structure.

SC LFC AIRFOIL DESIGN CONSIDERATIONS: DESIGN TOWARD HIGH MACH NUMBERS

The design Mach number, $M_{\infty_{Design}}$, of supercritical (SC) LFC airfoils is increased by thinning the airfoil either over the entire chord or by undercutting the structurally less-critical front and rear lower surfaces, resulting in relatively sharp-nosed SC airfoils (see examples of derivatives of SC LFC airfoil X63T18S: Fig. 3a and 3(b)). Lift is carried primarily in the front and rear sections of the wing, while the lower-surface center bulge, operating close to sonic condition, contributes primarily to airfoil thickness. The design Mach number is further increased by having an extensive low supersonic flat rooftop pressure distribution (M = 1.08 - 1.10) on the upper surface, preceded far upstream by a supersonic pressure minimum ($M \approx 1.20$ at s/c = 0.015 to 0.02), and followed by a steep subsonic rear pressure rise region where low drag boundary-layer suction is applied for full-chord laminarization. Alternately, a satisfactory steep pressure rise appears possible without suction on a slotted (2- element) airfoil by optimally subdividing the rear pressure rise on the wing and the slotted trailing edge cruise flap. Whitcomb's first SC airfoil had, indeed, such a slotted trailing edge flap, except that the flap chord had been larger (Ref. 3). The flow exit Mach number at the flap was then about sonic, resulting in an excessively sensitive flow in the flap gap and a non-optimum subdivision of the rear pressure rise over wing and flap.

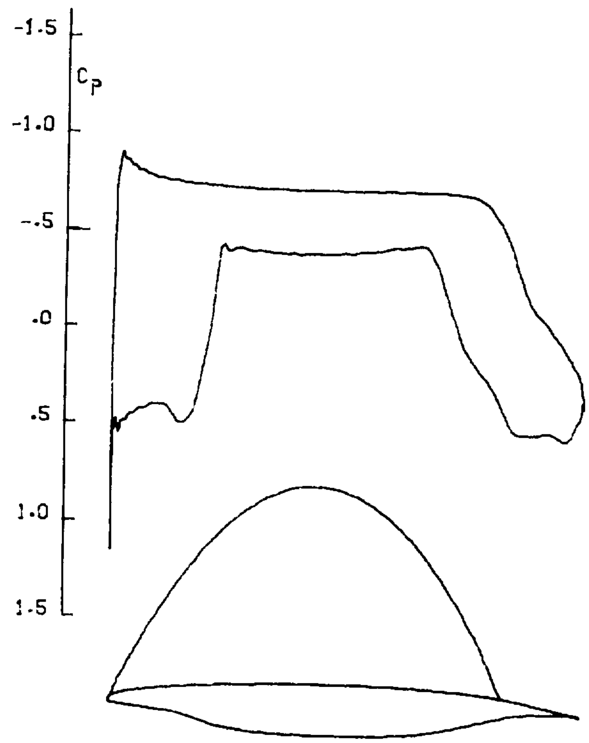


(A)

Figure 3

SC LFC AIRFOIL DESIGN CONSIDERATIONS:

DESIGN TOWARD HIGH MACH NUMBERS (CONCLUDED)

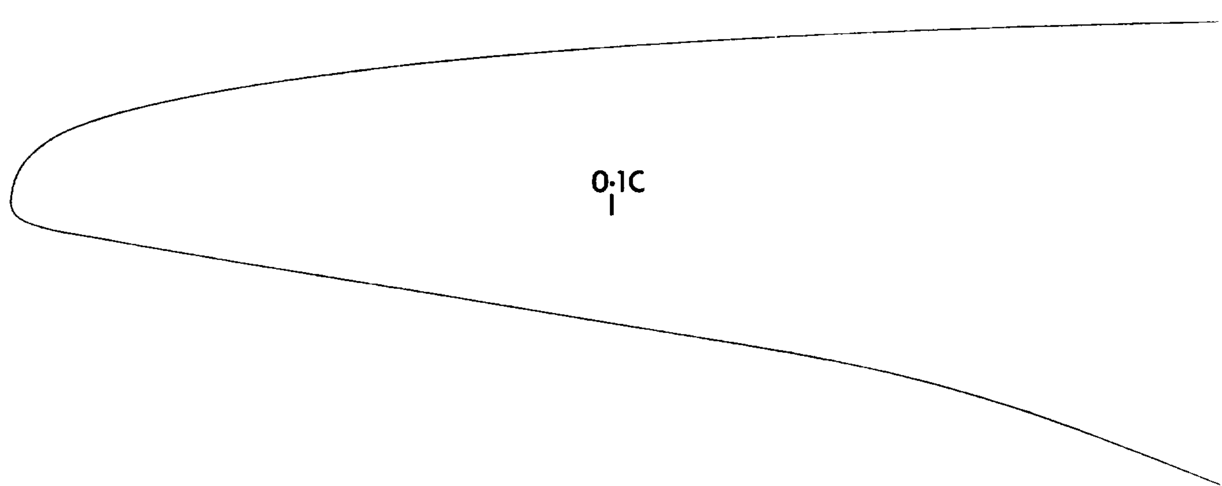


(B)

Figure 3

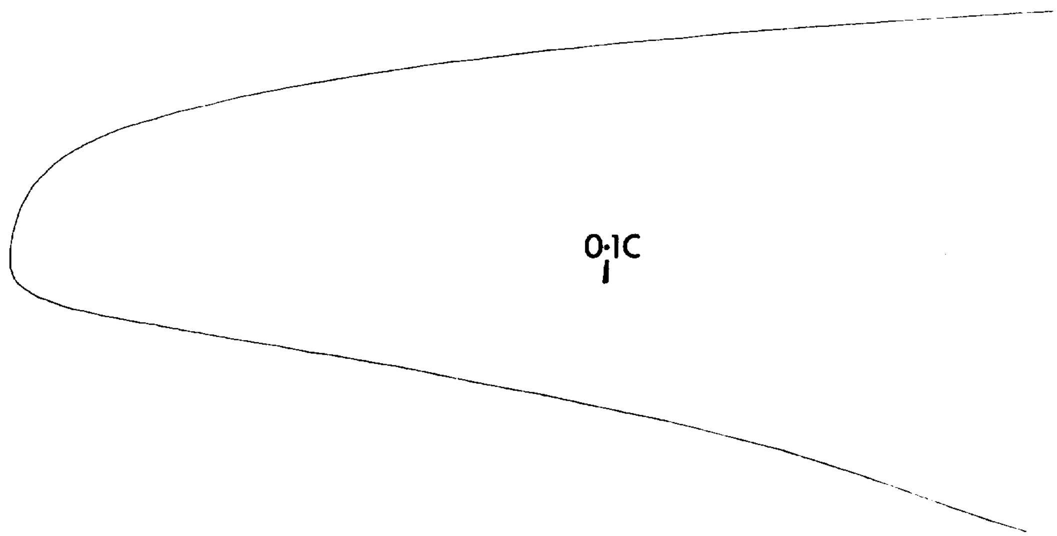
DESIGN OF LEADING-EDGE REGION

The superiority of supercritical airfoils (that have an extensive upper surface flat rooftop pressure distribution at low supersonic speeds, preceded by a front supersonic minimum) is explained as follows: The relatively strong expansion waves, radiating from the high-velocity region of the supersonic pressure minimum, are reflected from the sonic line as strong compression waves to the surface. This reduces the supersonic flow velocities further downstream in the flat rooftop area. As a result, the height of the supersonic bubble decreases. Alternately, the design Mach number increases for a given supersonic bubble height. The same result follows from elementary considerations: Since the supersonic flow of the front upper surface decays relatively fast towards the sonic line as a result of the small radius of curvature, substantially higher supersonic Mach numbers and correspondingly increased lift appear possible in the leading-edge region of the upper surface without significantly affecting the height of the supersonic bubble. This results in an increase in design lift coefficient, $C_{L_{Design}}$ or design Mach number (at a given $C_{L_{Design}}$). As the radius of curvature of the upper surface continuously increases in the downstream direction, the supersonic flow in the pressure-rise area downstream of the front pressure minimum must progressively decelerate and asymptotically join the extensive flat rooftop pressure distribution. The upper-surface nose contour of the SC LFC X66 airfoil (Fig. 4(a)) is characteristic to SC airfoils with a far upstream supersonic pressure minimum; it decisively influences the entire flow of the supersonic zone of the upper surface. Figure 4(b) shows the leading-edge contour of a similar SC LFC airfoil but with a substantially blunter nose and a similar supersonic pressure minimum on the front upper surface, i.e., the same considerations apply to SC airfoils with blunter leading edges.



(A)

Figure 4



(B)

Figure 4

SHOCK PREVENTION ON SC AIRFOILS AT OFF-DESIGN MACH NUMBERS

To delay or prevent off-design shock formation on SC LFC airfoils with a pressure minimum on the front upper surface at $M_\infty < M_{\infty_{Design}}$, tangency of the upper surface hodograph streamline with the hodograph characteristics (equivalent to limit line formation) must be delayed or avoided. This is possible by flattening the upper surface hodograph streamline, such that the flow on the upper surface decelerates sufficiently slowly and continuously in the hodograph plane over a particularly wide angular range of upper surface flow inclination angles form the location of the pressure minimum to the rooftop zone (see upper surface hodograph streamline of airfoil X66, Fig. 5). This implies that the supersonic pressure minimum should be located as far upstream as practical in a strongly inclined upper surface area. To further ensure a continuous upper surface flow deceleration in the hodograph plane for the prevention of shock formation in the entire $M_\infty - range$ below $M_{\infty_{Design}}$, the chordwise pressure gradients downstream of the front pressure minimum at design must be tailored to the local upper surface curvature, i.e., these pressure gradients must progressively decrease in downstream direction and asymptotically approach the flat rooftop value. Indeed, a Korn-Garabedian analysis for the similar X63T18S airfoil (Ref. 4) has not shown any double shock formation at $M_\infty < M_{\infty_{Design}}$ at constant α_{wing}.

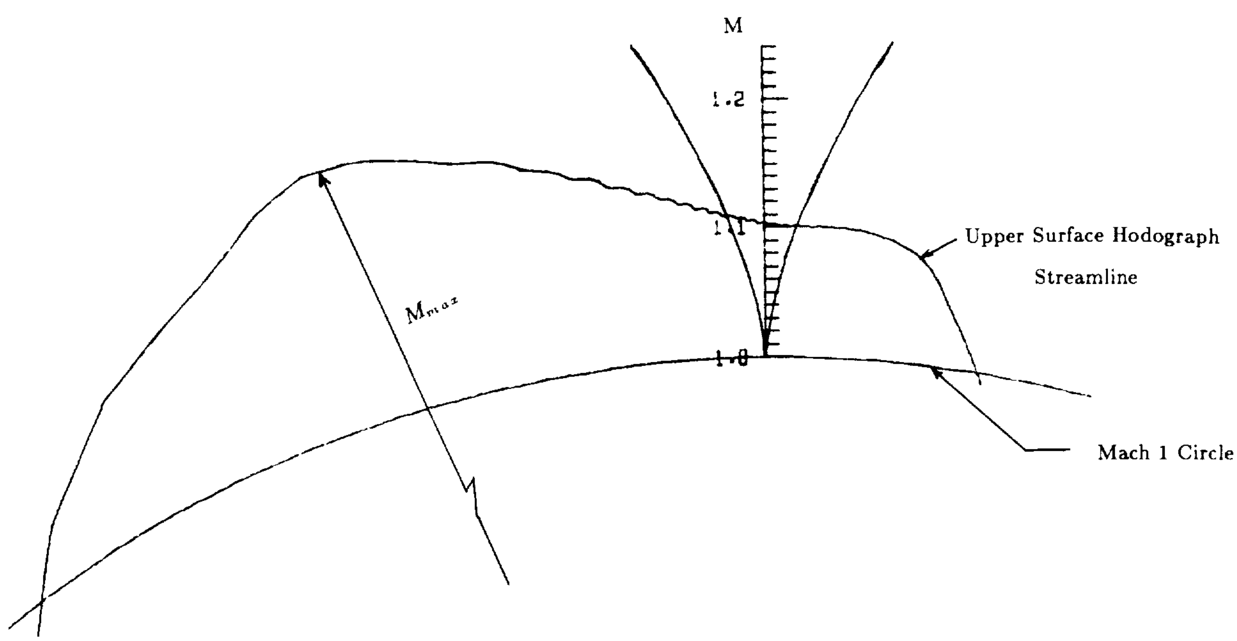


Figure 5

SHOCK-FREE DESIGN OF SC AIRFOILS

A Korn-Garabedian analysis (Ref. 4) of SC LFC airfoils with and without a particularly sharp front supersonic pressure minimum on the upper surface show a superior upper shock-free low-drag C_L – *limit* for the peaked airfoil compared to the airfoil with a flat supersonic rooftop pressure distribution and no front pressure minimum (Fig. 6). Since the supersonic flow on SC airfoils responds essentially to angular flow changes, the lift coefficient, C_L, of SC LFC airfoils should be varied by changing the airfoil camber at a constant angle-of-attack, α_{wing}, by deflecting a small-chord full-span trailing-edge cruise flap. A slotted flap for a SC LFC airfoil without suction in the steep rear pressure-rise area of the upper surface is preferred.

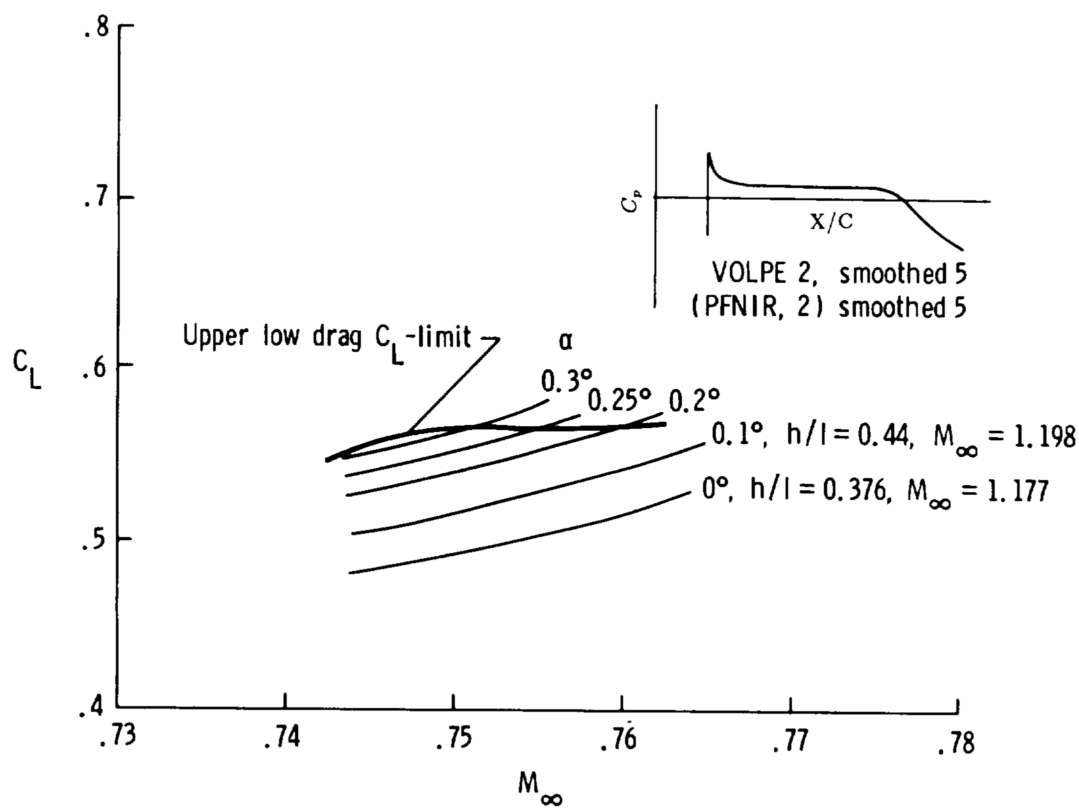
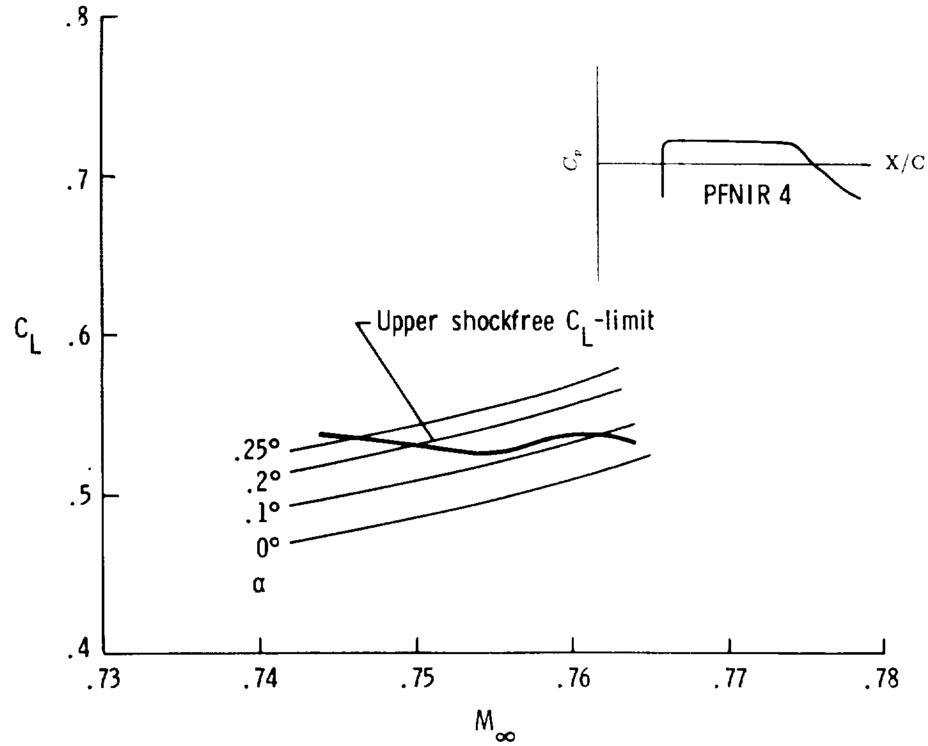


Figure 6



.8
.7
.6
.5
.4
C_L
C_p
X/C
PFNIR 4
Upper shockfree C_L-limit
.25°
.2°
.1°
0°
α
.73
.74
.75
.76
.77
.78
M_∞

(B)

Figure 6

LAMINARIZATION OF SWEPT WINGS: BOUNDARY-LAYER CROSSFLOW INSTABILITY

On SC LFC airfoils with a front supersonic pressure minimum on the upper surface, the boundary-layer crossflow, generated in the acceleration zone can be largely cancelled by a boundary-layer crossflow of opposite sign, generated in the pressure-rise zone downstream of the front pressure minimum (Fig. 7). If the boundary-layer crossflow can be minimized in the front acceleration zone of the upper surface by thinning the leading edge (undercutting the front lower surface), accelerating the flow rapidly to the supersonic pressure minimum, and/or applying local suction preferably in the area where the boundary-layer crossflow is about neutrally stable, then the crossflow instability is practically absent in the flat rooftop area of the upper surface and streamwise vortex - interaction with amplified Tollmien-Schlichting (TS) waves is practically eliminated in this area. For relatively sharp-nosed SC LFC airfoils of the X66- type, generally no suction is needed for the control of boundary- layer crossflow instability in the front acceleration zone up to $Re_c = 30$ million with 23^0 sweep.

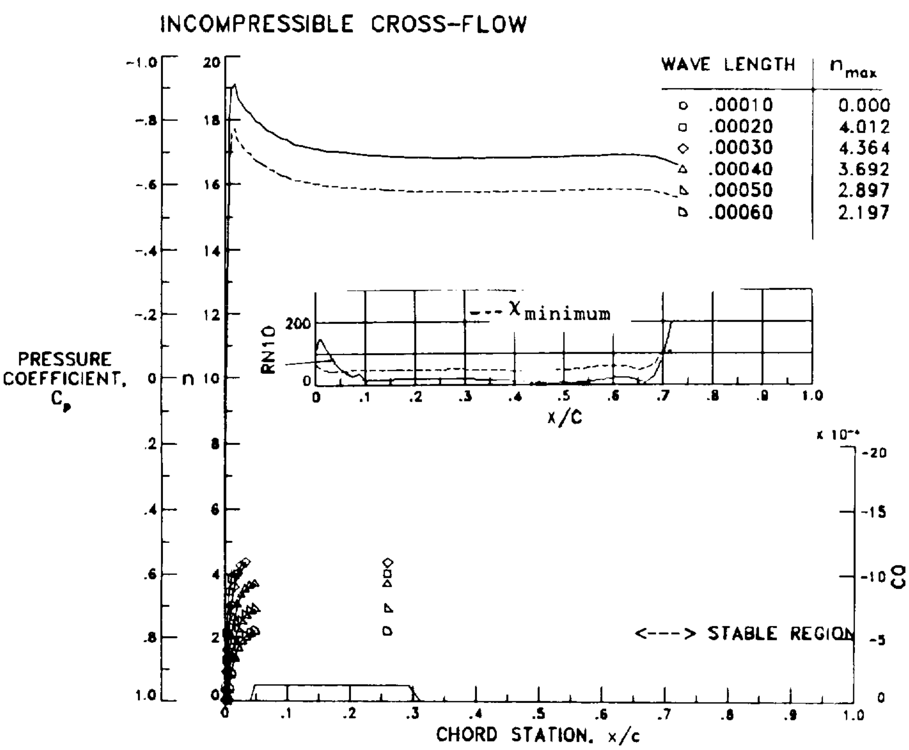


Figure 7

EFFECT OF TAPER

On tapered swept-back or swept-forward SC wings, the isobar sweep decreases or increases, respectively, from the wing leading edge to the trailing edge to superimpose an additional streamwise flow deceleration or acceleration (Fig. 8). The TS-instability in the flat rooftop region of the upper surface of X66-type SC LFC wings is then influenced in a favorable manner on tapered swept-forward wings and vice-versa on swept-back LFC wings, optimized for a high cruise Mach number, will have a slightly adverse upper-surface rooftop pressure distribution, preceded by a more pronounced supersonic pressure minimum. Additional spanwise suction strips may then be required in the rooftop region for adequate boundary-layer stabilization against amplified TS-waves. The avoidance of such slightly adverse upper-surface rooftop pressure distributions on tapered swept- back wings entails a penalty on the cruise Mach number.

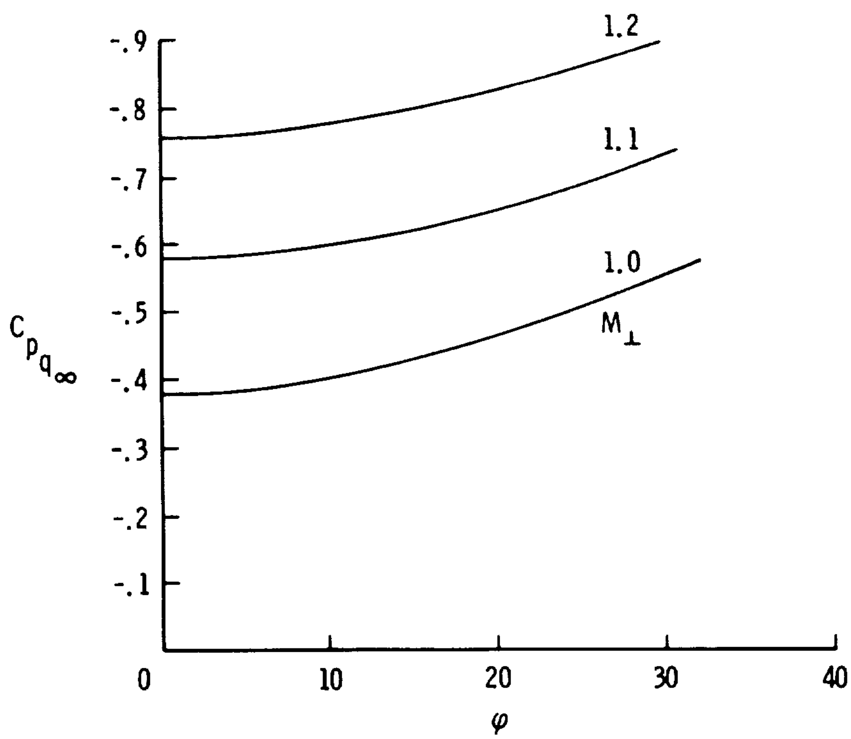


Figure 8

WING CHORD-REYNOLDS NUMBER CONSIDERATIONS

In addition to performance considerations, the design of a large LFC airplane is strongly influenced by all the many factors that affect suction laminarization. Therefore, since boundary-layer stability problems are alleviated at lower length Reynolds numbers and since the surface tolerances and roughness are inversely proportional to the unit Reynolds numbers, U_∞/ν, larger LFC airplanes should be designed such that performance optimization is compatible with the desire to alleviate the laminarization problems involved.

Since $Re_c = U_\infty C/\nu = 2\sqrt{w}\frac{\sqrt{(w/s)/(b^2/s)}}{a\mu C_L M}$ and $U = \frac{2(w/s)}{a\mu C_L M}$, it follows that Re_c is decreased by lowering the wing loading (W/s), raising the wing aspect ratio (b^2/s) and working with reasonably high cruise lift coefficients C_L, being easier possible with higher wing aspect ratios. Here, a is the velocity of sound, μ is the absolute viscosity of air, W is the airplane weight, s is the wing reference area, U_∞ is the freestream velocity, C is the mean-aerodynamic chord of the wing, ν is the kinematic viscosity of air, b is the wing span, and M is the Mach number. Thus the desire to reduce the induced drag-to-lift ratio $D_{ind.}/L = W/\pi q b^2$ (q is the dynamic pressure) for superior performance is well compatible with the desire to reduce Re_c.

INFLUENCE OF BOUNDARY-LAYER DISTURBANCES

For the design of a high subsonic speed LFC transport airplane the question arises concerning the initial disturbances introduced into the boundary layer. This is particularly important for LFC airplanes with extensive natural laminar flow in the flat rooftop area of the upper surface in the absence of suction (distributed suction along the entire chord highly stabilizes the boundary layer to allow correspondingly increased initial disturbances). With the atmospheric turbulence microscale generally much too weak to affect transition, the initial boundary-layer disturbances are generated primarily by the airplane and its propulsion system and possibly by suction-induced disturbances. As a result, it is particularly important to minimize the influence of propulsion noise by raising the airplane lift-to-drag ratio and avoiding propulsion noise in the frequency range of strongly amplified TS-disturbances. The present high bypass ratio fan engines (BPR $\approx$ 5 to 6) may not appear attractive for large LFC airplanes since their fan-tones and shock noise contain frequencies in the range of the strongly amplified TS-disturbances; the proposed super fans (BPR = 15 to 20) are much better in this respect since they rotate at relatively low subsonic tip speeds and allow substantial axial decaying of both the fan rotor pressure field and the many fan rotor-stator interference acoustic modes in the fan duct. Most of the fan tone noise is therefore generated at relatively low frequencies which are below the frequency range of strongly amplified TS-waves.

Turbulent fuselage boundary-layer noise may also contribute to initial boundary-layer disturbances. Turbulent fuselage boundary-layer noise of the dipole type generated by structural discontinuities such as fuselage bulkheads, etc., is more efficient sound radiator than quadruple-type boundary-layer noise (Ref. 5) and should, therefore, be avoided by designing the fuselage essentially as a continuous sandwich structure. The remaining quadruple-type fuselage boundary-layer noise is a rather inefficient sound radiator with relatively low frequencies.

PROS AND CONS OF SWEPT-FORWARD SC LFC WINGS

A swept-forward wing had been chosen in the area inboard of the external fuel pods for the large LFC airplanes discussed in this paper for several reasons:

1) As mentioned previously, the increasing sweep of the wing isobar from the wing leading to the trailing edge gives a more favorable chordwise pressure distribution for natural laminar flow in the region of the main wing-box structure, as compared to a swept-back wing.

2) The aerodynamic isobar sweep of a tapered swept-forward wing at the start of the rear pressure rise is larger than the wing structural sweep (especially with a steep rear pressure rise with suction or a slotted cruise flap,) and raises the aerodynamic span for a given structural span, and vice versa for a swept-back wing.

3) With the substantially reduced leading-edge sweep, both boundary-layer crossflow and leading-edge contamination problems (caused by flyspecks and atmospheric ice crystals) are greatly alleviated. As was found on the F94 LFC wing glove with its 10^0 swept leading edge (Ref. 2), laminar flow may even be possible in the presence of flyspecks at altitudes considerably below the airplane cruise altitude.

Disadvantages of swept-forward wings are wing divergence, excessive negative pressure peaks in the leading-edge region at the wing root, and spanwise boundary-layer crossflow at high C_L's near the wing root. For composite wings, wing divergence can be alleviated by properly aligning the spanwise wing bending fibers, sweeping back the wing outboard of the fuel pod, and actively deflecting the cruise flap and the active control surface of the fuel pod. The adverse aerodynamic behavior of the swept-forward wing in the wing root region can be alleviated by a suitable area-ruling of the fuselage and reducing the wing sweep near the root; this may be possible by thinning the inboard wing. (With the rapidly decreasing wing bending moments in the strut-braced inboard wing region, this is structurally possible). At the same time C_{D_∞} of this thinner inboard wing region is reduced somewhat to partially compensate for the strut parasite drag. With the forward sweep of the inboard wing thus reduced, spanwise boundary-layer crossflow near the wing root at higher C_L's is alleviated.

The rapid reduction of the inboard wing thickness also decreases the local Mach number of the wing upper surface in the region of the wing-strut intersection (the local flow is essentially 3-dimensional) and this allows a thicker wing in this structurally critical area where the moments are largest.

The outboard wing is particularly thin to minimize local wing sweep and improve high-speed buffeting near the wing tip where wing deflections are particularly large.

Variable camber leading edges were included in the design of this large LFC airplane to improve the low-speed characteristics of the X66 SC LFC airfoil with its relatively sharp leading edge. For take-off and especially landing, a slotted trailing-edge high-lift flap is assumed. Further design calculations have been conducted with similar SC LFC airfoils having a blunter leading edge, to further improve the high-lift characteristics at lower M_∞'s, this results in a penalty of about 0.004 to 0.005 in cruise Mach number.

APPROACHES TO INCREASE WING SPAN

Excessive structural weights associated with large span wings can be avoided by designing the wings to be supported by a wide-chord low-drag laminar strut. This reduces the wing bending and torsional moments and deformations. The reduced induced drag of the large span strut-braced wing by far compensates for the strut parasite drag.

A further increase in wing span and a reduction in induced drag can be achieved with an external, low-drag laminar-flow fuel nacelle located on the outer part of the wing and braced with laminar struts. These fuel nacelles reduce wing bending moments. Wing torsional deformations can be actively controlled by horizontal control surfaces at the rear of the fuel nacelle. The wing angle-of-attack at these nacelle locations should be kept at the same value as that at the wing root with the aid of suitable sensors. Excessive negative bending moments induced by these fuel nacelles during taxiing may be avoided by partially filling them on the ground and filling them up completely by redistributing fuel after take-off.

The wing span and aspect ratio can also be further increased with the use of advanced structural materials and actively lowering wing gust-, maneuver-, and dynamic loads as well as aeroelastic wing deformations; a full span cruise flap will permit this. The aeroelastic wing angle-of-attack changes induced by flap deflection can be largely compensated by deflecting the active horizontal control surfaces of the external fuel pods.

TOLLMIEN-SCHLICHTING (TS) INSTABILITY

With boundary-layer crossflow practically absent in the region of the upper-surface rooftop pressure distribution, the boundary layer must be stabilized essentially against amplified TS-waves by means of weak distributed suction applied form 5%- chord to 30% chord (non-dimensional suction massflow rates $C_q = 1.2 \times 10^{-4}$ *at* $Re_c = 30 \times 10^6$, 23^0 sweep). Figure 9 presents the corresponding TS-growth rates using the COSAL computer program (Ref. 6). The stabilizing influence of compressibility on the growth of amplified TS-waves is crucial for high subsonic speed LFC airplanes. For a 23^0 swept SC LFC wing of the X66-type, the laminar-flow length Reynolds number at $M_\infty = 0.83$ is 2.5 times larger than in incompressible flow for the same TS-disturbance growth factor. Very substantial breaks in suction distribution are then possible in the flat rooftop region of the upper surface at cruise conditions.

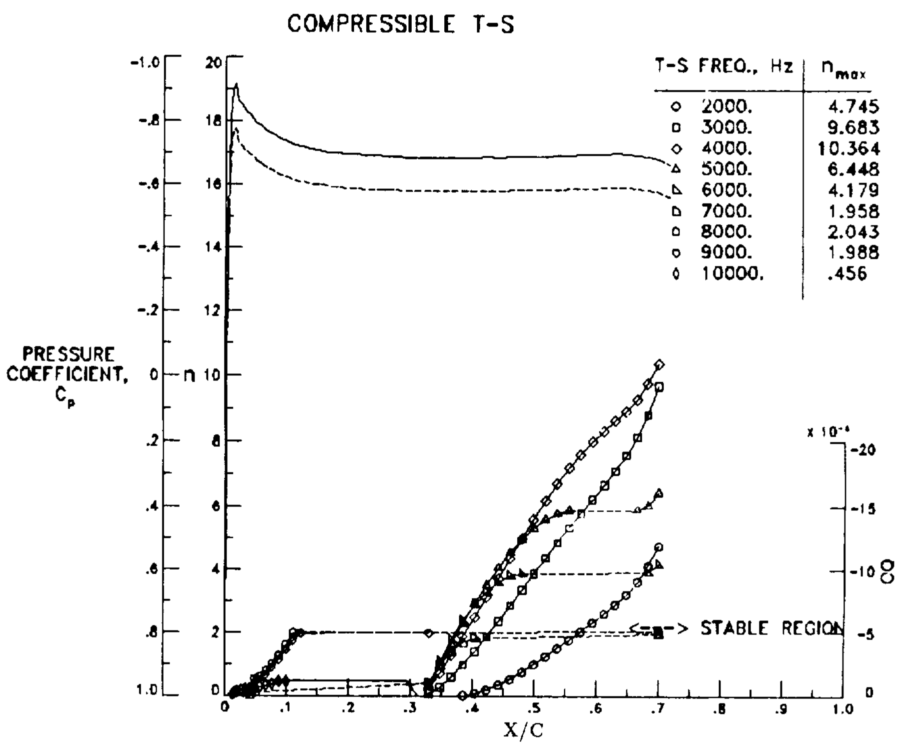


Figure 9

FUSELAGE LAMINARIZATION

Since the turbulent fuselage drag represents a large percentage drag contribution to an otherwise laminar LFC airplane, the question arises concerning the possible suction laminarization of the fuselage at high length Reynolds numbers, Re_L. Drag results obtained in the Ames 12-foot tunnel (Ref. 7) for the Northrop Reichardt LFC body of revolution (8 : 1 fineness ratio, 12-foot long) with minimum drag coefficient $C_{D_{min}} = 0.00026$ (based on body wetted area and including suction drag) are shown in Fig. 10. Drag reductions for this body were percentage-wise larger than for all-laminar flow wings tested at that time. The question then remains concerning the possible laminar flow Re_L – *values* of an LFC fuselage in fight at high subsonic speeds. In view of the practically non-existent atmospheric turbulence microscale responsible for transition ($Re_{L_{Laminar}}$) obtained for the Reichardt LFC body may be possibly doubled in low-speed flight to 120×10^6. The stabilizing influence of compressibility on the growth of amplified TS-waves may again increase this to perhaps 200-240 million in flight at high subsonic cruising speeds.

For the present, relatively conservative example, a fully turbulent fuselage was assumed, accepting a 7% and 10% equivalent fuselage drag reduction by riblets (Ref. 8) and fuselage boundary-layer air propulsion (Ref. 9) in the rear part of the fuselage, respectively.

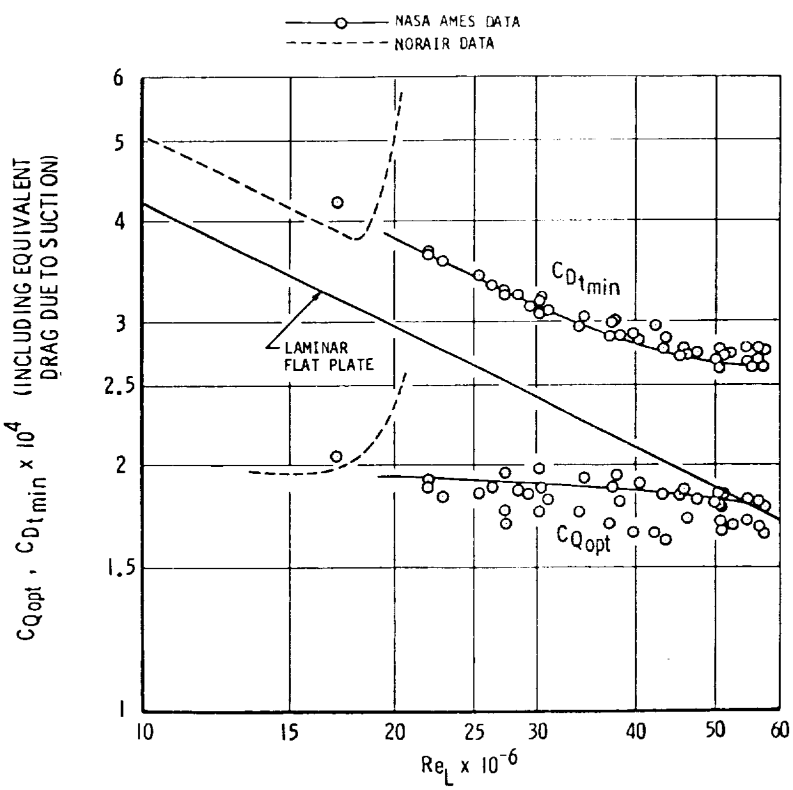


Figure 10

PROPULSION CONSIDERATIONS

Superfan-type bypass ratio 18 wing-mounted propulsion engines of about 18000 Kg take-off thrust were selected in the present study with an additional boundary-layer propulsion engine in the rear fuselage (thereby reducing the equivalent turbulent fuselage drag by about 10%) (Ref. 9). It is not clear whether to favor aft-mounted counter-rotating super fans with a direct drive or a geared front super fan. The aft fan may, in principle, allow a 3-spool gas generator with a correspondingly higher engine pressure ratio and thermodynamic efficiency. With the superfan generating essentially lower frequency noise below the range of amplified TS-waves, wing-mounted engines appear feasible for wing laminarization. Furthermore, extensive laminar flow by means of suitable geometric shaping and suction appears feasible on the external surfaces of the fan nacelles and even in the fan inlet up to the fan rotor. The parasite drag of these fan nacelles would then decrease drastically to narrow the difference in propulsive and overall efficiency between a superfan and a high-speed propeller. In addition, the superfan nacelle, located upstream of the wing, reduces the flow velocity in the area of the wing (area-rule considerations) to enable a correspondingly thicker wing in the area of the wing-strut juncture, thereby further reducing the performance gap between the superfan and high-speed turboprop.

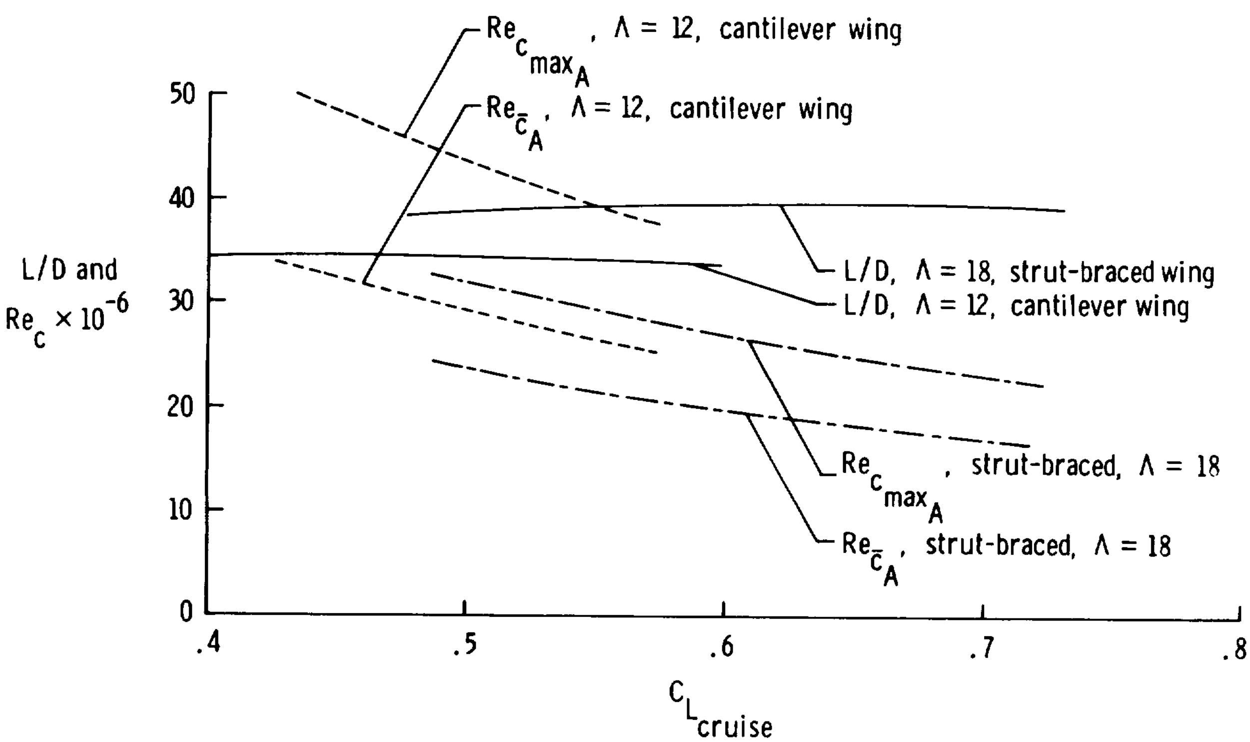
SUCTION DRIVE

The airplane of Fig. 1 was designed with limited suction in the front part of the wing, tail surfaces, engine nacelles and struts. No suction was considered in the rear pressure rise areas on these surfaces. For these conditions, the suction massflow rates and suction power are sufficiently small such that the suction compressors can be driven mechanically from the main propulsion engines via a direct drive. In this manner the cruise thrust of the suction compressor is contributed at a particularly high propulsive- and overall efficiency. (Thermodynamically, when the LFC suction compressor system is part of the cruise propulsive system, the suction compressors should be driven by a thermodynamically highly efficient engine, i.e. it is basically wrong to drive the suction compressors with thermodynamically inefficient separate engines.) At lower flight speeds, the suction compressors may be geared down to reduce their power input.

AIRPLANE PERFORMANCE

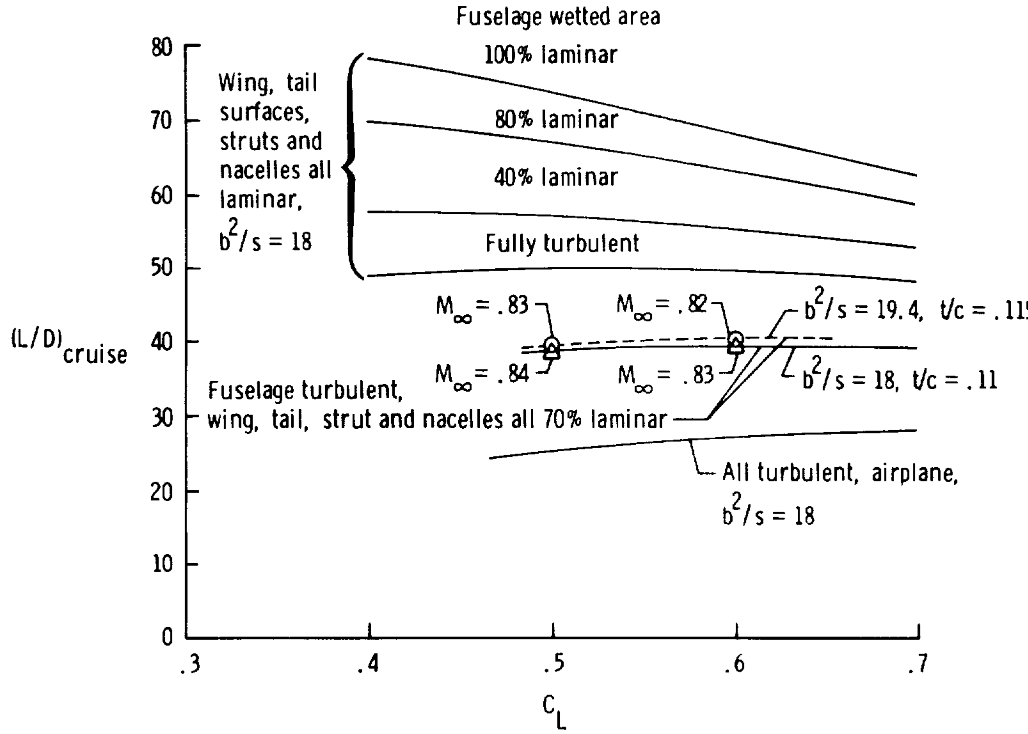
In this study, 70% laminar flow was assumed on wing and tail surfaces, struts and fan nacelles of the airplane shown in fig. 11. Fully turbulent flow was assumed on the fuselage (6 meters diameter, 60 meters length). Split wing tips were chosen to reduce the induced drag by about 8% ($\kappa = 0.94$ was assumed as induced drag factor). Figure 11 shows L/D versus C_L of this airplane, with L/D = 39.4 at $C_L \approx 0.6$. In practice, C_L might be reduced somewhat to raise the cruise Mach number at a slight penalty in L/D.

For comparison, L/D of the same airplane is shown both with fully turbulent flow (L/D $\approx$ 27.5) as well as with fully laminar flow on the wings and tail surfaces, engine nacelles and struts by means of suction and various degrees of suction laminarization of the fuselage. Figure 11 shows a comparison of L/D and Re_c of the strut braced and a cantilevered wing on a LFC airplane ($b^2/S = 12$) versus C_L. The superior L/D performance and the substantially lower wing chord Reynolds numbers of the strut-braced design are obvious.



(A)

Figure 11


Fuselage wetted area
100% laminar
80% laminar
40% laminar
Fully turbulent
Wing, tail surfaces, struts and nacelles all laminar, $b^2/s = 18$
$M_\infty = .83$
$M_\infty = .82$
$M_\infty = .84$
$M_\infty = .83$
$b^2/s = 19.4$, $t/c = .115$
$b^2/s = 18$, $t/c = .11$
Fuselage turbulent, wing, tail, strut and nacelles all 70% laminar
All turbulent, airplane, $b^2/s = 18$
$(L/D)_{cruise}$
80
70
60
50
40
30
20
10
0
.3
.4
.5
.6
.7
C_L

(B)

Figure 11

AIRPLANE RANGE

Assumptions

Take-off gross weight W_o = 180000 Kg,

$(L/D)_{average} = 37$,

spec. fuel consumption b = 0.48 kg/kg thrust at M = 0.83

i.e.,$\eta_{overall} = 0.42$,

gross weight empty = 0.38 × take-off gross weight W_o,

Payload = 50000 Kg. = 0.278 W_o,

0.06 W_o fuel reserves for take-off, climb, loitering. etc.

The unrefuelled range is R = 21564 Km = 11606 n. miles.

The all-out range without payload is about 68000 Km.

The same concepts can be applied with modifications to larger as well as smaller long range LFC transports.

CONCLUSIONS

M = 0.83 LFC transports, carrying large percentage payloads over a range of 20000 kilometers at cruise L/D's of 39 appear feasible with large span externally braced wings, external fuel pods, active controls, and 70% laminar flow on wing and tail surfaces, engine nacelles and struts, and a turbulent fuselage. To alleviate boundary-layer crossflow on the wing, the airfoils were designed for high M_∞'s (thereby reducing wing sweep) by undercutting the front and rear lower surface and selecting an extensive supersonic flat rooftop pressure-distribution on the upper surface with an upstream pressure minimum and a steep rear pressure rise. A slotted cruise flap improves the low drag $C_L - range$ and the rear pressure recovery. Weak suction from 0.05c to 0.30c appears adequate for 70% laminar flow on the upper wing surface.

A combination of a swept-forward inboard and a swept-back outer wing appears superior overall, especially for laminar flow and eliminating leading edge contamination probably caused by flyspecks and ice crystals. Wing divergence appears controllable by a combination of various methods.

Wing-mounted superfans with extensive laminar flow on their nacelles appear practical. Their dominant tone noise is below the frequency range of the most strongly amplified TS-waves.

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