Design Aspects of Long Range Supersonic LFC Airplanes With Highly Swept Wings

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SUMMARY

Supersonic Laminar Flow Control (LFC) airplanes with externally braced highly swept LFC wings of high structural aspect ratio (with the sweep increasing towards the wing root) offer particularly high supersonic cruise (L/D)'s with low sonic boom overpressures. At the design cruise condition the flow in the direction normal to the upper surface isobars is transonic (with embedded supersonic zones) and practically shockfree over most of the span. 3-body type supersonic LFC airplanes with a central fuselage and two smaller outboard bodies (alleviating wing bending and torsion) enable further increased spans and aspect ratios to reduce accordingly the lift induced wave- plus vortex drag as well as the volume induced wave drag. $(L/D)_{\text{cruise}}$ thus increases further.

Full span cruise flaps increase the low drag C_L-range and (together with the active control surfaces of the outboard bodies) may be used to actively reduce wing loads and aeroelastic deformations, suppress flutter and augment aerodynamic damping and stability to further increase the wing span and $(L/D)_{\text{cruise}}$. In addition, the low $C_{L,\text{opt}}$ of suction laminarized LFC airplanes (due to its very low $C_{D,o}$ with laminar flow) alleviates sonic boom and raises $M_{\text{design},\perp}$ of the airfoil to allow a reduction of the wing sweep angle φ, which in turn increases the span, reduces $C_{D,i}$ and raises $(L/D)_{\text{cruise}}$ accordingly, besides lowering sonic boom signature.

Variable wing sweep is desirable to reduce $C_{D,i}$ and raise L/D in low speed flight. The structural weight- and aerodynamic performance penalties involved can be minor with suitably designed highly swept strut-braced LFC wings.

$(L/D)_{\text{cruise}}$-values of 19 and 16 appear feasible at M_∞=2 and 2.5, respectively with reasonably extensive laminar flow over the airplane exposed surfaces. With 100% laminarization $(L/D)_{\text{cruise}}$ increases to 27 and 22 at M_∞=2 and 2.5, respectively.

With $\varphi = 67°$ and $72°$ at M_∞=2 and 2.524, respectively, and the high Re_c's of supersonic LFC airplanes, instability of the front wing attachment line- and crossflow boundary layer in the leading edge- and rear pressure rise zone become critical. Relatively sharp leading edges alleviate these problems. Boundary layer suction at the attachment line decreases $Re_{\theta,\text{a.l.}}$ and thus alleviates attachment line boundary layer instability further.

Boundary layer crossflow compensation, using a suitable flow overexpansion in the leading edge region, further alleviates the crossflow stability problems in the leading edge zone and practically eliminates boundary layer crossflow in the flat rooftop area of the upper surface. To minimize the suction power involved, suction in the front acceleration zone of the upper surface should be tailored such that the boundary layer crossflow in the entire suction area remains about neutrally stable.

With boundary layer crossflow thus practically absent, the upper surface rooftop boundary layer must be stabilized against Tollmien-Schlichting(TS)-disturbances by weak suction in spanwise suction strips. This is relatively easy due to the stabilizing influence of compressibility on TS-instability.

Boundary layer crossflow stabilization in the rear pressure rise area of the upper surface requires relatively strong local suction for 100% laminarization. The necessary suction power decreases by decelerating the flow in this area over a short chordwise distance and tailoring suction such as to maintain a neutrally stable crossflow in the upstream part of the pressure rise. The suction rates and suction power involved are modest, enabling extremely low equivalent $C_{D,\infty}$'s for the upper surface with all laminar flow.

NOMENCLATURE

b	span
c	Airfoil chord
l	Length of lift carrying system
n	Logarithmic boundary layer disturbance growth factor
n_{TS}	Logarithmic TS-type boundary layer disturbance growth factor
n_{CF}	Logarithmic crossflow boundary layer disturbance growth factor
s	Surface distance
v_o	Area suction velocity
w_n	Boundary layer crossflow velocity
$w_{n,max}$	Maximum boundary layer crossflow velocity
x	Chordwise distance
A_{jet}	Cross section of free jet bounded by Mach rim
C_D	Drag coefficient
$C_{D,k}$	Lift induced wave drag coefficient

$C_{D,i}$ Lift induced vortex drag coefficient
$C_{D,o}$ Zero lift drag
$C_{D,\infty}$ Equivalent wing profile drag coefficient
C_L Lift coefficient
C_p Surface static pressure coefficient with respect to ambient pressure
C_Q Nondimensional local suction mass flow rate $C_Q=\rho_{\text{wall}} v_o/\rho_{\text{ambient}} Q_\infty$
D_i Induced vortex drag
D_k Wave drag due to lift
L Lift
M_∞ Free-stream Mach number
$M_\perp$ Mach number component normal to isobars
M_w Mach number component along wing attachment line
Q_∞ Free- stream velocity
Re_c Reynolds number based on chord
Re_n Boundary layer crossflow stability limit Reynolds number based on $w_{n,max}$ and $\delta_{0.1}$
Re_θ Reynolds number based on boundary layer momentum thickness
S Wing area
W Airplane weight

Greek

α Angle of attack
δ Tunnel wall correction factor
$\delta_{0.1}$ Boundary layer thickness where $w_n=0.1 \cdot w_{n,max}$
ϵ_∞ Airfoil profile drag to lift ratio
ρ Density
φ Wing sweep angle
ψ Wave angle of boundary layer disturbance mode
$\eta_{overall}$ Overall efficiency of propulsion system
χ_{min} Minimum boundary layer crossflow stability limit Reynolds number based on $w_{n,max}$ and $\delta_{0.1}$

Subscripts

a.l. Attachment line
max maximum
min minimum
opt Optimum
t Total
LFC Laminar flow control
CF Crossflow
SST Supersonic transport
Tr Transition
TS Tollmien-Schlichting
$\perp$ Flow normal to isobars

A. INTRODUCTION, FORMULATION OF GOAL AND REQUIREMENTS

New technological advances, such as high strength- and stiffness materials, active control(for alleviation of loads and aeroelastic deformations, flutter suppression, augmentation of aerodynamic stability and damping), laminar flow control through geometry and boundary layer suction(LFC), advanced engines and manufacturing methods have led to a reevaluation of long range LFC supersonic transports(SST).

To achieve an unrefuelled range of the order of 20000kilometers with a substantial payload, the supersonic cruise lift to drag ratio L/D must be maximized. The minimization of the sonic boom signature, to hopefully allow supersonic cruise over land, influences the overall and detail design of such LFC SST's to an even higher degree than pure performance considerations alone.

The most advantageous use of low drag boundary layer suction for the laminarization of the airplane surfaces must be addressed.

If possible, to minimize ozone layer contamination by the engine exhaust and radiation hazards from the sun rays, the airplane cruise altitude should be restricted to 15kilometers or so.

To minimize the propulsion power and fuel required for take-off and the initial climb and keep airport noise within acceptable limits the airplane lift to drag ratio should be maximized in low speed flight. This may require variable wing sweep and other variable airplane geometry. In addition, the airplane should be laid out such that excessive drag and propulsion power are avoided in the transonic speed range. The question arises as to how best to meet these difficult and often conflicting requirements. In view of the overriding importance of the lift induced supersonic cruise wave drag, affecting both $(L/D)_{\text{cruise}}$ and sonic boom signature, its minimization is addressed first.

B. DESIGN APPROACHES TOWARDS A LOW LIFT INDUCED SUPERSONIC WAVE- PLUS VORTEX DRAG AND SONIC BOOM SIGNATURE

Nikolskii's and especially Kogan's concepts[1,2] provide an insight into the minimization of the lift induced supersonic wave drag*. Kogan derives the minimum sum of the lift induced supersonic wave- plus vortex drag by a momentum consideration on the rear characteristic surface of the lift carrying system(instead of the Trefftz- plane at subsonic speeds), being equivalent to the Mach cone in reversed flow(figure 1). Since the corresponding momentum contribution of the lift carrying system is limited to the zone within the intersection or Mach rim between its front Mach cone and rear characteristic surface and vanishes in the zone of silence beyond this Mach rim, the boundary condition for the lift induced secondary flow at the Mach rim is the same as at the boundary of a subsonic open jet wind tunnel, whose boundary is defined by the Mach rim . The sum of the lift induced supersonic wave- plus vortex drag is then equal to the induced vortex drag of the lift carrying system flying subsonically in this free jet wind tunnel, i.e. the supersonic lift induced wave drag $C_{D,k}$ is then equal to the induced drag correction imposed by the tunnel boundary: $C_{D,k}=\Delta C_{D,i}= -\delta C_L^2 S/A_{jet}$, where the tunnel wall correction factor δ can be obtained from the numerous tunnel wall correction calculations available in the literature (see summary report by A. Pope[3] on tunnel wall corrections and figure 2), with S=wing area, A_{jet}=crossection of free jet bounded by Mach rim (figure 3). δ is negative and positive for open and closed test sections, respectively.

The sum of the lift induced vortex- plus wave drag is then: $C_{D,i} + C_{D,k}= C_L^2/(\pi(b^2/S)) -\delta C_L^2 S/A_{jet}$, i.e.

* The first author is indebted to R. T. Jones for bringing this concept to his attention as well as for many valuable discussions during the early 1960's about supersonic configurations with low wave drag.

$C_{D,K}/C_{D,i}= -\pi\delta b^2/A_{jet}$.

Kogan's concept is valid only when both the span-and lengthwise lift distributions of the supersonic configurations closely approach the spanwise lift distribution with constant downwash in the Trefftz- plane for the wing operating in the subsonic free jet, bounded by the Mach rim . The optimum spanwise lift distribution of a wing operating in such a free jet deviates but insignificantly from an ellipse, at least for planar wings. In other words, the optimum lift distribution of supersonic wings with minimum lift induced wave- plus vortex drag should closely approach an ellipse both in span- as well as lengthwise direction. To alleviate wing structural loads and sonic boom overpressures, one might deviate form this optimum loading and let the lift fall off more slowly at the up- and downstream ends of the lift carrying system.

According to Kogan, to minimize the sum of the lift induced wave- plus vortex drag, the crossectional area A_{jet} of the free jet, bounded by the Mach rim, should be maximized by shifting this Mach rim as far away as possible from the wing tips as well as in vertical direction from the plane of the wing, while maintaining approximately elliptic lift distributions both in span- and lengthwise direction. This is possible with highly swept wings, swept sufficiently behind the free-stream Mach angle, such that the flow Mach number component $M_\perp$ normal to the upper surface isobar lines is either high subsonic or transonic similar to the design values of X-787 or X-66 type SC LFC airfoils with shock free flow[4,5].

Among supersonic configurations with low lift induced wave drag one may choose R.T. Jones' highly swept oblique wing[6], highly swept X- and joined or rhomboid type wings or symmetrically sweptback arrow type wings. Jones' oblique as well as the X-and joined wing automatically enable optimum and approximately elliptic lift distributions both in span- and lengthwise direction for minimum lift induced supersonic wave- plus vortex drag with straight lifting lines. To simultaneously achieve optimum (approximately elliptic) lift distributions in span- and lengthwise direction for supersonic configurations with strongly sweptback arrow type wings, the sweep of their lifting lines must progressively increase towards the wing root (figure 4). At the same time the front Mach cone starts further upstream from the extended wing root of a supersonic arrow wing with such an upstream wing root extension and is thus shifted further away from the wing tips. As a result A_{jet} increases substantially to approximately halve the lift induced supersonic wave drag, as compared to a highly swept supersonic arrow wing with straight lifting lines without an upstream wing root extension.

Using Kogan's concept the lift induced supersonic wave drag at M_∞=2 will be compared for various planar supersonic wing configurations, carrying a given lift over the same span and length (in flight direction) and assuming optimum lift distributions both in span- and lengthwise direction(figure 5). With these assumptions the highly swept supersonic X-wing has the lowest lift induced supersonic wave drag ratio $C_{D,k}/C_{D,i}$=0.199, followed by the highly swept supersonic joined wing($C_{D,k}/C_{D,i}$=0.281), the highly swept supersonic arrow wing with an upstream extended wing root($C_{D,k}/C_{D,i}$=0.323) and the oblique supersonic wing($C_{D,k}/C_{D,i}$=0.486). Thus, carrying a given lift over the same span and length, the lift induced supersonic wave drag ratio $C_{D,k}/C_{D,i}$ decreases substantially by distributing the lift into two highly swept individual lifting lines or surfaces, with their ends separated from each other by the wing span, especially if this were possible both at the up- and downstream ends of the lift carrying system(X-wing).

The lift induced supersonic wave- and vortex drag may be further reduced for supersonic biplanes with highly swept externally braced wings of very high aspect ratio. Such highly swept supersonic biplane wings could be attractive for supersonic LFC airplanes in view of their substantially smaller chords and Re_c's, thereby alleviating the boundary layer crossflow stabilization as well as the front wing attachment line flow problems of their highly swept LFC wings, provided the parasite drag of the external wing bracing can be minimized.

Assuming for the time being monoplane wings, the question arises concerning the best overall choice of a supersonic wing configuration with a low lift induced supersonic wave drag. Structural and especially wing divergence problems probably rule out highly swept high aspect ratio supersonic X-wings, unless their span and aspect ratio is reduced. But then their lift induced vortex drag and with it its lift induced wave drag increase to lose their lift induced drag advantage.

Roll-pitch coupling problems during roll acceleration with deflected ailerons as well as other considerations may limit M_{design} of the oblique wing to ≤ 1.6 to rule it out for $M_\infty \geq 2$ supersonic airplanes. The narrow chord wings of highly swept joined supersonic configurations present severe structural problems and were, therefore, also eliminated, leaving the highly sweptback arrow type supersonic wing with a 30% to 40% upstream wing root extension in up stream direction(figure 4). To minimize wing sweep and thus maximize the aerodynamic span of this supersonic arrow- type wing for induced vortex drag minimization, advanced SC LFC airfoils similar to the X-787 or X-66 type will be chosen over a large part of the wing span for the wing sections in the direction normal to the wing upper surface isobars, operating at their design points with conservatively high supersonic bubbles (in normal direction) on the upper surface. Its lift induced wave drag closely approaches the value of a supersonic oblique wing of the same aerodynamic span but carrying the lift over a 1.4 times larger lengthwise extent, while the induced vortex drag is the same for both configurations. Admittedly, lift generation in the highly swept area of the wing root extension of such a modified arrow wing is not easy; the problems involved, though, are considerably alleviated for suction laminarized supersonic LFC airplane configurations with particularly low $C_{D,o}$'s and correspondingly low $C_{L,\text{opt}}$'s.

The lift induced supersonic wave drag of highly swept supersonic arrow type LFC wings with extended wing roots was evaluated for different M_{design}'s, applying Kogan's concept and sweeping the wing at each M_{design} such as to maintain the same $M_\perp$- values as the shockfree design values of the SC X-787 airfoil. Figure 6 shows the corresponding ratio $C_{D,k}/C_{D,i}$ ($\dot{M}_{\text{cruise}}$)of such highly swept supersonic wings, optimized for these different M_{design}'s. At $M_\infty \approx$

2 to 2.5 $C_{D,k}/C_{D,i} \approx 0.5$ and decreases substantially at lower supersonic speeds, as the Mach rim moves progressively away from the wing tips at lower $M_{\mathbf{design}}$'s. The concept of a highly swept supersonic wing configuration with an extended wing root appears thus particularly attractive for somewhat lower supersonic cruise Mach numbers. To further reduce the ratio of the lift induced supersonic vortex- plus wave drag to lift $(D_i + D_k)/L= W/qb^2$ $(1/\pi - \delta/(A_{jet}/b^2))$, the span loading W/b^2 should be minimized by increasing the aerodynamic wing span b and with it its aerodynamic aspect ratio b^2/S, described as follows.

C. DESIGN APPROACHES TOWARDS LARGE WING SPANS

Advanced and possibly unconventional overall and detail design approaches are needed to increase the wing span without penalizing the wing structural weight. It may be worthwhile borrowing design approaches from the past, which at the time had been abandoned but which become now attractive again in the light of new aerodynamic refinements and technological advances. It is usually not appreciated that the requirement of a large wing span for induced drag reduction influences the design of high performance long range LFC airplanes to a far higher degree than most other design considerations. Therefore, design approaches will be emphasized and described which enable large span LFC wings without or with but minimum structural weight penalties[5,7]. Large spans with lower lift induced drags are possible without weight penalties for strut-braced supersonic arrow wings, i.e. the wings are braced externally by highly swept suction laminarized low drag struts in high modulus graphite structure. They take out both bending- and torsional moments and deflections, as discussed in references 5,7 for high subsonic speed LFC transports. The wing may be mounted on top of the fuselage or on highly swept pylon struts above the fuselage. For the optimized supersonic LFC transports with highly swept LFC arrow wings of high structural aspect ratio considerations of wing bending- and torsional deflection eventually dominate over pure strength considerations to favor large span strut- braced airplanes, even though their higher (L/D)'s and lower sonic boom signatures alone might not yet justify external wing bracing. Part of the strut parasite drag may be compensated for by using particularly thin LFC wing sections with a correspondingly lower profile drag in the strut- braced zone of the wing. This is structurally acceptable in view of the small wing bending moments in this zone, provided wing torsional moments are also taken out of the wing by the struts. Furthermore, since the section lift to drag ratio $1/\epsilon_\infty = C_L/C_{D,\infty}$ of the thin strut- braced part of the wing is higher than for the thicker wing outboard of the wing- strut intersection, the sum of the wing induced vortex- and profile drag can be further reduced and minimized by raising the loading in the strut-braced zone of the wing such that (according to E. Reissner) the sum of $\alpha_{i,\infty}+2\epsilon_\infty$ =constant along the wing span.

With these measures the sum of the wing- and strut profile drag, including the strut juncture drag, may not be appreciably larger than the profile drag of a cantilever SC LFC wing carrying the same lift. The saving in the lift induced wave- plus vortex drag by the larger span of the strut- braced LFC wing will then more than compensate for the low parasite drag of the suction laminarized struts and strut junctures with the wing and fuselage.

The flow over such highly swept struts is subsonic or transonic with relatively shallow embedded shockfree supersonic bubbles in the direction normal to the strut isobars. To minimize or preferably avoid local shock formation in strut juncture areas, these junctures must be carefully contoured according to the undisturbed flow streamlines around an infinitely long highly swept strut. Indeed, experiments by Hilton[8] in the Daingerfield supersonic wind tunnel on a 65° swept wing, mounted on the tunnel wall, practically did not show shock formation in the area of the juncture between the wing and tunnel wall at M_∞=1.73, when this juncture was shaped according to the undisturbed streamlines around an infinitely long 65° yawing wing of the same crossection. The wing pressure distribution had been subsonic in the juncture area. In contrast, an oblique shock originated from the wing leading edge in the juncture zone without such streamline contouring. Similar streamline contouring in the juncture zone between Goldsmith's 72° swept supersonic LFC wing[9] with the tunnel wall of the Tullahoma 1x1 meter A supersonic tunnel prevented local shock formation in this area and enabled subsonic type flow over the airfoil at M_∞=2.

Flow choking between the strut and lower wing surface can be avoided by carving out the lower wing surface according to the undisturbed streamlines around the strut and/or applying local area ruling[7].

Further increased wing spans and aspect ratios are feasible by alleviating wing bending- and torsion loads and deflections by externally mounted strut- braced suction laminarized bodies(carrying payload and/or fuel) along the span. Their control surfaces actively align the various bodies parallel to each other or at prescribed angles, as described in references 5,7 for high subsonic speed LFC transports, using for example inertial platforms etc. as sensors. Such an active wing angle of attack alignment is particularly important for supercritical LFC wings, which are inherently sensitive to angle of attack.

With suitably located external bodies, the volume induced supersonic wave drag of such a supersonic multibody configuration, consisting of a central fuselage, two smaller outboard bodies(figure 7) and possibly two additional relatively small fuel nacelles in the outer wing, can be substantially smaller than comparable single body configurations(according to supersonic oblique area rule considerations the equivalent length and fineness ratio of such a multibody configuration is considerably larger than for a single body airplane). A. Nastase[10] has shown that the volume induced supersonic wave drag is minimized by distributing the volume along the span. If these bodies and nacelles can be suction laminarized their parasite drag is relatively small. The strongly stabilizing influence of compressibility on TS- instability[11-14] at M_∞=2 to 3 is highly beneficial for their suction laminarization and in particular the central fuselage.

The wing span can be further increased by means of active control for alleviation of wing loads and aeroelastic deformations, flutter suppression, prevention of roll divergence and augmentation of stability and aerodynamic damping, as described in reference 5 for high subsonic speed LFC transports, using full span cruise flaps in combination with the active horizontal control surfaces of the external bodies, etc.

Highly swept supersonic LFC wings with transonic type flow on the upper surface are inherently sensitive to small wing angle of attack changes[4,5]. Therefore, C_L should preferably be varied by deflecting a small chord full span cruise flap, keeping the angle of attack essentially constant[4,5]. At the same time the front wing attachment line location remains practically fixed at different C_L's to minimize accordingly the variation of $Re_{\theta,\mathrm{a.l.}}$ with C_L.

D. IMPROVEMENT OF LOW SPEED CHARACTERISTICS BY VARIABLE WING SWEEP

To reduce induced vortex drag and improve the low speed characteristics at takeoff, climb, loitering and landing, wing sweep should be reduced at these lower flight speeds. With the strut-braced wing, the vertical distance between the wing attachment on the fuselage (or pylon struts) and the strut attachment on the fuselage can be used as a large basis for the wing rotation around the vertical axis to alleviate accordingly the structural problems and minimize the weight penalty involved with variable sweep. The wing can then be rotated around a vertical axis located close to the fuselage, i.e. variable sweep can be applied over a large percentage of the wing span to gain thereby the maximum benefit from variable wing sweep. As wing sweep is reduced at lower flight speeds additional horizontal stabilizing surfaces may have to be extended in the rear part of the fuselage to compensate for the forward movement of the wing aerodynamic center. Since a considerable span increase is possible with but a modest sweep reduction, when sweep is reduced along practically the entire wing span, one may not have to be as demanding in reducing wing sweep at lower flight speeds. The design complexities and drag penalties involved are accordingly less critical, caused, for example, by the angle of attack changes of the wing struts and the yaw of the wing-strut junctures, as wing sweep is reduced at lower flight speeds.

With the strut-braced variable sweep wing only tension and compression forces must be transmitted to the variable sweep attachment joints, as compared to the large bending moments in the joint area of variable sweep cantilever wings. To obtain an aerodynamically smooth joint during cruise one might rotate the wing and strut around two concentric circular rails, with the axis of rotation located at the leading edge of the wing- and strut. Considering the substantially larger permissible two- and three-dimensional surface disturbances for laminar flow at supersonic speeds the wing joint in the fully closed position (i.e., with the wing swept for supersonic cruise) may be designed sufficiently smooth and airtight to enable extensive or even full chord laminar flow with suction in the joint area. The greatly increased permissible two-dimensional surface disturbances, such as steps, gaps, etc. at supersonic speeds are explainable by the strongly stabilizing influence of compressibility at moderately high supersonic speeds on the growth of amplified TS-waves in the laminar separation zones of such steps, gaps, etc. (see similar results for jet wake instability in reference 15). Thus, one might not necessarily have to pay a cruise drag penalty for variable sweep, and the structural weight penalty involved with the variable sweep strut-braced wing could be relatively minor.

When wing sweep is reduced and the wing span increased for induced drag reduction at lower flight speeds suitable cover sheets, of course, must be provided to fill the wing gap in the joint area.

E. AERODYNAMIC DESIGN- AND PROPULSION CONSIDERATIONS

With the high structural and relatively high aerodynamic aspect ratio b^2/S of strut-braced LFC SST configurations, Re_c is not excessively high to enable accordingly extensive and in the limit full chord laminar flow on the wing by means of a suitable geometry and suction, taking into account the stabilizing influence of compressibility on TS-instability and using suitable measures to control boundary layer crossflow instability, as discussed later. Combining the resulting low $C_{D,\infty}$'s with the minimization of the volume induced supersonic wave drag of 3-body configurations and the extensive suction laminarization of the central fuselage, external bodies, tail surfaces and engine nacelles the airplane zero-lift drag $C_{D,o}$ is then extremely low to enable accordingly (together with the relatively large aerodynamic span and aspect ratio) high supersonic cruise lift to drag ratios at relatively low $C_{\mathrm{L,opt}}$-values.

More subtle considerations show secondary aerodynamic advantages of suction laminarized LFC SST's with extensive laminar flow and correspondingly low $C_{D,o}$'s: Since $C_{\mathrm{L,opt}} \sim \sqrt{C_{D,o}}$, their $C_{\mathrm{L,opt}}$ is substantially lower than for corresponding turbulent SST's to reduce accordingly $C_{L,\mathrm{design},\perp}$ of the airfoil (normal to the wing) and raise its M_{design}. To fly at a given Mach number a smaller wing sweep angle suffices then, enabling a correspondingly larger aerodynamic wing span with a lower induced vortex drag. Figure 8a shows a corresponding plot of $C_{D,i}$, $C_{D,k}$, $C_{D,i}+C_{D,k}$ and the ratio $C_{D,k}/C_{D,i}$ versus the wing sweep angle φ at M_∞=2. With decreasing φ the span b increases and $C_{D,i}$ decreases accordingly(in figure 8a the induced drag at $\varphi = 65°$ was arbitrarily chosen as 100%). Since the lengthwise wing aspect ratio of highly swept supersonic wings at M_∞=2 to 2.5 changes but insignificantly, when wing sweep is thus reduced, the wave drag due to lift is little affected by this decrease in wing sweep resulting from this low $C_{D,o}$(figure 8a). This may also be verified from $C_{D,k} = \text{-}\delta \cdot C_L^2 \cdot S/A_{jet}$, where δ and A_{jet} vary but insignificantly for relatively small sweep variations under otherwise the same conditions.

Figure 8b presents the variation of φ, $C_{L,\perp}$, $C_{D,k}$, $(C_{D,i}+C_{D,k})/C_{D,t}$, $C_{D,k}/C_L$ and C_L/C_D versus C_L for all laminar $M_\infty = 2.0$ LFC airplanes with strut-braced arrow wings with upstream wing root extensions(structural aspect ratio 30) and X-787 type SC LFC airfoils.

Thus, the extremely low friction drag of a suction laminarized SST configuration enables at the same time indirectly an additional reduction of the induced vortex drag and increase in (L/D) during supersonic cruise.

In addition, the rear pressure rise on the upper surface of the airfoil is simultaneously reduced at these lower

$C_{L,\mathbf{design}}$'s to ease accordingly control of boundary layer crossflow instability in this area.

Of course, the use of advanced SC LFC airfoils (for example of the X-787 or X-66 type) with a particularly high 2-dimensional design Mach number allows correspondingly less wing sweep to increase accordingly the aerodynamic wing span and thereby reduce the induced vortex drag and raise $(L/D)_{\mathbf{cruise}}$.

Figure 9 shows $(L/D)_{\mathbf{cruise}}$ versus the design cruise Mach number $M_{\mathbf{cruise,design}}$ for long range supersonic three-body type LFC airplanes with highly swept strut-braced high aspect ratio wings laid out for different cruise Mach numbers, both for the limiting case of practically all laminar flow by means of suction over the airplane exposed surfaces as well as with reasonably extensive laminar flow. The structural wing aspect ratio was kept constant for different design Mach numbers.

Remarkably high lift to drag ratios appear feasible with reasonably extensive laminar flow over the airplane exposed surfaces: $L/D = 19$ and 16 at $M_{\mathbf{cruise,design}} = 2$ and 2.5, respectively. With practically all laminar flow the corresponding values would increase to $L/D = 27$ and 22 at $M_{\mathbf{cruise,design}} = 2$ and 2.5, respectively. L/D decreases approximately inversely proportional to $M_{\mathbf{cruise,design}}$. With a wing loading of 360kg$/m^2$, $C_{\mathrm{L,cruise}}$=0.11 and M_∞=2 the cruise altitude of 15500 meters is below the critical ozone layer altitude.

The question arises concerning the variation of $\eta_{\mathbf{overall}}$ with $(L/D)_{\mathbf{design}}$, optimizing the powerplant for the particular cruise Mach number. Although the powerplant thermodynamic efficiency increases with increasing flight Mach number, the overall efficiency increases at a much slower rate than $M_{\mathbf{cruise}}$, if the engine is always optimized for the particular cruise speed. With the above quoted supersonic $(L/D)_{\mathbf{cruise}}$ and the correspondingly low cruise thrust turbofans of modest bypass ratio appear attractive for cruise. Their higher cruise propulsive efficiency compensates for their larger weight and parasite drag, especially if the engine nacelles can be laminarized by suitable means. The supersonic inlet diffuser becomes then crucially important. Carefully designed boundary layer suction may be used in internal compression inlet diffusors to minimize their losses. Such turbofans of moderate bypass ratio are, of course, desirable to reduce fuel consumption and engine noise in low speed flight and at take-off.

F. ALLEVIATION OF SONIC BOOM SIGNATURE

The important question arises as to how to minimize the sonic boom overpressures to hopefully enable supersonic cruise over land. The highly swept high aspect ratio strut-braced supersonic wing with its particularly low lift- and thickness induced wave drag contributes correspondingly to low sonic boom overpressures. The low zero lift drag of a suction laminarized supersonic LFC airplane leads to low optimum $C_{L,\mathbf{cruise}}$-values to reduce accordingly the lift induced perturbation velocities and the resulting sonic boom overpressures. The volume induced supersonic wave drag and the resulting sonic boom overpressures can be particularly low with suitable 3-body type supersonic configurations. The supersonic boom signature can be further reduced by displacing the shocks generated by the wing, fuselage and outboard bodies lengthwise, such that they do not coincide with each other, and by maintaining a slow and gradual buildup of the lift at the wing root and falloff at the tips (by further extending the wing root and tips lengthwise), such that a more gradual pressure rise instead of an N-wave is generated[16]. The sonic boom overpressures decrease further if similar approaches can be used to cut off the tops of the volume induced N-waves and if the near airplane pressure field can be maintained into the far field towards the ground (this is considerably easier in view of the large length of the highly swept high aspect ratio strut-braced LFC wing and its particularly low lift induced perturbation velocities, resulting from the low $C_{\mathbf{L,opt}}$-values of the suction laminarized airplane with its very low $C_{D,o}$).

The above described approaches may reduce sonic boom overpressures with but insignificant supersonic cruise (L/D)-penalties, possibly to such an extent that supersonic cruise at M_∞=2 to 2.5 may be accepted over land.

G. SUCTION LAMINARIZATION CONSIDERATIONS OF HIGHLY SWEPT HIGH ASPECT RATIO SUPERSONIC LFC WINGS

The question arises concerning the suction laminarization of highly swept supersonic LFC wings, especially with large aspect ratios possible through external bracing etc. Their isobars can be swept everywhere sufficiently far behind the free-stream Mach angle such that the flow in the direction normal to the isobars is transonic and similar to that on advanced SC LFC airfoils for example of the X-787 or X-66 type[4,5]. Thus, the experience gained with the suction laminarization of swept subsonic wings with such SC LFC airfoils may be used for highly swept supersonic LFC wings. In a first step it appears adequate to conduct a boundary layer development- and stability analysis on a highly swept supersonic LFC wing of constant chord, using for example the relatively sharp-nosed SC LFC airfoil X-66 in the direction normal to the wing and rotated by the sweep angle. Its two-dimensional design pressure distribution is shown in figure 10.

The high design Mach number of this airfoil is due to an upper surface pressure distribution with a far upstream supersonic pressure minimum, followed by decelerated flow with an asymptotic transition into an extensive low supersonic flat rooftop and a steep rear pressure rise either with low drag suction or a slotted trailing-edge cruise flap[4,5,17]. The design Mach number increases further by undercutting the front and rear lower surface, contributing thereby additional positive lift in these areas[4,5,17]. Lift is thus generated essentially in the front and rear of the airfoil, while the center bulge of the lower surface contributes primarily to wing thickness. (Strictly speaking $C_{L,\mathbf{design}}$ of airfoil X-66 may be excessively large for flight at lower supersonic speeds with very extensive laminar flow over the airplane exposed surfaces. At higher supersonic speeds $C_{L,\mathbf{design}}$ of airfoil X-66, on the other hand, may be insufficient and should preferably be raised).

The boundary layer development as well as the TS- and crossflow boundary layer instability were subsequently analyzed for the upper surface of airfoil X-66, rotated between 60° and 72° for M_∞=1.56 to 2.524, respectively, over a Re_c-range from 30.0×10^6 to 80.0×10^6. Particularly critical for such highly swept supersonic LFC wings with a finite leading edge radius, swept behind the free-stream Mach angle, are TS-type attachment line boundary layer instability and spanwise turbulent contamination along the front wing attachment line, caused either by amplified TS-type attachment line boundary layer oscillations in the presence of small initial disturbances or directly by large attachment line disturbances[18–25]. Relatively sharp leading edges, typical to the X-66 airfoil (probably requiring variable leading edge camber for satisfactory low speed characteristics), combined if necessary with low drag suction at the attachment line, will be needed to keep $Re_{\theta,\text{a.l.}}$ within acceptable limits and thereby alleviate the attachment line flow instability problems. Similar to a flat plate boundary layer compressibility effects are expected to reduce the TS-boundary layer disturbance growth in the presence of small disturbances to allow correspondingly higher $Re_{\theta,\text{a.l.}}$'s at the attachment line of highly swept wings at supersonic speeds. In addition, since the destabilizing influence of streamline divergence at the leading edge of swept wings on TS-instability (which causes a destabilizing lateral stretching of the attachment line TS-disturbance vortices) is relatively weak for highly swept wings the growth of amplified TS-waves at the attachment line of highly swept supersonic LFC wings should not be significantly affected by such TS-vortex stretching, in contrast to more moderately swept wings, for which such streamline divergence should be more critical.

Exploratory type transition experiments on yawing cylinders[26] at $M_\infty = 3.5$ in the presence of large disturbances indicate a modest stabilizing influence of compressibility ($Re_{\theta,\text{a.l.,Tr}} \approx 150$ to 160 at $M_w = 1.66$ and 240 at M_w=2.39, as compared to the low speed value[20] of 90 to 100).

It appears particularly important to minimize amplified attachment line boundary layer oscillations especially on highly swept wings, when such oscillations may represent relatively large initial disturbances feeding travelling boundary layer crossflow disturbance modes further downstream in the front acceleration zone of the wing.

With the attachment line boundary layer momentum thickness $\theta_{\text{a.l.}} = \theta^*_{\text{a.l.}} \sqrt{\nu / \left(\frac{\partial U}{\partial s}\right)_{\text{a.l.}}}$ follows the attachment line boundary layer momentum thickness Reynolds number $Re_{\theta,\text{a.l.}} \equiv V_{\text{a.l.}} \cdot \theta_{\text{a.l.}}/\nu = \theta^*_{\text{a.l.}} \cdot \sin\varphi \sqrt{Re_c / \left(\frac{\partial(U/U_o)}{\partial(s/c_\perp)}\right)_{\text{a.l.}}}$, where $\theta^*_{\text{a.l.}}$ = nondimensional attachment line boundary layer thickness = f($v^*_{o,\text{a.l.}}$), with $v^*_{o,\text{a.l.}} = v_{o,\text{a.l.}} / \sqrt{\nu \left(\frac{\partial U}{\partial s}\right)_{\text{a.l.}}}$. In incompressible flow $\theta^*_{\text{a.l.}} = 0.405$ for $v^*_{o,\text{a.l.}} = 0$. For $\theta^*_{\text{a.l.}}$ and $Re_{\theta,\text{a.l.}}$ in compressible flow see Poll[27].

In these expressions $(\partial U/\partial s)_{\text{a.l.}}$ = potential flow velocity gradient at the attachment line in the direction normal to the wing leading edge, $V_{\text{a.l.}}$ = spanwise potential flow velocity along the attachment line, $Re_c = Q_\infty \cdot c/\nu$.

Thus, $Re_{\theta,\text{a.l.}} \sim \sin\varphi\sqrt{Re_c}$, or since c and $Re_c \sim \cos\varphi^{-1}$ (when the wing of given normal chord $c_\perp$ is rotated by the sweep angle φ): $Re_{\theta,\text{a.l.}} \sim \sin\varphi/\sqrt{\cos\varphi}$ (references 20,22,26), as shown in figure 11 versus φ (assuming constant unit length Reynolds number Q_∞/ν). The rapid increase of $Re_{\theta,\text{a.l.}}$ with φ is evident.

Without suction at the attachment line $Re_{\theta,\text{a.l.}} \approx 180$ to 200 for a 67° yawing supersonic wing at M_∞=2 and $Re_c = 60.0 \times 10^6$, assuming the rather sharp-nosed X-66 type SC LFC airfoil in the direction normal to the wing: At $M_\infty = 2$ ($M_w = 1.84$) this value should be acceptable in the presence of small initial disturbances in view of the stabilizing influence of compressibility. These $Re_{\theta,\text{a.l.}}$-values are somewhat larger than $Re_{\theta,\text{a.l.,Tr}}$ in the presence of large disturbances. One might then provide at discrete stations along the attachment line local suction patches, which reduce $Re_{\theta,\text{a.l.}}$ below $Re_{\theta,\text{a.l.,critical}}$ for large disturbances, to reestablish, if necessary, an undisturbed laminar attachment line boundary layer[22].

The next question concerns the boundary layer crossflow stabilization in the front acceleration zone of the upper surface. For a wing rotated in incompressible flow by the sweep angle φ the boundary layer crossflow Reynolds number $Re_n \sim \sin 2\varphi$ (reference 28), i.e., Re_n peaks at $\varphi = 45°$ and decreases again beyond $\varphi = 45°$. On the other hand, with the higher boundary layer temperatures and the correspondingly lower air density in the vicinity of the wall in compressible flow at supersonic speeds, the boundary layer air in this innermost zone has less kinetic energy to withstand the same crossflow pressure gradients as in incompressible flow; as a result the boundary layer crossflow velocity and- Reynolds number Re_n are correspondingly larger under otherwise the same conditions. Thus, as φ and M_∞ increase, Re_n reaches a maximum beyond φ = 45° (tentatively 60° or so) and decreases then again at larger φ's. Compressibility at supersonic speeds stabilizes the boundary layer crossflow, though not nearly to the same degree as with TS-instability, since the critical crossflow disturbance layer is located much further away from the surface than the critical TS-layer[11–14]. Therefore, the change of temperature, kinematic viscosity and dissipation in the critical crossflow disturbance layer is correspondingly smaller than in the critical TS-layer to affect crossflow instability to a lesser degree than TS-instability.

The question arises concerning optimum boundary layer crossflow stabilization by means of suction with minimum suction power on highly swept supersonic LFC wings swept behind the free-stream Mach angle. For this purpose, the sweep-induced boundary layer crossflow in the front acceleration zone of the upper surface can be substantially alleviated by a relatively sharp leading edge (since δ and $Re_n \sim (\partial U/\partial s)^{-0.5}$ in the front acceleration zone, assuming the same normalized pressure distributions in this zone for different nose bluntness). Furthermore, the sweep-induced boundary layer crossflow generated in the front acceleration zone of the upper surface may be largely cancelled by a boundary layer crossflow of opposite sign generated in the pressure rise area downstream of a front pressure minimum[4,5], as shown in figure 10 for the X-66 airfoil[5]. Boundary layer crossflow in the front acceleration zone of the upper surface is further minimized by rapidly accelerating the flow in this area over a particularly short chordwise distance to the front pressure minimum[4,5].

Suction stabilization of the sweep-induced boundary layer crossflow in the front acceleration zone of the upper surface is possible with minimum suction power by starting suction at the location where the boundary layer crossflow becomes neutrally stable. Suction would then be applied such that Re_n stays close to the corresponding crossflow stability Reynolds number $\chi_{\min}$ in the entire area of the suction strip, i.e. n_{CF} grows but insignificantly or not all in the suction region. Suction must be extended sufficiently far downstream such that n_{CF} is permitted to grow to a maximum permissible value in the zone downstream of the suction region(29).

An example is shown for the SC LFC airfoil X-66, rotated 67° and 72° at M_∞=2 and 2.524, respectively, and $Re_c = 80.0 \times 10^6$. The stability calculations were performed by using COSAL program(14). The boundary layer profiles for the stability analysis were obtained using the Kaups-Cebeci code(30). Stability analysis results at M_∞=1.56 and 2.524 ($\varphi = 60°$ and $72°$) are presented in reference 31 for $Re_c = 30.0 \times 10^6$ and 60.0×10^6. The figures 12,13 show corresponding plots of C_p (or $M_\perp$), C_Q, and n_{CF} versus the surface distance S/C in the front acceleration zone of the upper surface. Relatively strong local suction is thus needed in a relatively narrow chordwise suction strip in the front acceleration zone of the upper surface for optimum local boundary layer crossflow control. Low drag suction may be applied either through fine electron- or laser-drilled perforated surfaces or a series of closely spaced continuous spanwise slots. Suction hole induced streamwise disturbance vortices may adversely superimpose with the sweep-induced boundary layer crossflow and its disturbance vortices to raise n_{CF} accordingly. Suction through closely spaced spanwise slots, located in an area where $M_\perp$ is subsonic, avoids these 3-dimensional disturbances.

The overall suction mass flow and -power needed for boundary layer crossflow control in the front acceleration zone of the upper surface are surprisingly low for such a highly swept supersonic LFC wing, explainable by the relatively sharp leading edge and the optimum boundary layer crossflow control used.

Figure 13 shows rapidly decreasing n_{CF}-values with increasing suction rates in the front part of the upper surface.

With the above described boundary layer crossflow compensation in the front part of the upper surface the boundary layer in the extensive flat or slightly downsloping rooftop area of the upper surface must be stabilized primarily against amplified oblique TS-disturbances. This is possible with relatively weak suction in one or several spanwise suction strips, starting shortly downstream of the front pressure minimum from 0.05c to 0.30c for the above example of airfoil X-66, $\varphi = 67°$ and $72°$, M_∞=2 and 2.524, respectively, for $Re_c = 80.0 \times 10^6$ (figures 14,15). The corresponding n_{TS}-values in the flat rooftop area are surprisingly low in spite of the large suction interruption between 0.30c and the start of the rear pressure rise, explainable by the strongly stabilizing influence of compressibility on the TS-disturbance growth at this Mach number. It is crucially important to avoid or minimize boundary layer crossflow in the rooftop area of the upper surface, if highly oblique inflectional boundary layer profiles with a correspondingly severe amplification of TS-disturbances are to be avoided.

On a tapered sweptback wing a slightly downsloping upper surface rooftop gives a slightly higher design Mach number than a flat rooftop(5), requiring probably additional narrow spanwise suction strips in the rooftop area for adequate TS-stabilization.

Strongly oblique amplified TS-disturbances, which have grown through the upper surface rooftop area to its downstream end, may represent relatively strong initial disturbances feeding travelling boundary layer crossflow disturbance vortices in the rear pressure rise area of all laminar highly swept supersonic LFC wings to possibly precipitate transition in the rear pressure rise area. Such initial disturbances may be minimized by rapidly damping the TS-disturbances at the downstream end of the rooftop, before penetrating too far into the rear pressure rise area. This is possible with relatively strong local suction at the start of the rear pressure rise, preferably keeping the TS-disturbances in the rooftop area at or below their critical threshold level for three-dimensional distortion. $n_{TS,\max}$ in the rooftop area may then have to be reduced by a value of 3 to 4 below the corresponding transition value.

The figures 16,17 show C_p, C_Q, and n_{CF} versus x/c in the rear pressure rise area of the upper surface of airfoil X-66 for $\varphi = 67°$ and $72°$, M_∞=2 to 2.524, respectively, for $Re_c = 80.0 \times 10^6$. The combination of a severe flow deceleration and relatively thick laminar boundary layer, combined with a lower boundary layer air density towards the wall (as a result of higher local temperatures in the supersonic boundary layer), generates a particularly severe boundary layer crossflow in the rear pressure rise area of supersonic LFC wings swept behind the free-stream Mach angle at the high Reynolds numbers of such wings. Relatively strong suction is then needed in the rear pressure rise area to maintain full chord laminar flow at high Re_c's, particularly in the area of the maximum chordwise pressure gradient. The crossflow disturbance vortex growth in the rear pressure rise area can be minimized by decelerating the flow rapidly over a particularly short chordwise distance, thereby reducing the disturbance growth distance involved, and by keeping the crossflow about neutrally stable over the first part of the rear pressure rise by sufficiently strong local suction. In addition, the rapid flow deceleration in the rear pressure rise area thins the corresponding Stokes-crossflow layer to shift accordingly the maximum crossflow velocity closer to the surface and raise accordingly $\chi_{\min}$. As a result of these measures the required suction rates and -power appear surprisingly modest, leading to extremely low equivalent wing profile drags for the upper wing surface with full chord laminar flow.

A similar boundary layer development and stability analysis is needed for the lower wing surface.

CONCLUSIONS

Supersonic long range LFC airplane studies were conducted to maximize (L/D) and alleviate sonic boom during supersonic cruise. Configurations with highly swept LFC wings of very high structural aspect ratio, with the sweep increasing towards the wing root and braced externally by wide chord laminarized struts (taking out wing bending- and - torsional loads and deformations) appear especially promising. At the supersonic cruise design condition the wing upper surface isobars are swept such that the flow in the direction normal to them is transonic (with embedded supersonic zones) and practically shockfree over most of the span, with $M_\perp$ equal to the 2-dimensional design values of advanced SC LFC airfoils, for example of the X-787 orX-66 type.

The alleviation of wing bending and torsional loads and deformations by suction laminarized externally mounted LFC bodies with active horizontal control surfaces, located in the outer part of the wing, allows further increased wing spans and aspect ratios to reduce accordingly the lift induced wave- plus vortex drag and thus raise $(L/D)_{\text{cruise}}$. Furthermore, the volume induced supersonic wave drag of a 3-body configuration with a central fuselage and two outboard bodies can be lower than for a single body configuration of equal total volume to further raise $(L/D)_{\text{cruise}}$.

Full span cruise flaps are desirable to control lift directly, improve the low drag C_L-range and (together with the active control surfaces of the outboard bodies) actively reduce wing loads and aeroelastic deformations, suppress flutter and augment aerodynamic damping and stability. The wing span can thus be increased to raise $(L/D)_{\text{cruise}}$ accordingly further. In addition, the low $C_{\text{L,opt}}$ of suction laminarized supersonic LFC airplanes (due to its very low $C_{D,o}$ with extensive laminar flow) raises $M_{\text{design},\perp}$ of the airfoil to allow a corresponding wing sweep reduction, which in turn allows increased spans to reduce $C_{D,i}$ and increase $(L/D)_{\text{cruise}}$ accordingly.

Variable wing sweep appears necessary for highly swept arrow wing configurations to lower $C_{D,i}$, raise L/D and maintain satisfactory characteristics in low speed flight. The variable sweep-induced structural weight- and aerodynamic cruise performance penalties can be minimized with highly swept supersonic strut-braced LFC wings of high aspect ratio.

With reasonably extensive laminar flow over the airplane exposed surfaces cruise lift to drag ratios $L/D = 19$ and 16 appear feasible at M_∞=2 and 2.5, respectively, for 3-body type supersonic LFC configurations with highly swept high aspect ratio strut-braced wings. With practically all laminar flow L/D might increase to 27 and 22 at M_∞=2 and 2.5, respectively.

The combination of a large lengthwise aspect ratio of the highly swept modified arrow wing, the 3-body type configuration and the low lift induced perturbation velocities of the suction laminarized airplane with its inherently low $C_{\text{L,opt}}$ minimize sonic boom overpressures. These can be further reduced by cutting off the tops of the sonic boom N-wave to possibly enable supersonic cruise over land.

Relatively sharp leading edges and attachment line boundary layer suction alleviate attachment line boundary layer instability, which is particularly critical for highly swept supersonic wings.

The sweep-induced boundary layer crossflow in the leading edge zone can be minimized by a relatively sharp leading edge and compensating the crossflow in the front acceleration zone of the upper surface by an opposite crossflow in a local pressure rise area further downstream, as well as stabilizing the crossflow optimally by suction, such that the crossflow disturbance vortices remain about neutrally stable in the suction region of the front acceleration zone. The boundary layer of the extensive flat rooftop zone of the upper surface is then essentially free from crossflow disturbances and must be stabilized against amplified TS-disturbances by weak suction in this area in one or several spanwise suction strips. Compressibility effects at M_∞=2 to 2.5 strongly reduce the TS-disturbance growth in the flat rooftop area of the upper surface to allow laminarization at high Re_c's.

To maintain 100% laminar flow relatively strong suction is needed in the rear pressure rise area for boundary layer crossflow stabilization. The suction power involved is minimized by decelerating the flow over a particularly short distance and stabilizing the crossflow boundary layer especially in the upstream part of the rear pressure rise, avoiding amplified crossflow vortices in this area.

The required suction mass flow rates and- power are modest, enabling extremely low equivalent $C_{D,\infty}$'s for the upper surface with all laminar flow.

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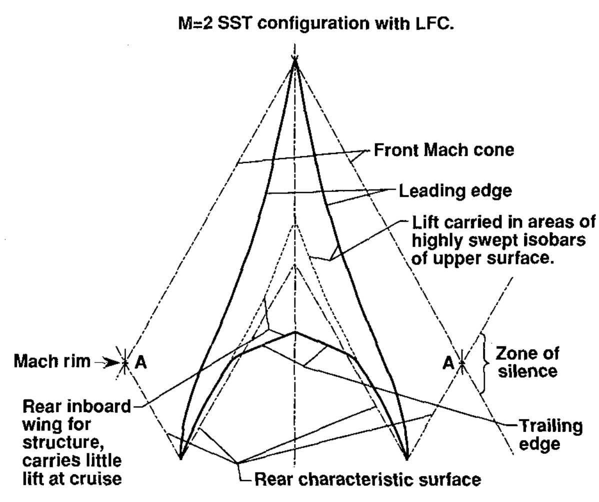


Fig. 1 Explanation of Kogan's Momentum Consideration (reference 2) on Rear Characteristic Surface of Highly Swept Supersonic LFC Airplane Configuration #1 with Cantilever Wings ($M_{\text{design}} = 2$).

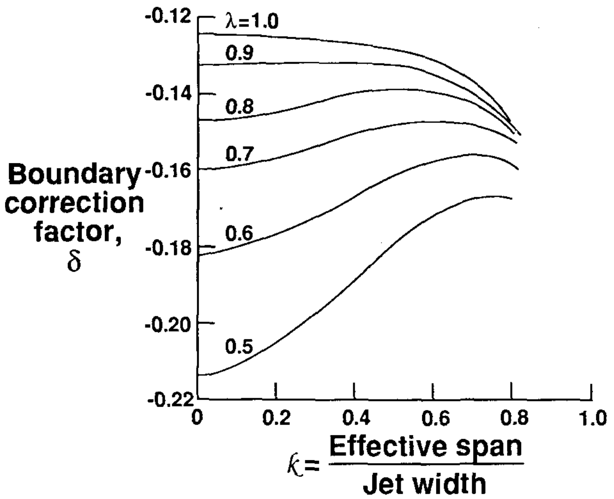


Fig. 2 Open Jet Wind Tunnel Wall Correction Factor δ (reference 3).

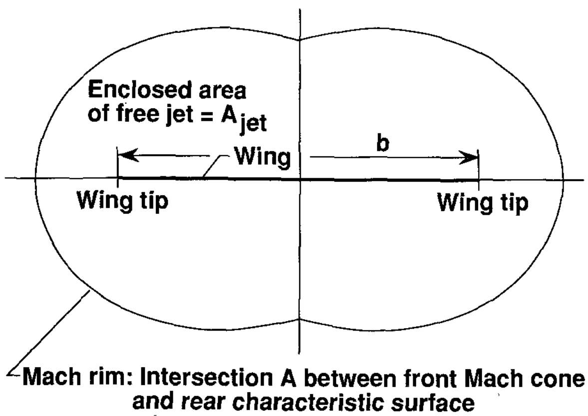


Fig. 3 Mach Rim for Configuration #1 at M_∞=2.

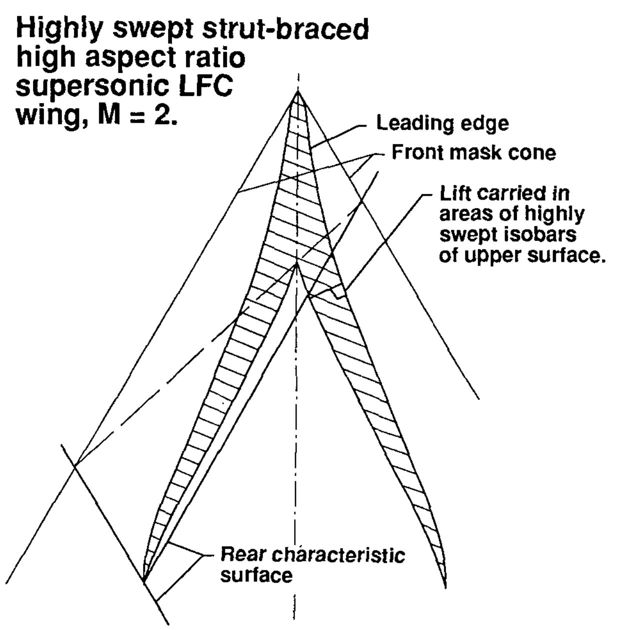
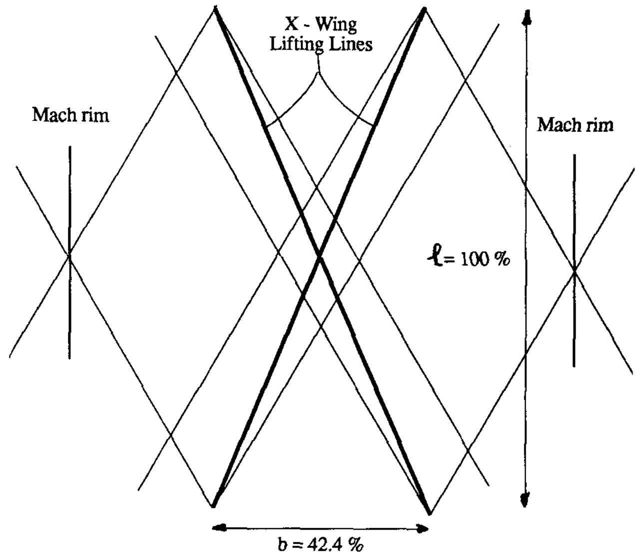
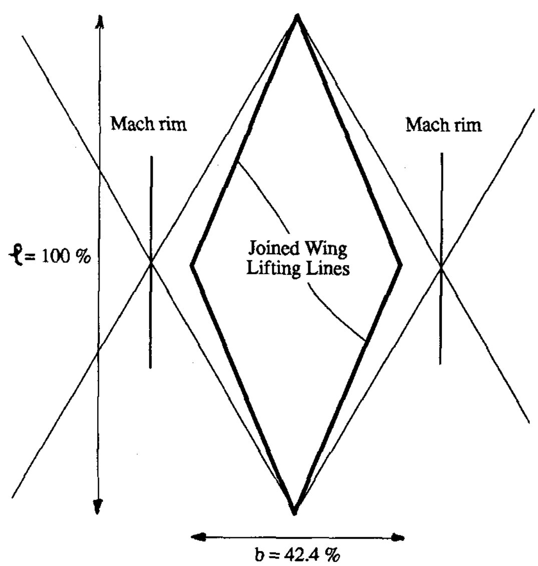


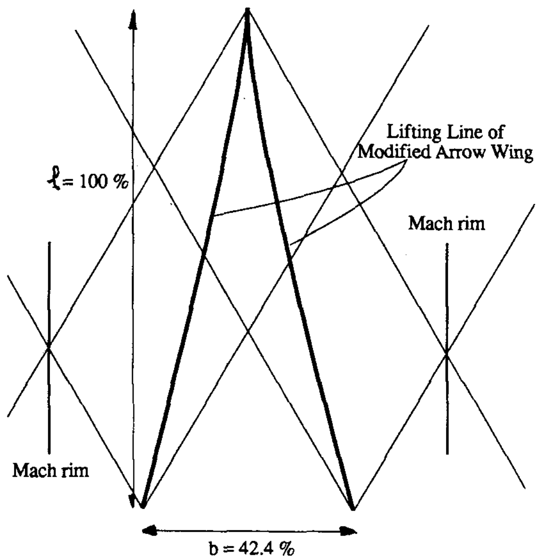
Fig. 4 Highly Swept High Aspect Ratio Strut-Braced Supersonic LFC Wing, M_{design} = 2.



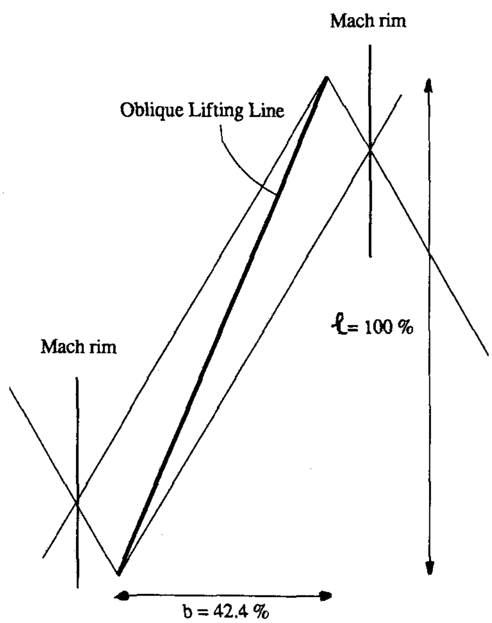
X - Wing



Joined Wing



Arrow Wing
With upstream wing root extension



Oblique Wing

Fig. 5 Supersonic lift induced wave drag at M_∞=2 of various supersonic configurations of given span and length of the lift carrying system.

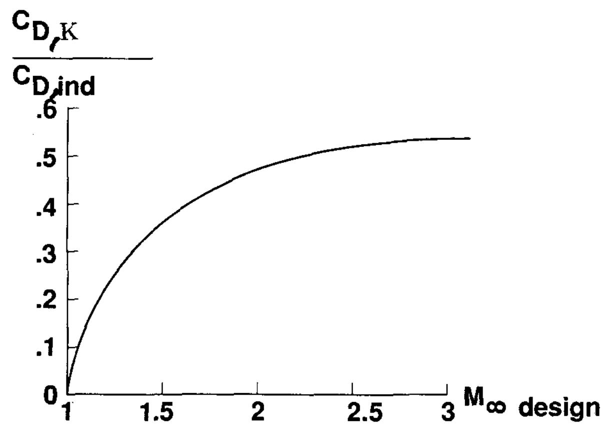


Fig. 6 $C_{D,k}/C_{D,i}$ versus $M_{\text{cruise,design}}$ for LFC Airplane Configurations of the type #2 with resonably extensive as well as practically all laminar flow over the airplane exposed surfaces.

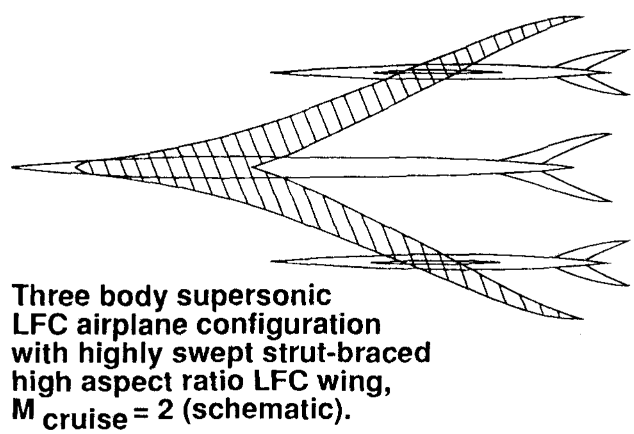


Fig. 7 3-body Type $M_{\text{design}} = 2$ Supersonic LFC Airplane with Highly Swept High Aspect Ratio Strut-Braced LFC Wing (Schematic), Configuration #2.

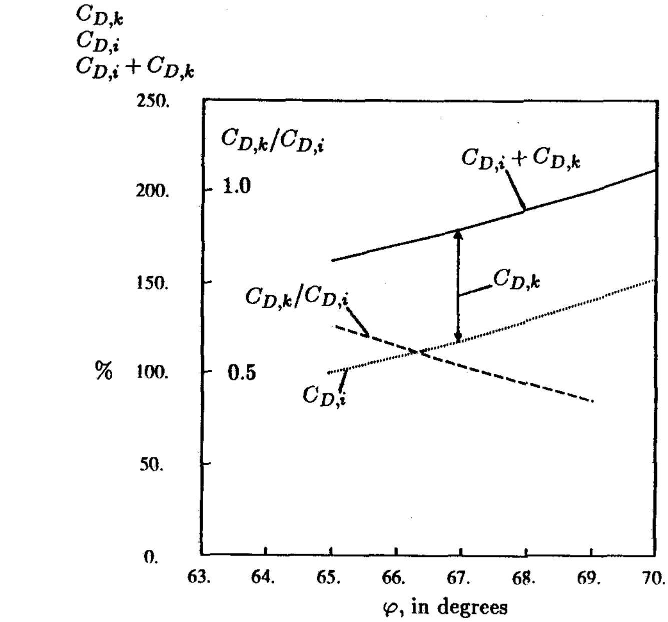


Fig. 8a All laminar M_∞=2 LFC airplanes with strut-braced modified arrow wings and X-787 type SC LFC airfoils. Variation of φ, $C_{L,\perp}$, $C_{D,k}$, $(C_{D,i} + C_{D,k})/C_{D,t}$, $C_{D,k}/C_L$ and C_L/C_D versus C_L. $(b^2/S)_{struct.}$=30.

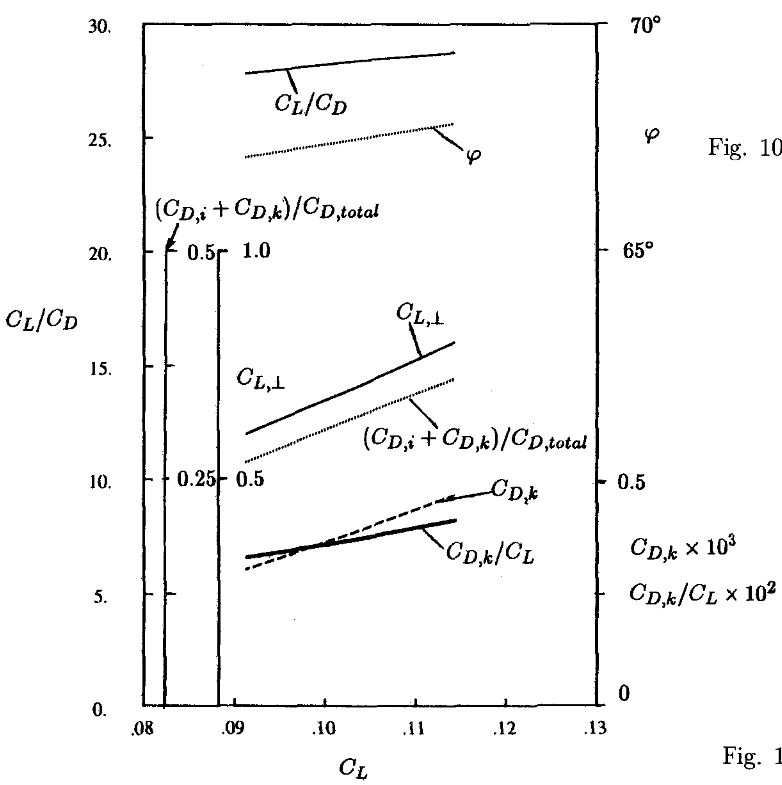


Fig. 8b Variation of $C_{D,i}$, $C_{D,k}$ and $C_{D,i} + C_{D,k}$ versus φ for M_∞=2 arrow wing with upstream wing root extension(structural wing aspect ratio = 30).

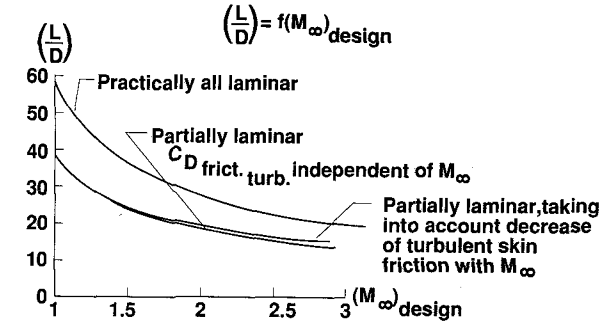


Fig. 9 $(L/D)_{cruise}$ versus $M_{cruise,design}$ for LFC Airplane Configurations of the type #2 with resonably extensive as well as practically all laminar flow over the airplane exposed surfaces.

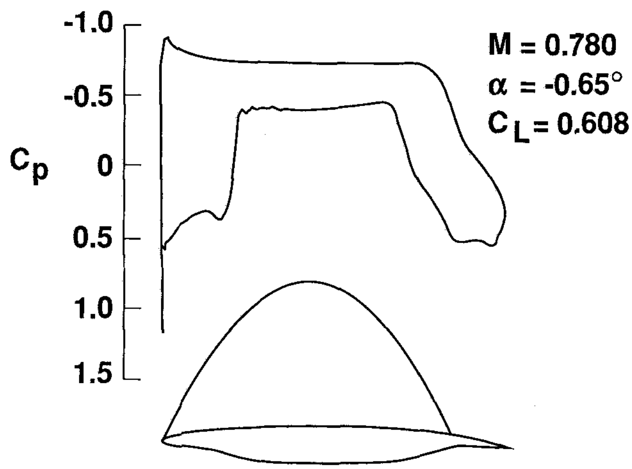


Fig. 10 Design C_p-distribution of the X-66 SC LFC airfoil

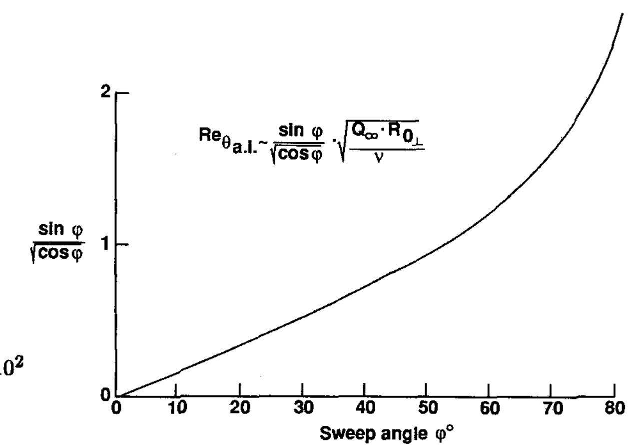


Fig. 11 $sin\ \varphi/\sqrt{cos\ \varphi}$ versus wing sweep angle φ (in connection with attachment line boundary layer instability).

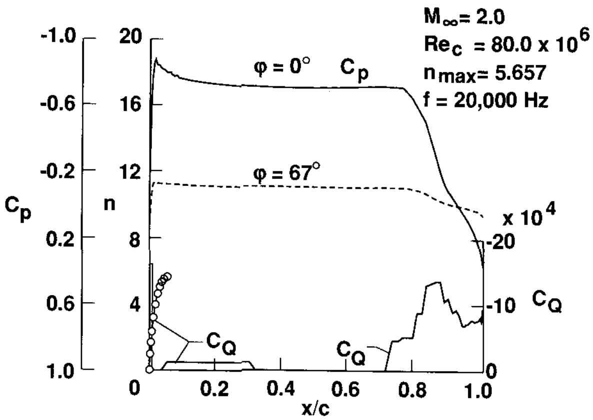


Fig. 12 C_p, C_Q and n_{CF} versus (x/c) in leading edge region of upper surface of 67° yawing X-66 airfoil at M_∞=2, Re_c = 80.0 × 10^6.

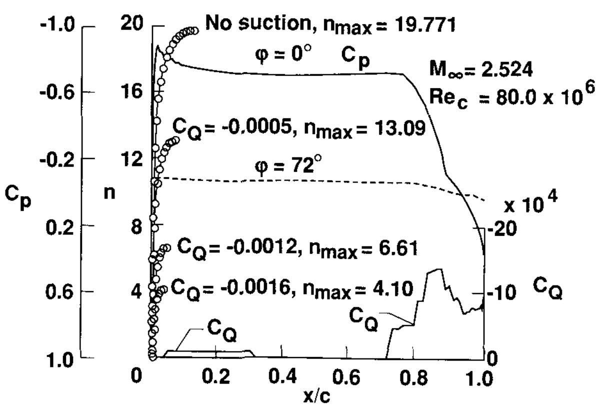


Fig. 13 C_p, C_Q and n_{CF} versus (x/c) in leading edge region of upper surface of 72° yawing X-66 airfoil at M_∞=2.5, Re_c = 80.0 × 10^6.

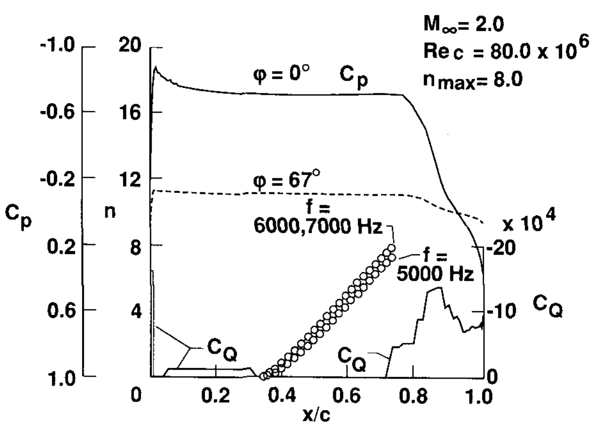


Fig. 14 C_p, C_Q and n_{TS} versus (x/c) in flat rooftop area of upper surface of 67° yawing X-66 airfoil at M_∞=2, Re_c = 80.0 × 10^6.

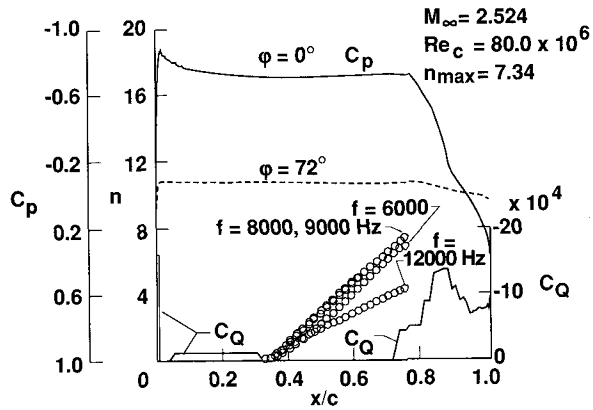


Fig. 15 C_p, C_Q and n_{TS} versus (x/c) in flat rooftop area of upper surface of 72° yawing X-66 airfoil at M_∞=2.5, Re_c = 80.0 × 10^6.

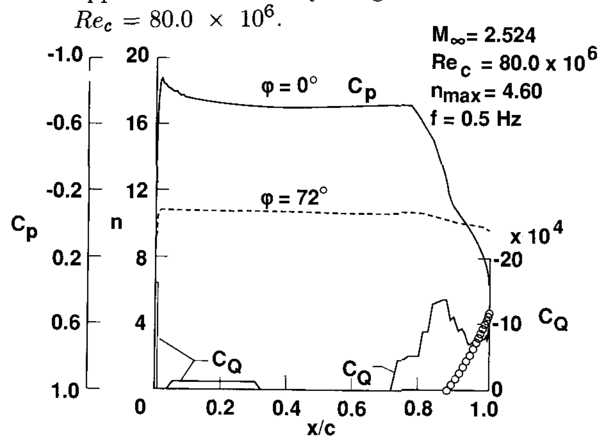


Fig. 16 C_p, C_Q and n_{CF} versus x/c in rear pressure rise area of upper surface of 67° yawing X-66 airfoil at M_∞=2, Re_c = 80.0 × 10^6.

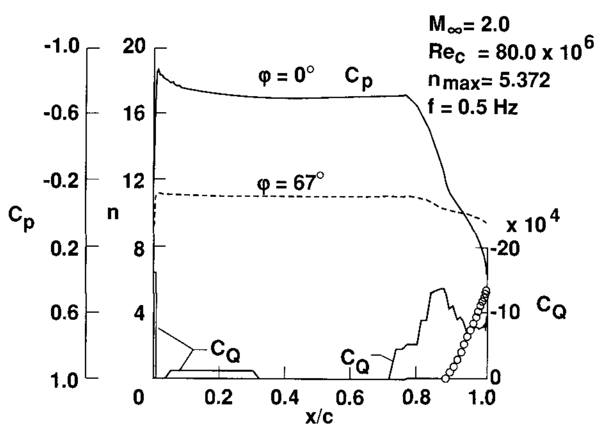


Fig. 17 C_p, C_Q and n_{CF} versus x/c in rear pressure rise area of upper surface of 72° yawing X-66 airfoil at M_∞=2.5,