INLET TECHNOLOGY FOR POWERED-LIFT AIRCRAFT

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SUMMARY

The concepts, analytical tools, and experimental data available for designing inlets for powered-lift airplanes are discussed. It is shown that inlets can be designed to meet noise, distortion, and cruise drag requirements at the flight and engine operating conditions of a powered-lift airplane. The penalty in pressure recovery for achieving the required noise suppression was 0.3 percent.

INTRODUCTION

Discussed in this paper are some of the concepts, analytical tools, and experimental data that form the technology base for designing inlets for powered-lift aircraft. While the objective of the paper is to discuss technology, the QCSEE inlet design problem is used as a focal point of the discussion. Inlets for powered lift differ from conventional subsonic inlets largely because the requirements imposed on them are more stringent. The requirements for the QCSEE (quiet, clean, short-haul experimental engine) inlet are shown in figure 1: (1) The inlet must also provide to the fan a low-distortion airflow at a high pressure recovery. High pressure recovery is more important to a low fan pressure ratio powered-lift engine like QCSEE than the current higher fan pressure ratio engines. Good inlet aerodynamic performance, in general, means no . .al flow separation can occur for any of the flow conditions to which the inlet may be subjected, namely, static conditions, which may set the design of the top region of the lip; a 15-m/sec (30-kn), 90° crosswind, which may set the design of the side of the inlet; and an 41-m/sec (80-kn), 50° upwash, which controls the design of the bottom region of the lip. This last condition greatly exceeds that for conventional aircraft. (2) As discussed in the preceding paper (ref. 1), the inlet must yield greater noise suppression than conventional inlets. This may be achieved by wall treatment, a high throat Mach number, or a combination of these two approaches. (3) The inlet should have low drag. Again, when the powered-lift engines like QCSEE have a lower fan pressure ratio, the fan and, thus, the inlet diameter are relatively large so the inlet drag is a greater fraction of the engine thrust. Designing for a low cruise drag is thus of greater importance. Similarly, when the airplane is climbing out after takeoff, the failure of an engine should not result in excessive drag related to inlet aerodynamics.

SYMBOLS

a/b	lip internal fineness ratio, ratio of ellipse semimajor to semiminor axis
A_h	area circumscribed by inlet highlight
A_m	maximum inlet frontal area
A_0	cross-sectional area of free-stream tube of air entering inlet
CR	contraction ratio
d_f	fan diameter
h	honeycomb backing depth
l	length of inlet
l_a	length of acoustic treatment
M_f	axial Mach number at the fan face
M_{max}	maximum Mach number
M_0	free-stream Mach number
M_t	average throat Mach number
q_t	dynamic pressure corresponding to the average throat Mach number
r_f	fan radius
r_h	radius to the highlight
r_t	throat radius
V_0	free-stream velocity
V_t	average throat velocity
α	inlet flow angle of attack due to upwash
α_{sep}	separation flow angle
ΔP	total pressure loss
υ_{max}	diffuser maximum wall angle
σ	open area ratio
ψ	crosswind flow angle

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stream tube at climbout is larger than the engine inlet. But, if the fan is unpowered due to engine failure, the fan offers a resistance to the flow of air through the nacelle so some of the air spills around the inlet. The streamline pattern then becomes similar to that shown for cruise, and the potential for inlet drag exists in the additive drag on the approaching streamline. The additive drag can be low if the spillage is low. A high throat Mach number inlet tends to reduce the inlet highlight area and this is in the direction of reducing the spillage. Furthermore, the high lip thickness, which was selected to achieve a high upwash angle tolerance, presents a large lip frontal area on which to generate leading edge thrust to offset the additive drag. Thus the high throat Mach number inlet described should have a low engine-out drag.

With regard to the air spillage, feathering the fan blades, as can be done with a variable pitch fan, produces lower resistance to internal flow than a fixed pitch fan and thus reduces the airflow spillage around the inlet lip. Thus, from the point of view of achieving a low engine-out inlet drag, the variable pitch fan may have an advantage over the fixed pitch fan.

An interesting aspect of high throat Mach number inlets not discussed in this paper is throat Mach number control to maintain suppression. This topic is discussed in reference 24.

CONCLUDING REMARKS

Some of the concepts, analytical tools, and experimental data available for designing inlets for powered-lift aircraft have been discussed. It has been shown that inlets can be designed that meet the noise, distortion, and cruise drag requirements at the flight and engine operating conditions that occur for a powered-lift airplane. The penalty in pressure recovery for achieving the required noise suppression was 0.3 percent.

The effect of high flow velocities on wall treatment on noise suppression is one area that can use more detailed study.

There are also some inlet characteristics that remain to be explored such as (1) the effect of the nonaxisymmetric internal boundary layer due to the inlet upwash angle on the fan source noise and on the suppression characteristics of wall treatment and (2) the effect of the inlet upwash angle on the directivity of the noise propagating from the inlet.

It's expected that some of the acoustic technology that has been developed can be applied to quieting current conventional airplanes and that some of the inlet flow analysis methods and data can be applied to the design of high angle of attack inlets for VTOL airplanes such as the inlet for a tilt nacelle and the inlet for a fan in wing or pod.

Boundary-layer properties determined from such analyses (ref. 9) are shown in figure 4. The results are shown for the internal surface of the windward side of the inlet as suggested by the lower sketch.

In the figure the local skin friction coefficient is plotted versus the surface distance from the inlet stagnation point. A zero value for the local friction coefficient indicates separation. Beginning with the zero angle of attack case, the boundary layer, starting at the stagnation point on the inlet lip, is first laminar. In the laminar region the skin friction drops rapidly with increasing surface distance to the first minimum which occurs on the inlet lip. Then, transition from laminar to turbulent boundary layer takes place and the local skin friction increases. Next, in the region of fully developed turbulent flow, the friction coefficient reaches a second minimum part way down the diffuser.

The two minima are locations of potential separation. As the angle of attack is increased from 0 to 20°, the skin friction at the second minimum goes to zero, indicating separation in the inlet diffuser. When the angle of attack is increased to 40°, the diffuser separation moves upstream slightly. At a 50° angle of attack the skin friction at the first minimum has gone to zero, and the separation has jumped to the lip. This, of course, precedes and thus engulfs the diffuser separation.

Flow separation in general depends on such factors as surface roughness, free-stream turbulence, and the size of the inlet. The diffuser separation depends also on the diffuser shape, including the maximum wall angle θ_{max} and the condition of the boundary layer entering the diffuser (ref. 10). The influence of these factors is currently being investigated.

Effect of separation location on total pressure loss. - The location of the flow separation within the inlet affects the amount of total-pressure loss it causes as shown in figure 5 (ref. 9). The ordinate is the total-pressure loss coefficient $\Delta P/q_t$ (where ΔP is equal to 1 minus the pressure recovery and q_t is the dynamic pressure corresponding to the average throat Mach number). The abscissa is again the surface location on the inlet. Note that lip separation causes much larger losses than diffuser separation. Also, large flow distortions are usually associated with lip separation. To emphasize the importance of lip separation, fan blade failures have been observed for a model fan when it was subjected to several repetitions of separated lip flow. Because of its grave consequences, the following discussion deals with lip separation.

Separation Bounds

Returning to figure 4, the angle of attack at which the flow first separates from the lip, 50° in figure 3, is called the lip separation angle. The data of figure 4 are for an inlet at one flow condition (V_0 = 80 kn, M_t = 0.50). The lip separation angle for an inlet can be determined for a wide range of free-stream velocities and throat Mach numbers. The separation angle presented as a function of an appropriate independent variable is called the inlet separation bound.

Local surface Mach numbers less than unity. - Figure 6 considers cases (ref. 11) where the throat Mach numbers are sufficiently low that the flow can be considered incompressible; i.e., the local surface Mach numbers never exceed unity. The results are plotted as separation angle α_{sep} versus throat to free-stream velocity ratio, the parameter suggested in the discussion of figure 3. This plot fairly well collapses the data over the complete angle of attack range from zero to 180°. (Similar results are shown in ref. 12.)

Several of the QCSEE inlet operating conditions are shown in figure 6. As can be seen, the region of primary interest to powered lift is that for separation angles less than 90°. Also, it can be judged by the location of the requirements relative to the separation bound that the 50° flow angle at 80 knots is the more difficult condition; and it is the one that will be used in subsequent examples.

Local surface Mach numbers greater than unity. - The inlet throat Mach number affects the separation bounds as shown in figure 7, which is a plot of separation angle versus throat Mach number (ref. 13). The data are for a constant free-stream velocity of 80 knots so that an increasing throat Mach number corresponds also to increasing V_t/V_0 as indicated by the second abscissa. For values of throat Mach numbers less than about 0.60, the curve is rising and concave upward as were the previous cases for low throat Mach numbers. For higher values of throat Mach number, the local surface Mach number exceeds unity, and the curve becomes concave downward with the separation angle finally decreasing with increasing throat Mach number. This kind of separation is associated with shock - boundary-layer interaction on the lip as depicted in the sketch for $M_{max} > 1.0$ (fig. 7). A more detailed analysis of inlet separation is given in reference 14. The throat Mach number thus has a strong effect on separation angle.

Note that the choking flow limit occurs for an average throat Mach number of less than unity. The reasons for this will be shown shortly.

Effect of lip contraction ratio. - Figure 8, which repeats the coordinate system and data of the previous figure but adds the data for both a larger and smaller inlet contraction ratio (ref. 13), shows the effect of increasing contraction ratio (increasing lip thickness) is to increase the separation angle.

Also shown in the figure is the QCSEE operating region of 50° at 80 knots for airflows (throat Mach numbers) from flight idle to full throttle. A critical condition is that of flight idle at a 50° upwash. The inlet with the 1.37 contraction ratio does not meet the requirements at flight idle or at takeoff; the inlet with a 1.46 contraction ratio satisfied the full range of conditions.

Having defined an inlet that satisfies the condition of no lip separation, we turn next to the subject of noise suppression.

Noise Suppression

Fan noise characteristics. - To understand the acoustic results, it is

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necessary to understand two characteristics of the fan noise listed and illustrated in figure 9, its radial and angular distribution. (1) Radial distribution of intensity: Noise generated by the fan tends to be greatest toward the fan tip or near the duct wall. (2) Acoustic ray directions: As suggested by the sketch, sound waves can have velocity components in the radial and circumferential directions as well as the axial direction. When significant radial and circumferential components exist, the axial component may be considerably less than the speed of sound. These nonaxial components are related to what acousticians call acoustic modes. The propagation of these modes upstream in the inlet duct is influenced by the duct geometry and the flow Mach number.

Suppression methods: Two sound suppression methods are also listed and illustrated in figure 9, acoustic wall treatment, and high throat Mach number. (1) Wall treatment: The sound, as it proceeds up the inlet duct, can be absorbed by wall acoustic treatment. This can be especially effective when the sound is concentrated near the wall as in the case illustrated. (2) High throat Mach number: There are two aspects of this topic to be considered. (a) Because the axial component of the sound wave is generally less than the speed of the sound, a throat Mach number (the ratio of the flow velocity to the speed of sound) less than unity will choke off the propagation of the sound wave out of the inlet. (b) Even for throat Mach numbers significantly less than one, the local Mach numbers near the wall can approach or exceed one as illustrated by the throat Mach number profile in figure 9. This profile is due to the wall curvature in the lip and throat regions. Again, because the noise is concentrated near the wall and has an axial velocity less than the speed of sound, these high local Mach numbers can be very effective in reducing the noise.

As was seen in figure 7, the choking weight flow limit is less than that corresponding to an average throat Mach number of unity. The nonuniform velocity profile across the throat plane shown in figure 9 is the reason for this. An average throat Mach number of unity can occur only for a uniform throat velocity profile.

Inlet acoustic performance: The acoustic performance of two inlets is shown in figure 10. Although the data of figure 10 are new, some of the results are similar to those that may be found in references 15 to 22. The plot shows the reduction in sound pressure level (SPL) of the source noise in the one-third octave band, containing the blade-passage frequency (BPF). This is plotted versus the average throat Mach number. The lower curve is for a hard wall or untreated inlet. Noise suppression starts at a throat Mach number of about 0.60. The suppression then increases rapidly with increasing throat Mach number. The suppression starts at such a low throat Mach number because of the source noise characteristics and throat Mach number profile previously described. If the noise source had been a simple plane wave normal to the inlet axis and if the throat velocity profile had been flat, little or no suppression would have occurred until the average throat Mach number was unity, and at that condition the noise would have been choked off abruptly.

The upper curve is for an inlet with the same geometry as the hard wall inlet but with the walls acoustically treated with honeycomb covered by a perforated plate as illustrated in figure 9. The honeycomb has a backing depth h

of 1.5 percent of the fan diameter, and the ace plate has a 6.2 percent open area. An 8- to 9-dB suppression results at the lower throat Mach numbers. The incremental suppression contributed by the treated wall decreases when the throat Mach numbers become high enough to also cause suppression. The reduced effectiveness of the treatment may be due to the higher velocities over its surface. This is an area as yet not fully understood. Acoustic results similar to those shown have also been obtained at static conditions for a model of the QCSEE inlet.

Shown on the ordinate are the QCSEE inlet suppression requirements, in decibels, of perceived noise level, PNdB. The ΔPNdB and ΔSPL are about the same if the source noise has a dominant fan tone as is the case here. The approach noise suppression of 8 PNdB, which is required at the lower throat Mach numbers that will occur during this maneuver, can be achieved by the wall treatment alone. The 13 PNdB required for takeoff can be achieved at a high throat Mach number for the hard wall inlet, or by the treated wall inlet at a slightly lower throat Mach number.

Inlet aerodynamic performance. - The pressure recovery for the same two inlets is shown versus the average throat Mach number in figure 11. In general, the pressure recovery decreases with increasing throat Mach number. For Mach numbers below 0.7 this is primarily a friction loss as suggested by the fact that the dashed curve, representing a constant total-pressure loss coefficient $\Delta P/q_t$, fits the data. The combination of the physical roughness associated with the porosity of the treated wall and the "pumping" in and out due to the noise causes the effective wall friction of the treated wall to be about 8 percent more than the hard wall. Large total-pressure losses occur precipitously near the choking flow limit. These large losses occur at a lower throat Mach number for the treated inlet. The inlet is entering supercritical operation here. The losses are associated with the occurrence of a region of local supersonic flow and weak shocks which produce a rapid growth in the boundary-layer thickness. The measured boundary-layer profiles, however, indicate that flow separation has not yet occurred for any of the data points in the figure.

The curves are labeled to show where 13-dB suppression is obtained. The treated inlet shows a small advantage in pressure recovery over the hard wall inlet to achieve the required suppression. The higher pressure recovery is 0.990. If no noise suppression had been required, a hard wall inlet could have been designed with a throat Mach number of perhaps 0.6, where the pressure recovery is 0.993. Thus, 0.3 percent pressure recovery loss is chargeable to achieving the required inlet noise suppression using a high throat Mach number inlet with acoustic wall treatment. This corresponds to less than 1.0 percent loss in takeoff thrust for an engine like QCSEE with a 1.27 fan pressure ratio at takeoff.

The results shown are for zero angle of attack. The effect of angle of attack on the aeroacoustic performance of treated wall inlets remain to be determined.

Thus far we've discussed the procedure for selecting an inlet design to avoid separation and to achieve the desired noise suppression. We turn finally to considerations of the inlet drag.

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Inlet Drag

Cruise drag. - As shown in figure 12, there are three potential sources of drag to be considered: additive drag, pressure drag, and friction drag. The additive drag on the streamline approaching the inlet will be cancelled by the lip suction thrust if the external frontal area of the inlet $A_m - A_h$ is an appropriate fraction of the spillage frontal area $A_h - A_0$ as discussed in reference 23, for example. Pressure drag can be reduced by shaping the external contour to avoid shock-boundary layer interaction at cruise speed. In the case of QCSEE the cruise Mach number is 0.72. At this Mach number the additive and pressure drags can be made essentially zero by proper design.

The friction drag is unavoidable and depends on the inlet wetted area and hence its length and diameter. For powered-lift inlets that require a high degree of suppression like the QCSEE inlet, a significant factor in determining the inlet length is the length of acoustic treatment required. Also, this treatment must be in a region of local Mach number low enough to be acoustically effective. The lip and throat region then add to the length. The required treatment length makes the diffuser wall angles small enough to prevent diffuser separation due to a high θ_{max} from being a problem. For the QCSEE inlet, the total length to fan diameter ratio turns out to be about one.

The maximum diameter of the inlet is determined by a sequence of factors that are only briefly reviewed here: the fan annulus area, the flow rate through the fan (the fan face Mach number), the throat Mach number for noise suppression, the contraction ratio for the 50° upwash, and the external lip thickness determined to avoid additive drag.

For the QCSEE inlet it was found that the lip shape selected to meet the most difficult flow condition, i.e., an 80-knot, 50° upwash at flight idle, could be applied all around the inlet and still result in a nacelle thickness over the fan that is only 10 percent of the fan radius. This thickness is also about the minimum required for the nacelle structure. With a circumferentially uniform lip the entire inlet can be built axisymmetrically. This has the advantage of simplicity. Because the lip was designed for the most difficult flow condition, the less difficult conditions, like the crosswind requirements, are automatically satisfied. An inlet like the one shown is thus a low-cruise-drag inlet that meets all the noise and flight requirements that have been specified.

An important overall observation is that the high throat Mach number desired for noise suppression is consistent with the thick lip that is desired for high upwash angle tolerance and a thin nacelle thickness over the fan for low cruise drag. In contrast, an inlet designed for a throat Mach number of 0.6 would have had a larger maximum diameter and would not have met the noise suppression requirements.

Engine-out drag. - It is desirable to maintain a low engine drag in event of an engine failure during climbout following takeoff because this helps maintain a safe climb angle and minimizes undesirable rolling and yawing moments. The fan, when it is powered, sucks air into the inlet so that capture

stream tube at climbout is larger than the engine inlet. But, if the fan is unpowered due to engine failure, the fan offers a resistance to the flow of air through the nacelle so some of the air spills around the inlet. The streamline pattern then becomes similar to that shown for cruise, and the potential for inlet drag exists in the additive drag on the approaching streamline. The additive drag can be low if the spillage is low. A high throat Mach number inlet tends to reduce the inlet highlight area and this is in the direction of reducing the spillage. Furthermore, the high lip thickness, which was selected to achieve a high upwash angle tolerance, presents a large lip frontal area on which to generate leading edge thrust to offset the additive drag. Thus the high throat Mach number inlet described should have a low engine-out drag.

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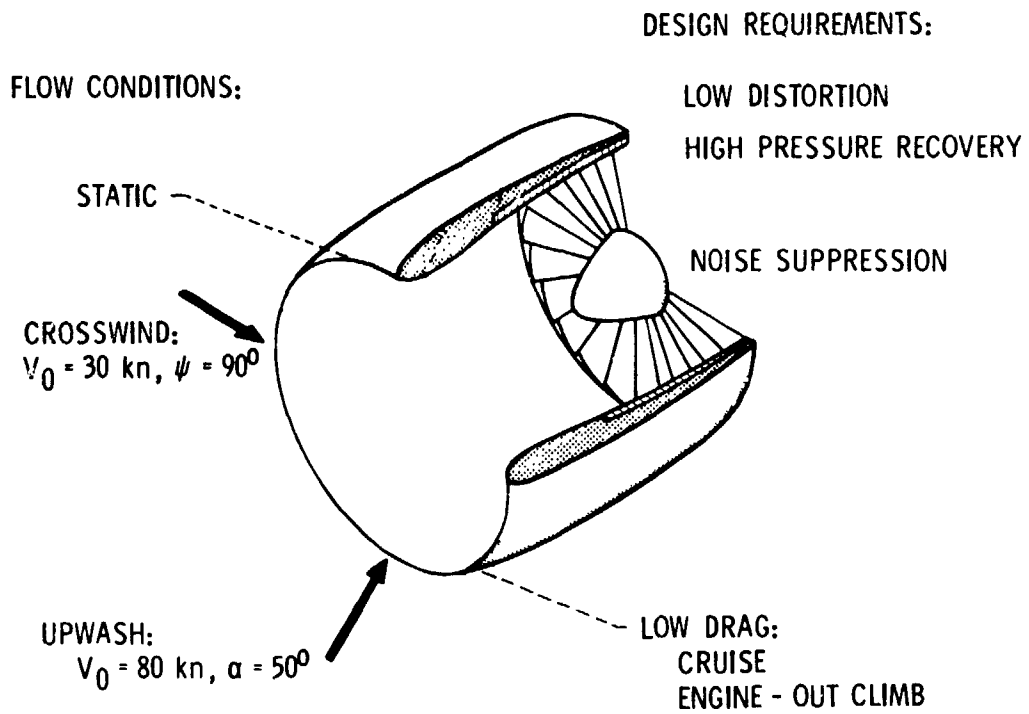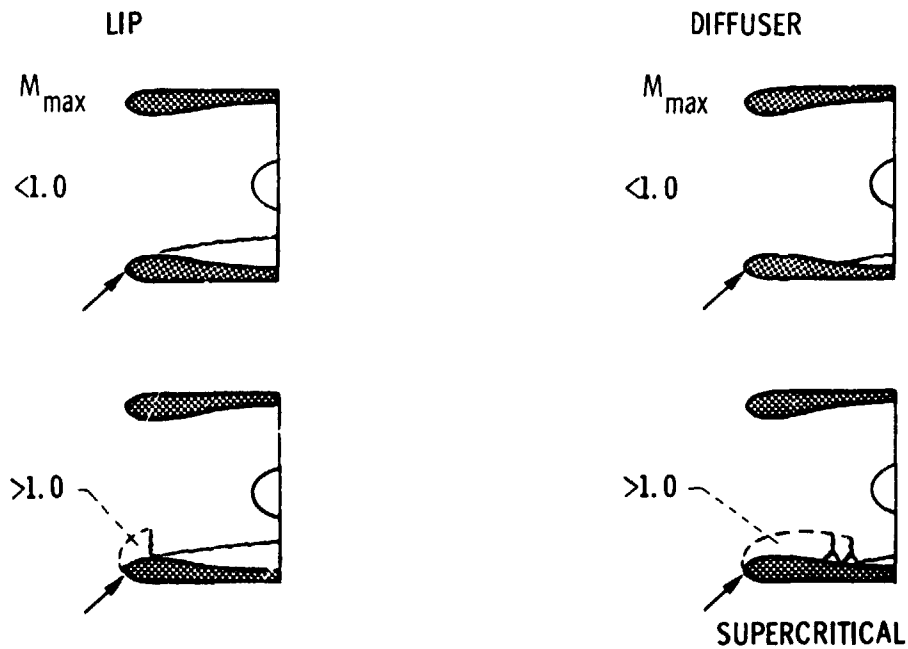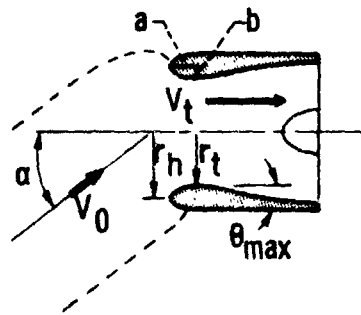
FLOW CONDITIONS:

DESIGN REQUIREMENTS:

LOW DISTORTION

HIGH PRESSURE RECOVERY

STATIC —

NOISE SUPPRESSION

CROSSWIND:
$V_0 = 30$ kn, $\psi = 90^0$

UPWASH:
$V_0 = 80$ kn, $\alpha = 50^0$

LOW DRAG:
CRUISE
ENGINE - OUT CLIMB

Figure 1.- QCSEE inlet requirements.

LIP

DIFFUSER

M_{max}

M_{max}

<1.0

<1.0

>1.0

>1.0

SUPERCRITICAL

Figure 2.- Kinds of separation.

GEOMETRIC	FLOW
a/b	α
θ_{max}	M_t
$CR \equiv (r_h/r_t)^2$	V_t/V_0

Figure 3.- Separation parameters.

SEPARATION INDICATOR, LOCAL SKIN FRICTION COEFF

STAGNATION POINT — LIP   DIFFUSER
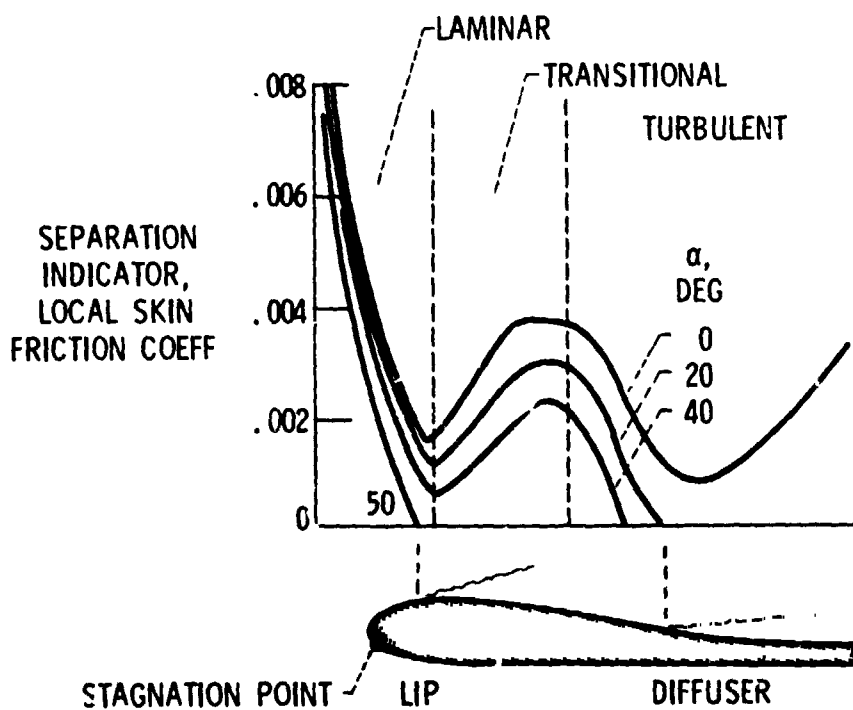
Figure 4.- Boundary-layer analysis of inlet separation.
$V_0 = 80$ kn; $M_t = 0.50$.
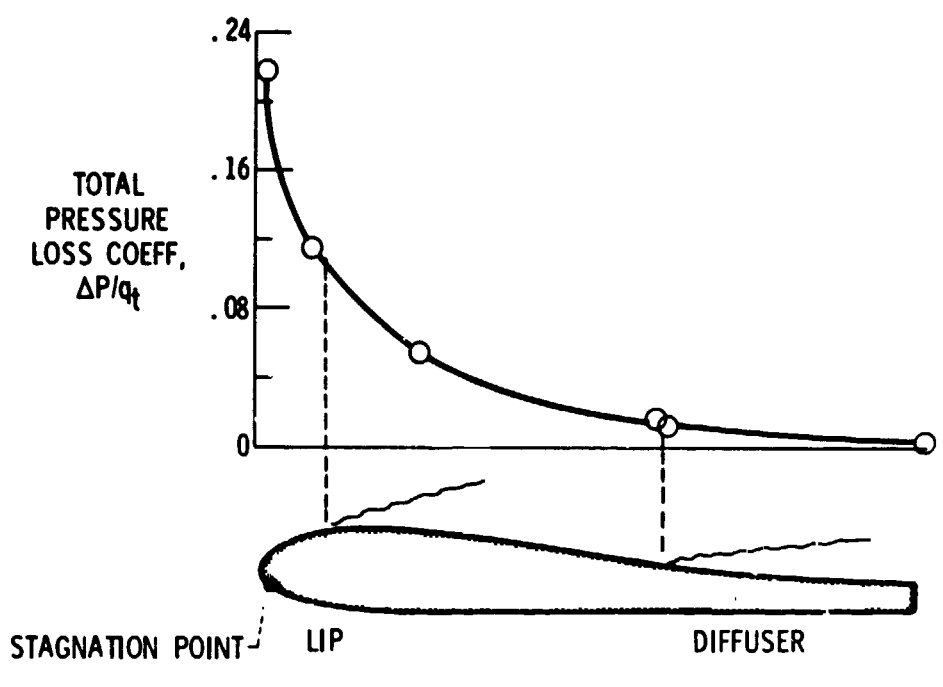
Figure 5.- The variation of inlet total-pressure loss with separation location.
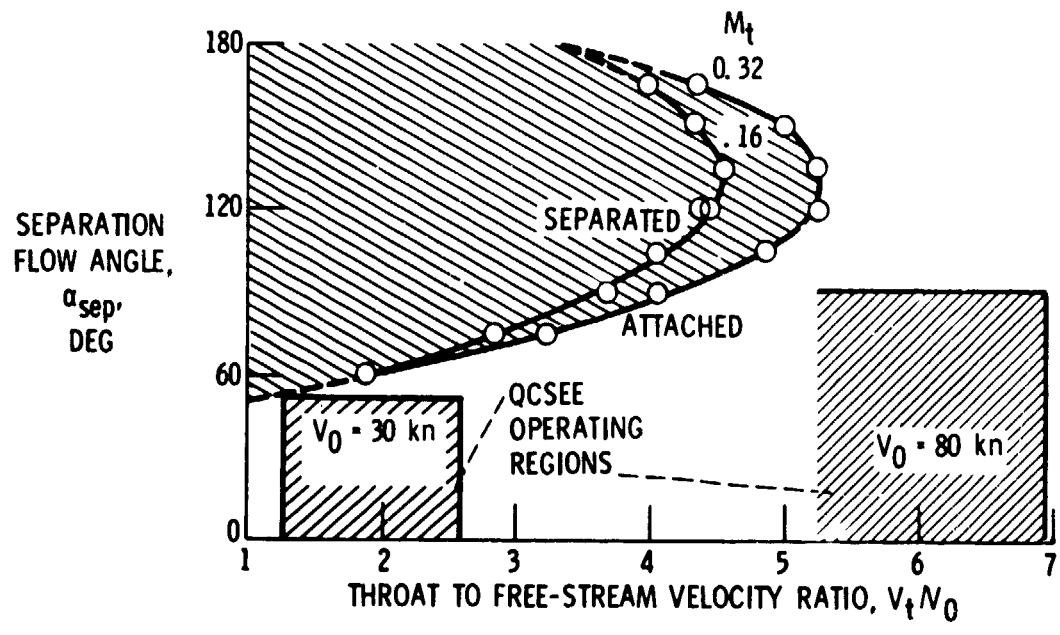
Figure 6.- Lip separation bound, $M_{max} < 1$. CR = 1.30.
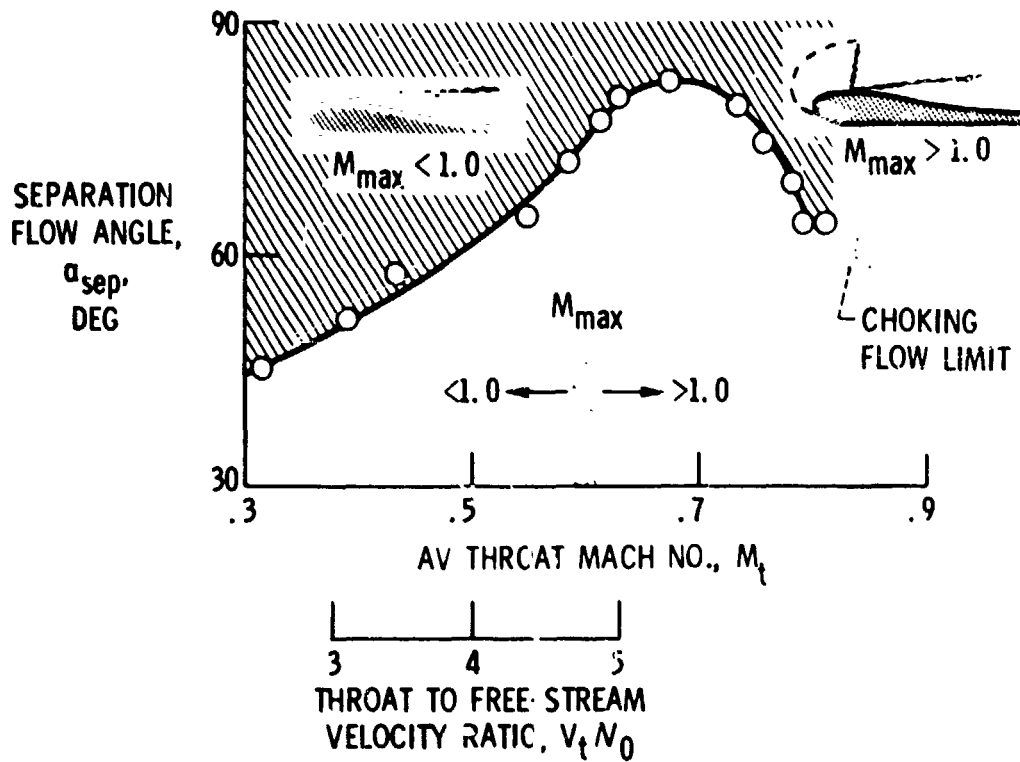
Figure 7.- Lip separation bound.   CR = 1.46; V_0 = 80 kn.
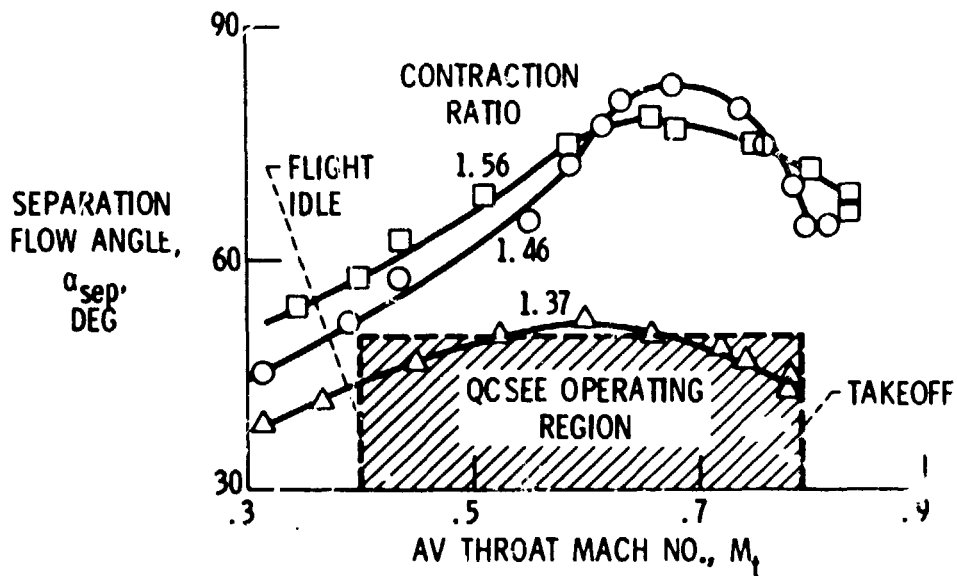
Figure 8.- The effect of contraction ratio on lip separation bounds.
V_0 = 80 kn.

SUPPRESSION METHODS:
ACOUSTIC WALL TREATMENT
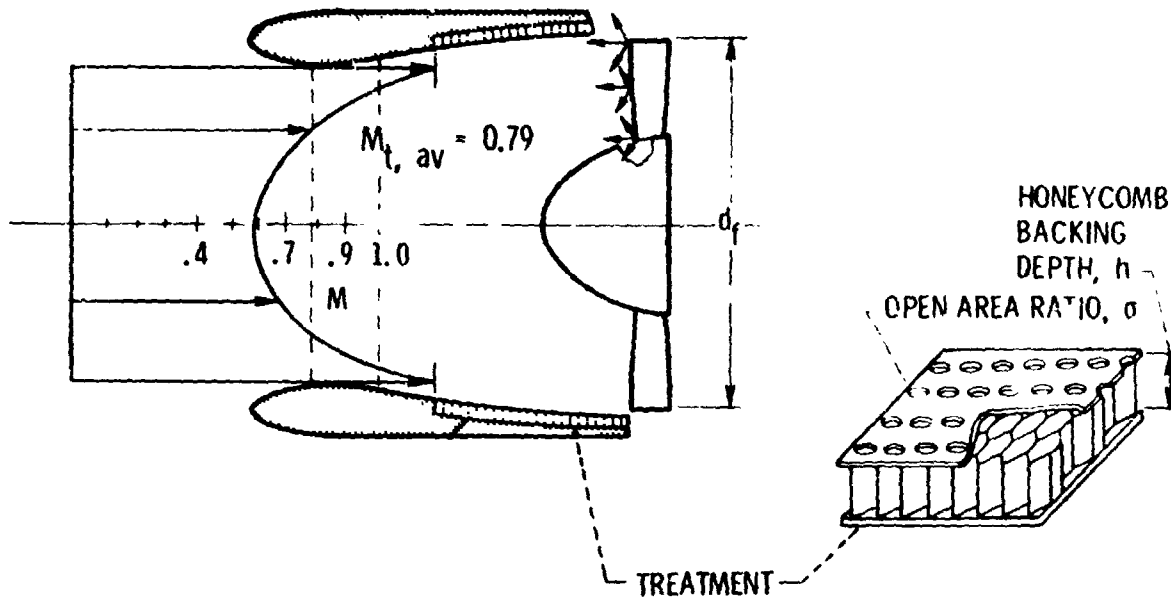HIGH THROAT MACH NO.

FAN NOISE DISTRIBUTION:
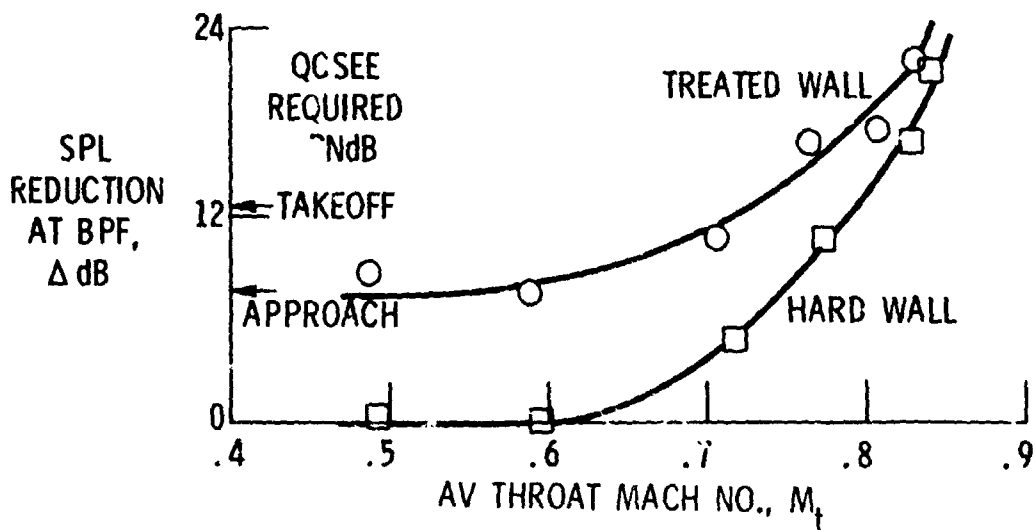RADIAL
ANGULAR

Figure 9.- Inlet noise suppression concepts.

Figure 10.- Inlet acoustic performance. $CR = 1.34$; $l_a/d_f = 0.83$;
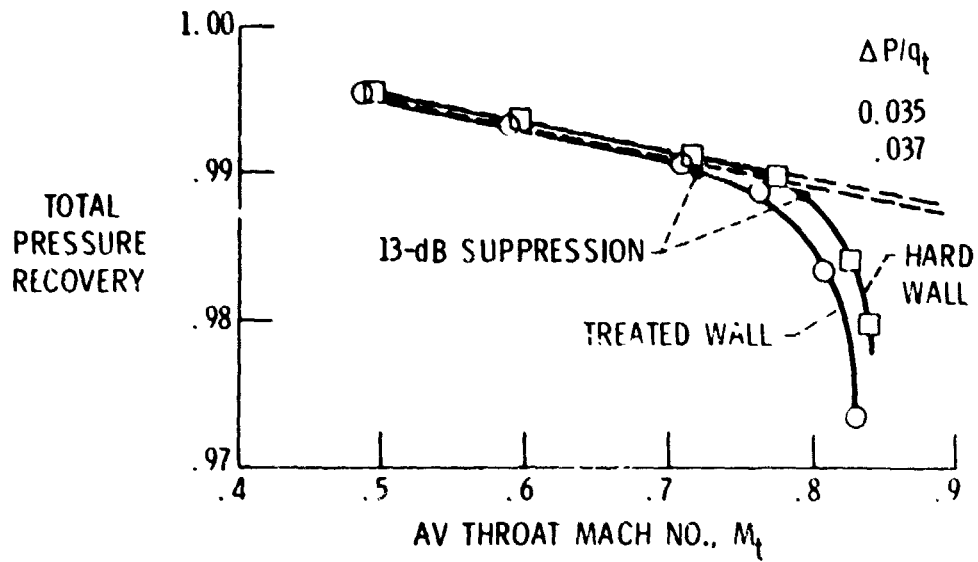$\sigma = 6.2\%$; $h/d_f = 1.5\%$; $V_0 = 80$ kn; $\alpha = 0^o$.

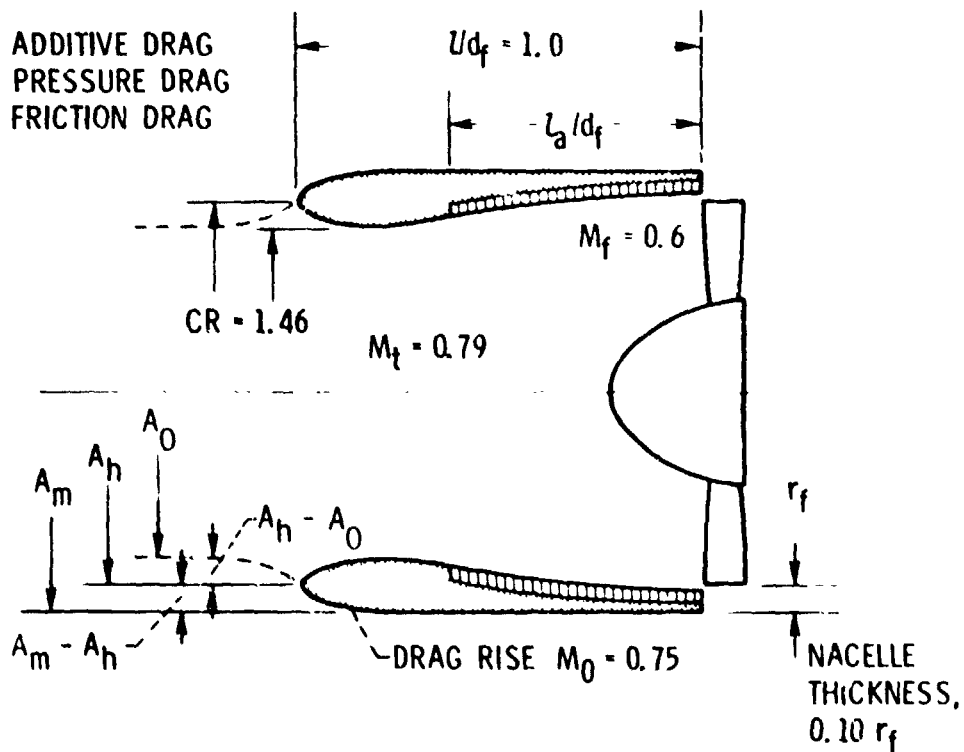Figure 11.- Inlet aerodynamic performance. $CR = 1.34$; $l_a/d_f = 0.83$; $\sigma = 6.2\%$; $h/d_f = 1.5\%$; $V_0 = 80$ kn; $\alpha = 0^\circ$.

Figure 12.- Inlet drag considerations.