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RECENT APPLICATIONS OF THEORETICAL ANALYSIS TO V/STOL INLET DESIGN

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ABSTRACT

The theoretical analysis methods, potential flow, and boundary layer, used at Lewis are briefly described. Recent application to Navy V/STOL aircraft, both fixed and tilt nacelle configurations, are presented. A new three-dimensional inlet analysis computer program will be described and preliminary results presented. Finally, a suggested approach to optimum design of inlets for high angle-of-attack operation is discussed.

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INTRODUCTION

Current configurations being considered for subsonic V/STOL aircraft give rise to a variety of problem areas for the propulsion system inlets, for example, high angle-of-attack, extremely short inlets, wide range of operating conditions, and three-dimensional geometries. A rational evaluation of the viability of the proposed configurations requires analytical tools capable of investigating specific problems associated with the inlets and other components of the various configurations. One such analytical tool is the Lewis method for analyzing the potential and viscous flow in subsonic inlets. The axisymmetric version of this method (documented in refs. 1 and 2) has been successfully applied to various aspects of V/STOL inlet design and analysis over the past several years (refs. 3 to 7). The more recent two-dimensional version of the method for potential flow is documented in reference 8 and applied to V/STOL inlets and nozzles in reference 9. The new three-dimensional version is described in reference 10 and documented in reference 11.

This paper will present a brief description of the axisymmetric potential flow and boundary layer analysis methods. Then application of this method to inlet problems arising from both tilt-nacelle and fixed-nacelle V/STOL aircraft configurations will be illustrated. Next, the new three-dimensional inlet potential flow analysis will be described and preliminary results will be presented. Finally, an approach to the design of optimum subsonic inlets will be suggested.

SYMBOLS

A	area
a	speed of sound
C_f	skin friction coefficient
D	fan diameter
ℓ	inlet length
M	Mach number
m_b	boundary-layer bleed mass flow rate
S	surface distance
V	velocity
$\dot{W}$	inlet mass flow rate
α	inlet incidence angle (angle of attack)
β	inlet yaw angle

δ^*	boundary-layer displacement thickness
θ	circumferential coordinate
ρ	density

Subscripts:

cor	corrected for local supersonic flow
de	diffuser exit
i	incompressible
s	static conditions
T	throat
t	total (stagnation) conditions
tip	fan tip
0 ∞	free stream
*	critical conditions (i.e., at Mach 1)

AXISYMMETRIC ANALYSIS METHOD

The basic problem to be solved is to calculate the compressible potential and, when desired, the viscous flow in an arbitrary axisymmetric inlet at any combination of operating conditions of inlet mass flow rate, $\dot{W}$, free-stream velocity V_∞, and inlet incidence angle, α (fig. 1). At nonzero incidence angle the flow in and around the inlet is three-dimensional. At the present time there is no exact practical compressible viscous flow method of solution (computer program) capable of handling this inlet problem. Therefore, the problem is solved in several steps (fig. 1) as follows:

1. Geometry representation
2. Incompressible potential flow basic solutions
3. Combined solutions with compressibility correction
4. Boundary layer calculations

Geometry

The inlet is assumed to be axisymmetric and is represented by its meridional profile. This profile is broken into segments at convenient tangent points as shown in figure 1.

The geometry program prepares coordinate-point input for efficient use of the potential flow program.

Potential Flow

The Douglas-Neumann program (refs. 12 and 13) is used for calculating the incompressible potential flow in the form of three independent basic solutions: a static solution ($V_\infty = 0$), an axisymmetric streamflow solution ($V_\infty \neq 0,\ \alpha = 0$) and a pure crossflow (or angle of attack) solution ($V_\infty \neq 0,\ \alpha = 90^\circ$). These three basic solutions are combined into a solution of interest having arbitrary flow conditions of V_∞, α, and mass flow W (fig. 1). Thus, once the basic flow solutions are obtained for a specified geometry, any solution of interest for that geometry can be obtained without repeating the more time-consuming potential flow calculations.

The velocity obtained by the linear combination is incompressible and is corrected for compressibility by the Lieblein-Stockman compressibility correction (ref. 13).

$$V = V_i\left(\frac{\rho_t}{\bar{\rho}_s}\right)^{V_i/\bar{V}_i} \tag{1}$$

where all the terms on the right hand side are obtained from the incompressible flow solution or the input flow conditions. This correction requires no alteration of the inlet geometry and it can handle local sonic and supersonic velocities. If the local velocity is supersonic it is further corrected (since it is, in effect, based on the wrong relation between area and velocity) by the following empirical formula

$$V_{cor} = a_*\left[1 + \left(\frac{V}{a_*} - 1\right)^{\frac{\sqrt{1.2}}{A_*/A}}\right] \tag{2}$$

where V_{cor} is the corrected supersonic velocity; V is the supersonic velocity obtained from equation (1); a_* is the critical velocity (i.e., the velocity at Mach 1); and A_*/A is the sonic-to-local area ratio and can be obtained from

$$\frac{A_*}{A} = \frac{V}{a_*}\left[1.2 - 0.2\left(\frac{V}{a_*}\right)^2\right]^{2.5} \tag{3}$$

Boundary Layer

In cases where the boundary layer behavior is required the surface Mach number distributions obtained from the potential flow solution are used as input to the Herring-Mellor axisymmetric compressible boundary layer program. Reference 2 contains a complete documentation of the boundary layer program and references to the original sources. The program calculates boundary layer profiles, displacement thickness δ^*, skin friction coefficient C_f, etc., at each station, and also predicts transition from laminar to turbulent flow. Separation (whether laminar or turbulent) is predicted when C_f is zero. The boundary layer calculation can handle bleed, as will be illustrated later, and is currently being revised to handle tangential blowing.

In cases where the boundary layer is relatively thick the accuracy of both the potential flow and the boundary layer calculations can be improved by adding the displacement thickness δ^* to the geometry and repeating all the calculations. The greatest improvement in accuracy will be seen in the diffuser. Some users have automated the δ^* addition including an iterative loop, adding a new δ^* each iteration until satisfactory convergence is attained.

A common use of the boundary layer calculation is to obtain inlet separation bounds. A separation bound is a plot of angle of attack at incipient separation versus the ratio of throat-to-free-stream velocity. To facilitate finding the separation bound the combination routine and the boundary layer routine have been combined and an automatic α sweep incorporated. Thus, for a given V_T and V_0 the α at incipient separation can be found in one computer run.

Comparison with Experiment

To indicate the accuracy of the method of obtaining the compressible potential flow a comparison of the analysis with experiment is given in figure 2. There it can be seen that the agreement is quite good even in the region of supersonic flow. Although the agreement is not always this good, this is a typical case. Several additional comparisons are given in reference 4.

APPLICATIONS TO SUBSONIC V/STOL AIRCRAFT

Two types of aircraft currently under consideration for subsonic V/STOL missions are the fixed-nacelle deflected thrust configuration and the tilt nacelle configuration. The analysis method will be applied to two inlet problems arising from each of these configurations.

Fixed Nacelle

A possible fixed nacelle configuration is shown in figure 3. The problems to be addressed herein (taken from ref. 14) are related to the shortness of the fixed nacelle inlet. The combined requirements of engine location and pilot visibility lead to the need for very short inlets.

Short inlets usually have no diffuser, thus the fan face is at the throat and the throat Mach number is lower than for a conventional inlet. The lower throat Mach number is unfavorable for cruise since it requires a larger throat diameter which tends to result in larger nacelle maximum diameter. To reduce the needed maximum diameter the inlet lip must be made thinner. In brief, short inlets tend to need thin inlet lips.

Short, thin inlets give rise to two problems that will be discussed: thin inlet lips have higher peak surface velocities on the lip at low speed conditions than inlets with thicker lips and short inlets have greater velocity and flow angle distortion at the fan face at angle of attack than longer inlets.

Inlet Lip Peak Velocity. - The higher peak surface velocities on a thin inlet lip increase the probability of boundary layer separation. Therefore it is worthwhile to try to reduce these peak velocities. The peak velocities are higher because the reduced lip surface area of the short thin inlet requires a higher loading (i.e., a lower pressure) to turn the flow into the inlet. This high loading, and thus the peak velocity, can be reduced by providing additional lip surface area. This additional area can be obtained without an increase in overall inlet thickness by inserting a slot in the inlet cowl which in effect creates an additional lip as shown in figure 4. The geometry inset of figure 4 shows both the original unslotted short inlet lip and the same lip slotted.

The potential flow calculations have been used to determine the velocity distributions on both the slotted and unslotted inlets (fig. 4). Since the slot is a flow passage a new flow condition in addition to $\dot{W}$, V_∞, and α must be specified to obtain a practical solution. For the case shown on figure 4 which is a static case (i.e., $V_\infty = 0$) the additional condition was the Kutta condition prescribed at the trailing (lower) edge of the slat (B on fig. 4). The results of figure 4 show that the peak velocity of the unslotted lip can be reduced significantly by the use of the slot. It was assumed that the lowest peaks on the slat and main lip would occur when those peaks were equal; therefore the goal in the design procedure was to obtain equal peaks as seen on figure 4.

The potential flow program has been used to investigate the effect of slot and slat variables such as slot area distribution and slat wall contour in order to arrive at promising designs. Several such designs have been built and will be tested in the Lewis 9×15 low speed wind tunnel.

Fan Blade Incidence Angle. - Another problem with short inlets is that there is not sufficient length to smooth out circumferential velocity and flow angle gradients induced by inlet angle of attack. These circumferential gradients produce changes in fan blade incidence and, hence, fluctuating loads on the rotating fan blades. The variation of fan blade incidence might limit the allowable range of thrust modulation and the fluctuating loads might produce intolerable fan blade stress. In either case, it is desirable to predict the change in fan blade incidence as an aid in short inlet design. The potential flow analysis has been used to predict the change in blade incidence for short inlets of two different lengths and the results are shown for the blade tip on figure 5. It can be seen that incidence variations reach ±4° for an inlet length to diameter ratio $\ell/D = 0.05$. Variations that large are probably intolerable. The effect of increasing inlet length to $\ell/D = 0.25$ is also shown in figure 5. The flow angle variation has been reduced to ±1.5°, a more acceptable range. The distortion shown on figure 5 is for an angle of attack of 45° and a V_∞ of 35 knots. The distortion will be lower at lower angle of attack and/or lower V_∞.

Tilt Nacelle

Another approach to subsonic V/STOL is the tilt nacelle. A tilt nacelle airplane in the approach configuration is shown in figure 6. As can be seen the inlet is exposed to very high angles of attack. Two problems associated with high angle of attack will be discussed: wake ingestion from the leeward side of the inlet and control of internal flow separation on the windward side by boundary layer bleed.

Wake Ingestion. - In a recent wind tunnel test of a tilt nacelle inlet unanticipated high fan blade stresses were measured at high angle of attack and very low free-stream velocity. Usually fan blade stress is a minimum at a low free-stream velocity. It was conjectured that the inlet was ingesting vorticity shed from the leeward side of the inlet. This conjecture was qualitatively verified by flow-visualization tests of a simple inlet model in a small wind tunnel.

To get a quantitative feel for the phenomenon, flow fields were obtained from the potential flow program. Some three-dimensional streamlines are shown on figure 7 for a throat-to-free-stream velocity ratio of 10 and an inlet angle of attack of 90°. It can be clearly seen that the rear stagnation point is off the body and that flow ingestion from the rear (leeward) side of the inlet occurs. If the free-stream velocity is high enough to produce a wake, that wake will probably be ingested. Further calculation indicates that as V_T/V_0 decreases, the stagnation point moves toward the body and for this inlet occurs on the body at a V_T/V_0 of about 5.1. Thus for a given inlet geometry a range of flow conditions over which rear wake ingestion is likely to occur could be determined.

Boundary Layer Bleed. - Internal boundary layer separation on the windward side of this inlet is another problem arising in a tilt nacelle inlet. If changing the inlet geometry is prevented by other constraints (e.g., cruise requirements) then it may be necessary to control the boundary layer to prevent separation. One method of control is to bleed off part of the boundary layer. This bleeding can be handled by the boundary layer calculations and an example is shown in figure 8. There the skin friction distribution on the internal surface of the windward cowl is shown. When the skin friction becomes zero, the boundary layer separates as shown for the no bleed case. The bleed curve shows that a relatively small amount of bleed can "control" the boundary layer and prevent separation. In this case, the bleed extended circumferentially over 120°. The circumferential extent of bleed required can be estimated by comparing the circumferential distribution of the diffusion velocity ratio with the diffusion limit as shown in the inset.

THREE-DIMENSIONAL INLET ANALYSIS

Many inlets proposed for subsonic V/STOL aircraft are fully three-dimensional as opposed to axisymmetric. Most of these cannot adequately be analyzed with an axisymmetric program. An example is the scoop inlet shown on figure 9. Other examples are curved centerline (S-duct) inlets, nonround inlets, inlets with canted highlight plans. Therefore a three-dimensional inlet program was recently acquired under contract (ref. 10).

The three-dimensional method is essentially the same as the axisymmetric method previously described. Four basic flow solutions are obtained (instead of three) since a solution of interest now consists of four conditions: inlet mass flow, free-stream velocity, angle of attack, and angle of yaw.

Preliminary results for a rather coarse paneling are shown on figure 10 for the scoop inlet. The scoop inlet was originally conceived as a noise suppression device. However, wind tunnel tests (ref. 17) indicated improved angle-of-attack performance over a baseline inlet of the same lip shape. The reason for the improvement can be seen on the pressure plots of figure 10. The windward lip ($\theta = 0^{\circ}$) is less highly loaded than the leeward lip ($\theta = 180^{\circ}$). Thus at 0° angle of attack the inlet is effectively operating at a negative angle of attack giving a greater angle-of-attack margin than a nonscoop inlet having the same lip shape.

These examples are just a few of many current investigations using the potential flow and boundary layer programs. Next a method of using the program to design optimum inlets will be discussed.

OPTIMUM INLET DESIGN

In reference 15 a method is proposed for obtaining the optimum internal lip and diffuser wall shape for subsonic inlets that must operate under a variety of flow conditions. Briefly, the method consists of comparing inlet operating requirements with estimated inlet separation characteristics to identify the most critical inlet operating condition. This critical condition is taken to be the design point and is defined by the values of inlet mass flow, free-stream velocity, and inlet angle of attack. An optimum inlet design is then obtained at the design point flow condition. By an optimum inlet is meant the shortest, thinnest, most efficient inlet with attached flow that satisfies the operating requirements.

In reference 15 the approach to optimizing the inlet is to optimize the flow distributions over the inlet surfaces. The optimum flow distribution recommended are a high flat top velocity distribution on the inlet lip to turn the flow quickly into the inlet and a low, flat bottom skin friction distribution on the diffuser wall to diffuse the flow rapidly and efficiently to the velocity required at the fan face. Sample optimum flow distributions are shown on figure 11. The limit on peak velocity marked on figure 11(b) is the empirical Mach number or diffusion limit for separation-free operation (ref. 16). A safety margin is recommended below the flat roof top velocity and the limit. The lower limit on skin friction (fig. 11(c)) is, of course, zero and a safety margin is recommended here also. The safety margins allow for inaccuracies in the calculation and unanticipated operating excursions. Refinements to the recommended optimum distributions and extension of the optimum design method are discussed in reference 15.

CONCLUDING REMARKS

The theoretical analysis methods, potential flow, and boundary layer, used at Lewis have been described. Recent application to subsonic V/STOL aircraft, both fixed- and tilt-nacelle configurations have been presented. A recently-suggested approach to optimum inlet design has been discussed. A new three-dimensional inlet analysis computer program has been described and preliminary results presented.

The computer programs for axisymmetric geometries have proved useful for many years and, in fact, have already exceeded their initially-expected period of usefulness. The three-dimensional version is expected to be equally long-lived. Even when three-dimensional exact compressible-flow programs become available the approximate programs will still be used for many calculations, especially preliminary screening, because of their computational efficiency and relative ease of use.

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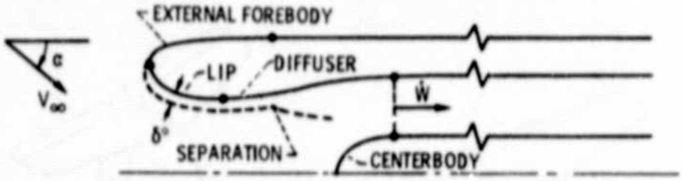

GEOMETRY REPRESENTATION
INCOMPRESSIBLE POTENTIAL FLOW
COMPRESSIBILITY CORRECTION
BOUNDARY LAYER CALCULATIONS
PROFILES, δ*, ETC., TRANSITION, SEPARATION

Figure 1. - Axisymmetric inlet analysis.

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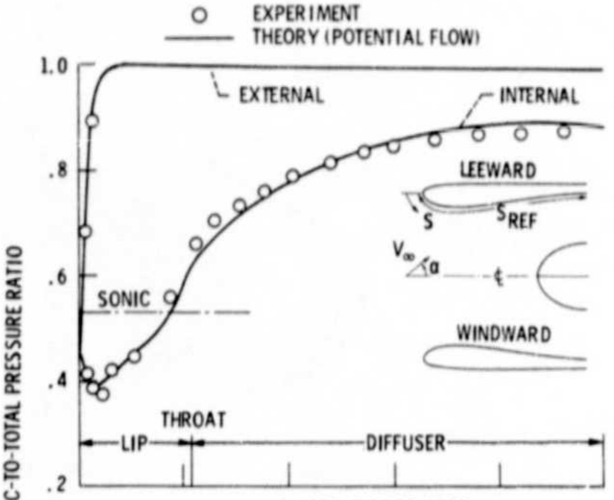
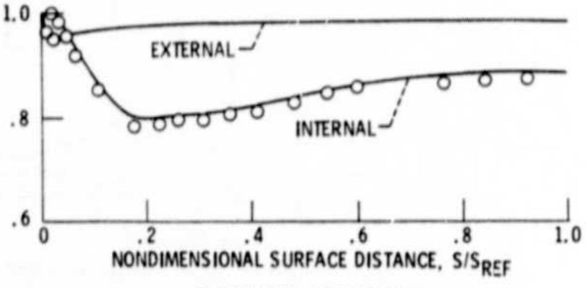


(a) WINDWARD SIDE OF INLET.



(b) LEEWARD SIDE OF INLET.

Figure 2. - Comparison of theory with experiment.

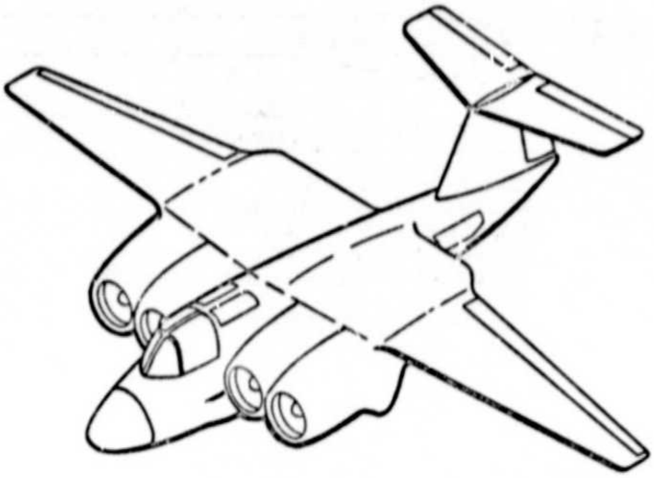


Figure 3. - Possible fixed nacelle V/STOL aircraft.

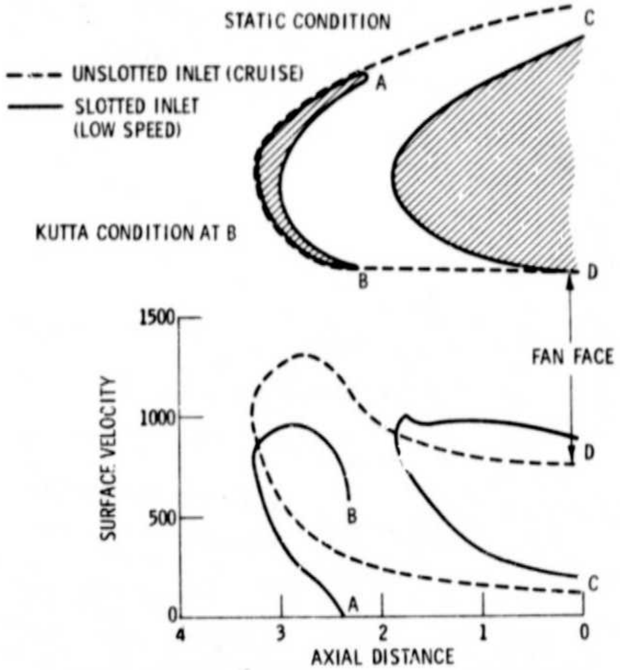


Figure 4. - Effect of slot on inlet surface velocity.

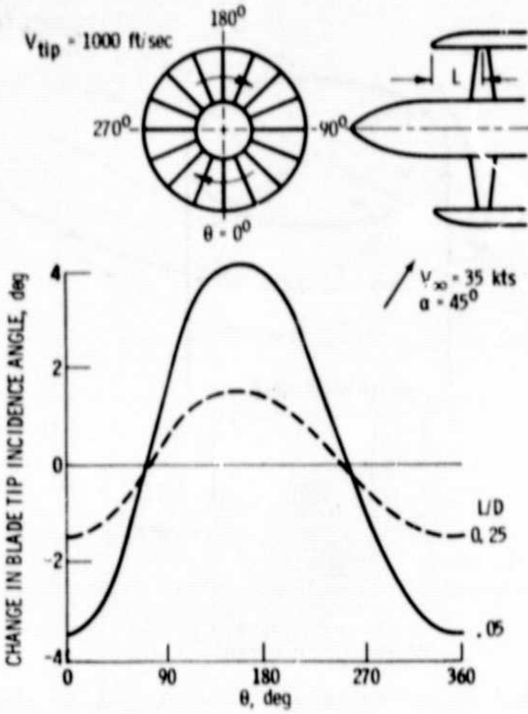


Figure 5. - Fan inflow distortion at angle of attack.

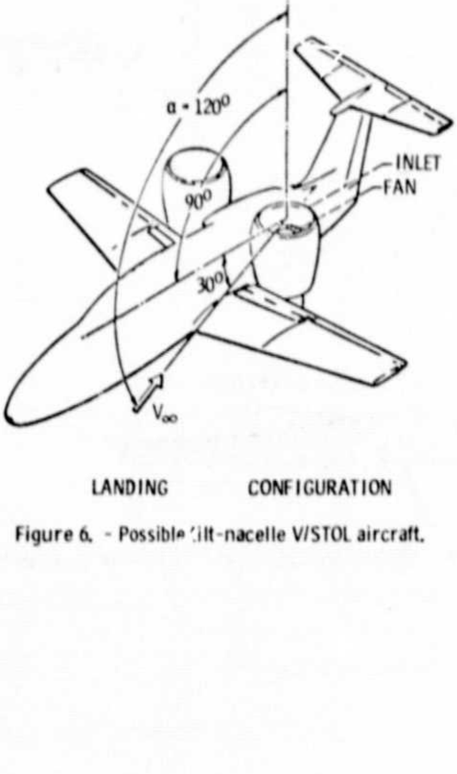
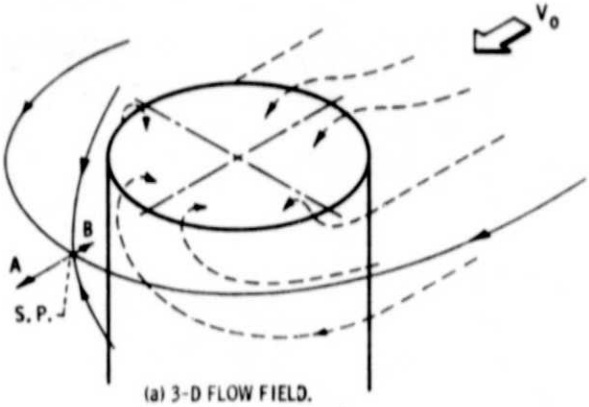
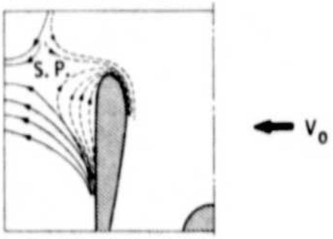


Figure 6. - Possible tilt-nacelle V/STOL aircraft.



(a) 3-D FLOW FIELD.



(b) LEEWARD LIP DETAIL.

Figure 7. - Flow field of tilt-nacelle inlet. $V_T/V_0 = 10$, $\alpha = 90^0$.

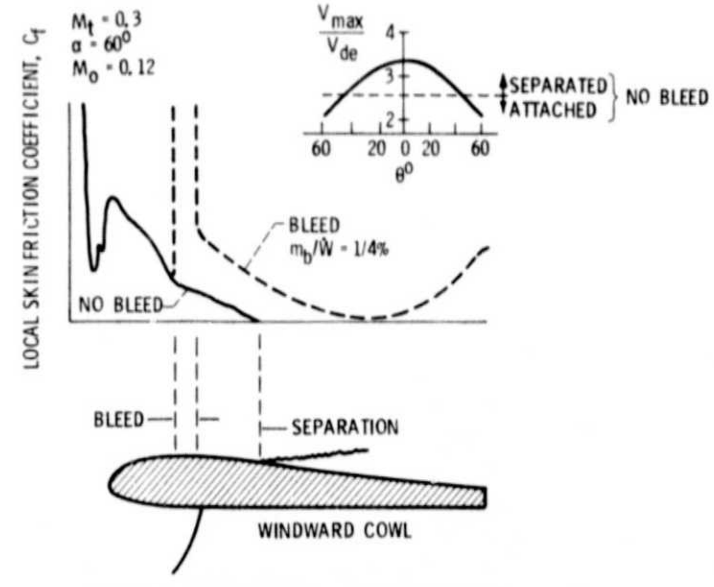


Figure 8. - Effect of boundary-layer bleed on inlet separation.

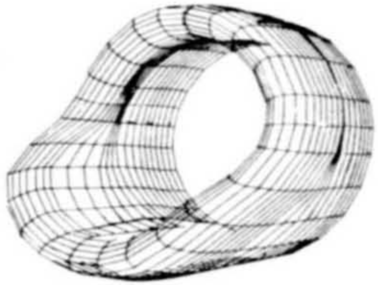


Figure 9. - Three-dimensional scoop inlet.

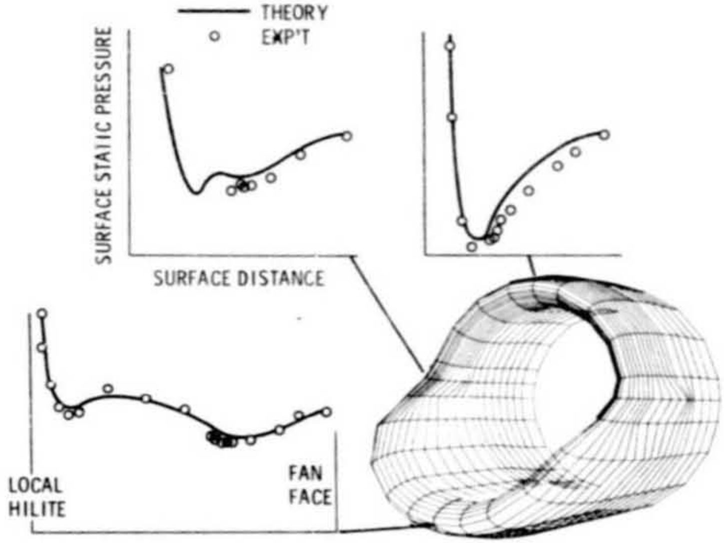
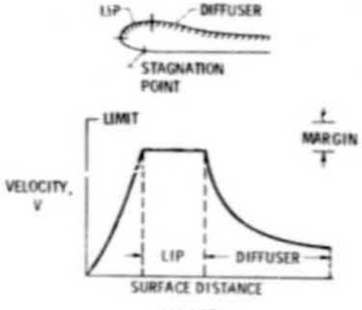
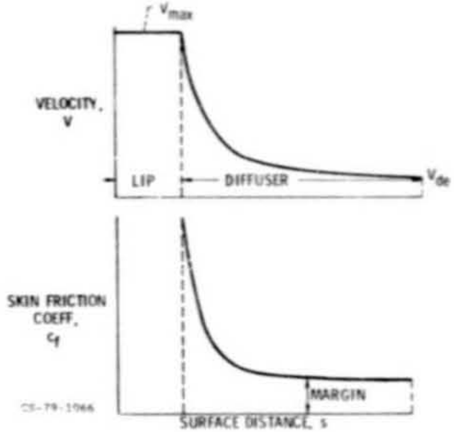


Figure 10. - Comparison of 3-D theory and experiment, scoop inlet. $V_T/V_\infty = 1.7$, $\alpha = 0$, $\beta = 0$.



(a) LIP.



(b) DIFFUSER.

Figure 11. - Optimum flow distributions.