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# An Approach to Optimum Subsonic Inlet Design

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# An Approach to Optimum Subsonic Inlet Design

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ABSTRACT

The approach 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. Optimum flow distributions on the inlet surface are determined to be a high, flat top Mach number 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. These optimum distributions are then modified to achieve other desirable flow characteristics. Example applications are given. Extension of the method are suggested.

NOMENCLATURE

| | |
|---|---|
| A | area |
| a | bisuperellipse major axis, eq. (1) |
| b | bisuperellipse minor axis, eq. (1) |
| $c_f$ | skin friction coefficient |
| CR | contraction ratio, eq. (2) |
| h | diffuser height |
| $\ell$ | diffuser length |
| M | Mach number |
| p,q | bisuperellipse exponents, eq. (1) |
| r | radius |
| s | surface distance |
| V | velocity |
| x | axial distance |
| $x_\lambda$ | axial location of diffuser maximum wall angle |
| y | radial coordinate |
| $\alpha$ | inlet angle of attack |
| $\lambda$ | diffuser maximum wall angle |

Subscripts:

| | |
|---|---|
| avg | average |
| cb | centerbody |
| de | diffuser exit or fan face |
| $h\ell$ | highlight |
| limit | limiting value |
| max | maximum value |
| sep | incipient separation |
| t | throat |
| 0 | free stream |

INTRODUCTION

A problem in the development of the engine nacelle for many current subsonic airplanes is the design of the inlet which must provide flow with low total pressure losses and low distortion to the fan or engine over a wide range of operating conditions. Different operating conditions require different inlet geometries in order to achieve low loss and low distortion.

At cruise a thin inlet lip is required for low drag; at low speed (static, approach, etc.) a relatively thick lip (like a bellmouth) is required to turn the flow into the inlet. Furthermore, minimum nacelle weight requires that the inlet be as short and as thin as other constraints permit. Thus, the low speed requirements conflict with most of the other requirements and considerable effort must be directed to designing inlets for efficient low speed performance within the geometric constraints imposed by cruise conditions and minimum weight requirements.

To ensure a manageable scope this paper will be limited to the problem of designing short thin inlets for low-speed operations. Furthermore, attention will be directed only to the components of the inlet nacelle internal surface, namely the lip and the diffuser wall. Other inlet components that should eventually be included in optimization are the external forebody and the centerbody. For the present approach these components will be assumed to be predetermined and fixed. However, suggestions on incorporating them into the design procedure will be given.

At low flight speed conditions the inlet lip must turn the flow into the inlet and this turning requires relatively low pressure acting over a sufficiently large surface. Low pressure means high velocity and large surface means large lip length and/or thickness.

The higher the surface velocity becomes, the shorter and thinner the lip can be made. However, the high surface velocity must be diffused to the required velocity at the fan face. To achieve the required low loss and low distortion this diffusion should take place without boundary layer separation.

Thus there is a conflict between the high velocity requirement to keep the lip short and thin and the low velocity requirement to avoid separation.

Several approaches to designing short thin inlets for separation-free operating have appeared in recent years. The initial approach, which concentrated on the separation-free aspect, was to design inlets that had a relatively low peak velocity on the inlet lip (refs. 1 to 3, e.g.). The usual procedure was to calculate the velocity distributions of several geometries at several flow conditions and choose the geometry that had the minimum peak velocity at the most critical conditions. This approach can result in unnecessarily conservative inlets, that is, inlets that are larger than necessary to avoid separation.

More recently quantitative limits on the peak velocity have been determined for typical V/STOL inlets (ref. 4). These limits provide a means for including to some extent the constraint of short thin geometry into the inlet design. The new procedure is to investigate several geometries and choose the one that has the highest peak velocity that does not exceed the limits (refs. 5 and 6). This approach will result in a closer-to-optimum inlet, that is, a shorter, thinner inlet, than the first approach. In reference 6 an additional improvement was incorporated in that a single most severe operating condition was selected for the design process. This improvement reduces the number of calculations required to obtain a final design.

The present paper recommends an approach that results in an optimum inlet, that is, the shortest, thinnest separation-free inlet. The approach optimizes the flow distribution over the entire inlet lip and diffuser wall and is similar to the approach of Liebeck (ref. 7) and of Smith (ref. 8) who were interested in optimum flow distributions on subsonic airfoils for maximum lift. The goals and constraints of high-lift airfoil design are analogous to those of low-speed inlet design.

The organization of the present paper is as follows. First, airplane and engine requirements will be discussed with the goal of selecting the most critical inlet operating condition which then becomes the design point. Next, the method of determining the optimum inlet at the design point will be indicated. Then, example applications to lip shape and to diffuser wall shape will be given. Finally, suggestions for extending the method will be briefly discussed.

The procedure and examples treated herein are related to V/STOL inlet design but they should be applicable to any low-speed inlet design.

## DESIGN METHOD

Subsonic inlets of current interest, especially for V/STOL aircraft must operate under a variety of severe flow conditions. Therefore, the first step in a design method is to select the most critical inlet operating condition as the design point so that if the inlet performance is satisfactory at that condition, it will be satisfactory at all other operating conditions.

### Design Point Selection

Critical inlet regions. Three separate low-speed operating conditions may be identified that can be critical for different regions of the inlet as illustrated on figure 1. Usually the most severe conditions, that is, the highest local velocities, occur at the bottom or windward portion of the inlet at high angles of attack. The sides of the inlet must be able to tolerate crosswinds; conditions here can be similar to the high angle of attack conditions on the bottom but usually less severe because the free-stream velocity is lower. Finally, the top of the inlet usually needs to be designed only for static conditions since it poses no internal flow problems at the other conditions.

The reason for considering the three regions of the inlet, even though the bottom one is usually most severe, is that a symmetric inlet designed for the most severe conditions may be too conservative over a considerable portion of the circumference, that is, it may be thicker at the side and top than necessary for crosswind and static requirements. Thus the weight and cruise drag may be unnecessarily penalized. To avoid unnecessary penalties each region (bottom, sides, and top) of the inlet can be optimized separately and the three regions faired smoothly together to produce an asymmetric inlet (refs. 4, 5, and 9).

For simplicity the present discussion will be limited to optimizing the windward (bottom) region of the inlet. The procedure for optimizing the other circumferential regions of the inlet will be the same.

Critical operating condition. The wide range of airplane flight conditions that can be encountered by a tilt-nacelle V/STOL inlet is shown on figure 2. Angles of attack can be as high as 120$^\circ$ and there is a wide range of throat Mach numbers. The flight conditions together with the inlet throat Mach number define the inlet operating conditions. It is not obvious what the worst or critical operating condition is, and a rational approach toward making this choice is desired.

A useful plot for finding the critical condition is angle of attack $\alpha$ versus the ratio of throat velocity-to-free-stream velocity $V_t/V_o$ (fig. 3). The inlet operating conditions obtained from figure 2 (or other sources) will appear as a region on figure 3. The boundary of this region is called the inlet requirement. The requirement is that the inlet flow remain attached at all operating conditions up to this boundary.

The next step is to obtain an estimate of the inlet separation characteristic (fig. 3) which is a curve that defines the limit of separation-free, or attached inlet operations. For separation-free operation at the required operating conditions the entire inlet requirement boundary must be below the inlet separation characteristic. The critical operating condition is the point on the requirement curve that is closest to the characteristic. This is the design point noted on figure 3.

This selection of the design point is not as easy as it sounds or as figure 3 might appear to make it. Since initially the inlet is not known there is no a priori way of determining the inlet separation characteristic. Therefore an initial estimate must be made and an iterative procedure incorporating the inlet optimization is required to get the final inlet characteristic, that is, the characteristic that represents the final optimum inlet. This iterative procedure is illustrated in the form of a flow chart in figure 4.

Briefly the procedure is: establish requirement; estimate separation characteristic (existing theoretical and experimental studies will be helpful); select design point, determine optimum inlet, calculate new separation characteristic from optimum inlet, select new design point, determine new optimum geometry, and so on to satisfactory convergence.

## Optimum Flow Specification

The general inlet optimization problem is to design the shortest, thinnest, most efficient inlet that will meet the design point requirement. This general problem will be restated in terms of criteria on the inlet surface flows. As stated previously, attention is limited for this paper to the internal surface of the windward side of the inlet. This surface is considered to consist of two components: the lip and the diffuser (fig. 5).

For each inlet component, a different property of the flow will be used as the basis for the optimization. For the lip it is the local surface velocity distribution. For the diffuser it is the local skin friction distribution.

Ideal optimum. The optimum lip geometry is postulated to be the shortest, thinnest lip that will turn the flow into the inlet at low-speed conditions without separation anywhere in the inlet. This rapid turning requires low pressure which, of course, means high velocity. As mentioned earlier limits have been determined (ref. 4) on the peak velocity for subsequent attached flow in the diffuser. These limits are (1) compressibility limit, $M_{max} < (M_{max})_{limit}$ and (2) diffusion limit $V_{max}/N_{de} < (V_{max}/V_{de})_{limit}$

The most rapid turning is obtained when the lip local velocity is everywhere equal to the peak velocity. The resulting flat rooftop velocity distribution on the inlet internal surface is shown in figure 6. Both the velocity and Mach number distributions are given because of the two independent limits $(M_{max})_{limit}$ and $(V_{max}/V_{de})_{limit}$. If either of these limits is exceeded the flow will separate. There should be a safety margin between $V_{max}$ and the limits $(V_{max}/V_{de})_{limit}$ and $(M_{max})_{limit}$ to allow for uncertainties in the limits and for unanticipated excursions beyond the design point in the actual inlet operation. An inlet designed for such a $V_{max}$ will be the inlet with the shortest surface length that does not separate at the design point. (If a shorter, thinner inlet is needed then the $(V_{max})_{limit}$ and/or $(M_{max})_{limit}$ will have to be exceeded and boundary layer control (e.g., bleeding or blowing) will be required to ensure separation-free operation.)

The diffuser task of interest here is to diffuse the high lip velocity to the required diffuser exit velocity. The optimum diffuser is the one that has minimum length and minimum loss for the required amount of diffusion. Stratford (refs. 10 and 11) has determined that a diffuser that has near zero skin friction over its length is both the shortest and has the lowest loss. This requirement results in a velocity distribution that has initial rapid deceleration followed by a more gradual deceleration as illustrated in figure 7(a). The optimum skin-friction distribution is as shown on figure 7(b). Both Smith (ref. 8) and Povinelli (ref. 12) verify that Stratford-type diffusion is extremely efficient but that performance falls off if the entrance boundary layer is thick (ref. 8) or if the entrance total pressure profile is distorted (ref. 12). However, for the first approach the Stratford diffusion will be accepted as the optimum and thus the design goal is to obtain a skin friction distribution similar to the one shown in figure 7(b). There must, of course, be a safety margin between the minimum $C_f$ and zero to allow for uncertainties in the calculation and unanticipated operating excursions beyond the design point. Some additional constraints that may have to be considered but are beyond the scope of this paper are: (1) minimum length required for acoustic treatment for noise suppression, (2) minimum length required to damp out velocity distortion due to high angle of attack requirements, and (3) minimum length or special constraints on diffuser wall shapes to minimize radial velocity gradients at the fan face that arise from the diffuser wall shapes.

Modified optimum. The idealized optimum lip and diffuser suggested above may not always be the practical optimum for inlet application because the idealized optimum can result in diffuser separation. This section will present modifications to the optimum that should result in more favorable boundary layer behavior.

The flat rooftop velocity on the lip (fig. 6) may deliver a laminar boundary layer to the diffuser entrance. The rapid deceleration of the optimum diffuser velocity distribution may cause the laminar boundary to separate before it transitions to turbulent. To avoid this laminar separation there should be a slight deceleration (called a transition ramp in ref. 7) just ahead of the rapid deceleration in the diffuser to cause the boundary layer to transition to fully turbulent before encountering the rapid diffusion. The resulting modified optimum distribution is shown on figure 8.

The optimum skin friction distribution (fig. 7) may not be satisfactory if there is a possibility that the inlet will be exposed to operating conditions sufficiently beyond the design point that the $C_f$ becomes zero. Because of the flat distribution, $C_f$ will go to zero simultaneously throughout most of the diffuser and the result is extensive boundary-layer separation. This type of separation can produce intolerable blade stress and/or thrust loss. In cases where it is necessary to eliminate the possibility of extensive separation the optimum $C_f$ distribution can be modified by sloping (as shown in fig. 9). Then a zero $C_f$ value, and hence separation, occurs first at the diffuser exit and this local separation is usually quite tolerable. As flow conditions continue to worsen the separation creeps forward toward the throat that is the separation is controlled and sudden extensive separation is avoided. It is important to verify experimentally the theoretical conclusion that sloping $C_f$ distribution does control the rate of separation extent (ref. 13). An additional benefit of a skin-friction distribution like that of figure 9 as reported by Povinelli (ref. 14) is that it gives improved performance over the Stratford optimum (fig. 7) at higher throat Mach numbers.

Calculational Procedure

Since the velocity distribution on the inlet lip and the skin-friction distribution on the diffuser at nonzero angle of attack operation are three dimensional it is out of the question to prescribe the full flow distributions and calculate the wall shapes. Instead the windward lip and diffuser shape are assumed; the resulting inlet profile is analyzed to obtain the velocity, Mach number, and skin-friction distributions. If the desired optimum flow distributions are not obtained the geometry is perturbed and the calculation repeated until the resulting distributions are satisfactorily close to the optimums. To carry out this procedure two things are required: (1) readily-perturbed analytic expressions for specifying lip and diffuser wall shapes and (2) an analysis method for axisymmetric inlets at angle of attack.

Geometry specification. An analytic expression that has had wide use in recent years for inlet lips is the bisuperellipse

$$(x/a)^p + (y/b)^q = 1.0 \qquad (1)$$

It is suggested for both the lip and the diffuser wall shapes. In both cases this curve provides an easy systematic way of varying the pertinent geometric parameters.

In the case of the lip the important variables are the lip shape (or curvature distribution), the fineness ratio, and the thickness or contraction ratio (fig. 10). The curvature distribution is controlled by the exponents $p$ and $q$. The fineness ratio is the major-to-minor axis ratio $a/b$. The example to be given later will illustrate the effect of varying $a/b$. The lip thickness is $b$ but the contraction ratio, CR, is the more commonly used measure of lip thickness and is given by

$$CR = A_{h\ell}/A_t = r_{h\ell}^2/r_t^2 = (r_t + b)^2/r_t^2 \qquad (2)$$

where $r_t$ is the throat radius and is assumed to be fixed before the lip optimization is performed. Therefore, varying CR is the same as varying $b$.

In the case of the diffuser the bisuperellipse can be used provided one of the exponents is less than 1.0 and the other is greater than 1.0. This combination produces a curve having an inflection point which is necessary for typical inlet diffuser wall shapes (fig. 11). (If $p = q = 1$ a conical diffuser results.)

For the diffuser $p$ and $q$ are not directly specified; instead the maximum wall angle $\lambda$ and it's axial location $x_\lambda$ are specified since $\lambda$ and $x_\lambda$ are important diffuser parameters. Since $p$ and $q$ are functions of $\lambda$ and $x_\lambda$ they are thus determined.

The diffuser length is equal to $\ell$ and is an important diffuser parameter.

The parameter $h$ is determined by the diffuser area ratio $A_{de}/A_t$.

$$A_{de}/A_t = \left(r_{de}^2 - r_{cb}^2\right)\Big/r_t^2 = \left[(r_t + h)^2\right]\Big/r_t^2 \qquad (3)$$

As stated above $r_t$ is usually determined before the optimization. Also $r_{de}$ is usually predetermined and thus $h$ may not be free for optimizing. The centerbody radius $r_{cb}$ is also usually determined by the fan design.

Thus $\lambda$, $x_\lambda$, and $\ell$ are the typical free diffuser parameters. The example will illustrate the effect of varying $x_\lambda$.

Flow analysis. The method of analysis is that of reference 15 and consists of a potential flow analysis and a boundary layer analysis. The potential flow analysis (documented in ref. 16) consists of an exact incompressible flow analysis for axisymmetric bodies at angle of attack and a compressibility correction.

The boundary layer analysis (documented in refs. 17 and 18) uses the velocity distribution supplied by the potential flow calculation and calculates the development of the axisymmetric compressible boundary layer.

## EXAMPLE APPLICATIONS

Determining the optimum lip and diffuser geometries will be illustrated with examples taken from earlier studies. These studies were not undertaken with the present optimizing approach in mind but in several cases flow distributions resulted that are close enough to the optimum that they adequately illustrate the method. One example will be given for the lip and one for the diffuser.

### Lip

The example of lip shape selection is taken from reference 2. The lip is an ellipse, that is, $p = q = 2$ in equation (1), with $b$ (or CR) fixed; the fineness ratio $a/b$ will be varied. Figure 12 shows the lip geometry and the Mach number distribution for three values of $a/b$. Also shown is $(M_{max})_{limit}$ from reference 5. The $a/b = 2.0$ Mach number distribution is very much like the modified optimum distribution of figure 8. However, the margin between the rooftop and $(M_{max})_{limit}$ may be too large. The designer would have to make the decision as to whether or not additional trials should be made on some other geometric parameters to decrease the margin and correspondingly reduce the inlet length and thickness. As mentioned earlier other lip parameters that may be varied are the exponents $p$ and $q$ and the lip contraction ratio CR. Examples of $p$ and $q$ variations can be found in references 1 and 2; examples of CR variation can be found in references 2, 5, and 6.

### Diffuser

The example of diffuser shape selection is taken from reference 19 and will show the effect of varying $x_\lambda$ the location of the maximum wall angle. The value of $\lambda$ was not changed. Figure 13 shows the diffuser geometries and the skin-friction distribution for three different values of $x_\lambda$. The wall shape with $x_\lambda = 0.5$ is a cubic; each of the other two is constructed of two bisuperellipses fitted together at $x_\lambda$ to produce an inflection point.

From the skin-friction curve it can be seen that the $x_\lambda = 0.25$ case is closest to the idealized optimum. On the other hand, the $x_\lambda = 0.5$ case is perhaps closer to the modified optimum; however, it will have greater losses because the skin friction is higher than the 0.25 case over most of the diffuser. The $x_\lambda = 0.75$ diffuser is unacceptable because it separates. It also has higher $C_f$ values and hence has a greater loss than the other two diffusers.

Examples of other diffuser parameter variations can be found in references 16 and 19.

## EXTENSIONS OF THE METHOD

In the discussions and examples of the present paper the procedure was limited to the internal lip and diffuser surfaces. Furthermore, for simplicity, the effects of the inlet external forebody and of the centerbody on the lip and diffuser were neglected. However, there may be occasions when these components cannot be neglected.

The external forebody is designed primarily for cruise conditions, however, at some low-speed flow conditions it may affect the lip performance (ref. 3). If this effect occurs at the design point, it might be profitable to include the forebody in the design optimization.

The centerbody has been included in the design method only for its effect on the diffuser exit area (fig. 11) and was tacitly assumed to be very short. However, its length may vary considerably. The centerbody may extend only a short distance into the diffuser (fig. 11) or it may extend beyond the highlight. It can have significant affect on the diffuser and sometimes the lip flow distribution and therefore on the inlet separation characteristics depending on its location (refs. 20 and 21). The centerbody then should be included in the inlet optimization.

The previous discussion treated the forebody and centerbody only for their effects on the lip and diffuser, however, the proposed method could also be extended to the design of the external forebody and the centerbody themselves.

Another parameter that was assumed fixed in the first approach but that may need to be included in more complete design is the throat radius $r_t$ (figs. 10 and 11). The throat radius is sometimes determined by the design throat Mach number which would then become a design variable. Also $r_t$ may be determined by the diffuser area ratio $A_t/A_{de}$ which becomes the design variable.

## CONCLUDING REMARKS

An approach to optimum subsonic inlet design has been suggested. The chief elements of the suggested design procedure are estimating the most critical operating condition and making it the design point, specifying optimum flow distribution on the inlet surface, finding a geometry that produces the optimum flow condition and iterating the previous steps since the geometry affects the design point. The final geometry after satisfactory convergence of the iteration process should be the optimum, that is, the shortest, thinnest, most efficient inlet for the given requirements.

The method has been illustrated with examples from earlier studies. Extensions have been indicated to include other inlet components and other inlet design parameters that were assumed fixed in the present discussion. The method appears to be promising but its usefulness must be verified by application to an actual practical inlet design. If successful the method should be able to reduce the amount of wind tunnel testing required for inlet design.

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[1]Copies available on request to N. Stockman of LeRC.

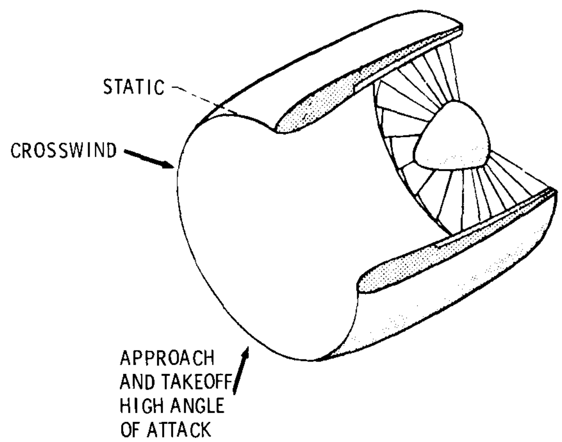



Figure 1. - Critical inlet regions.

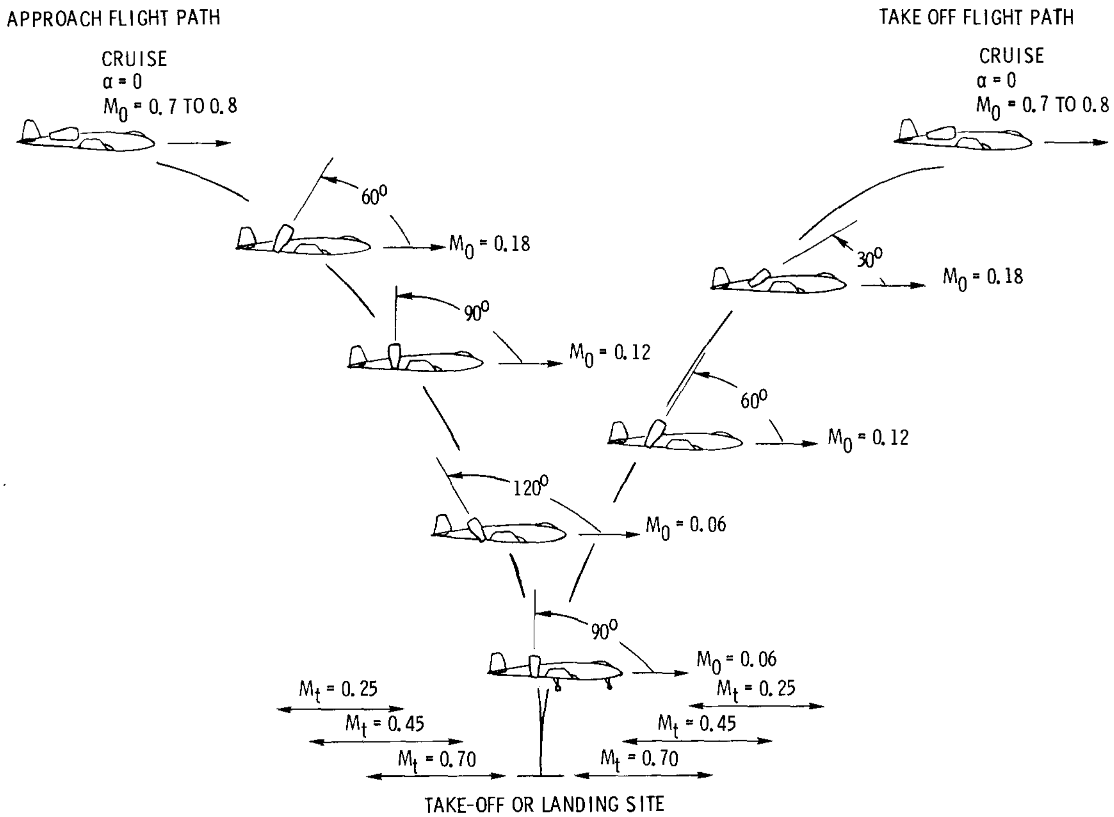



Figure 2. - Representative flight conditions for tilt-nacelle VTOL aircraft.

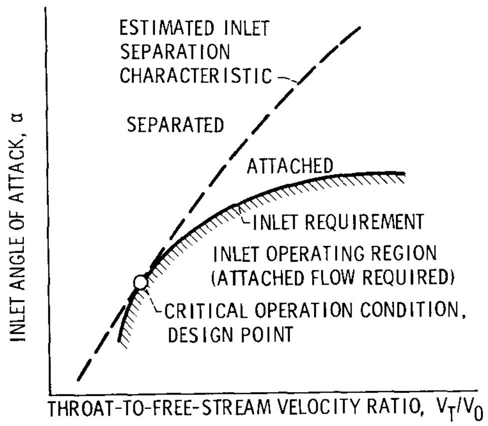



Figure 3. - Selection of critical condition for inlet design.

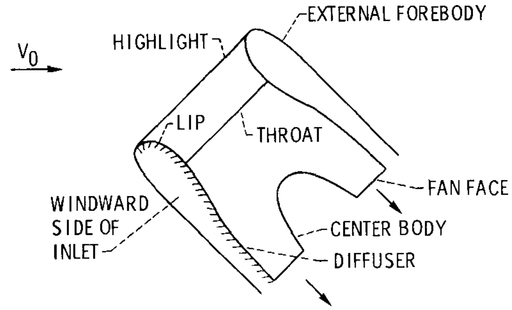



Figure 5. - Inlet components.

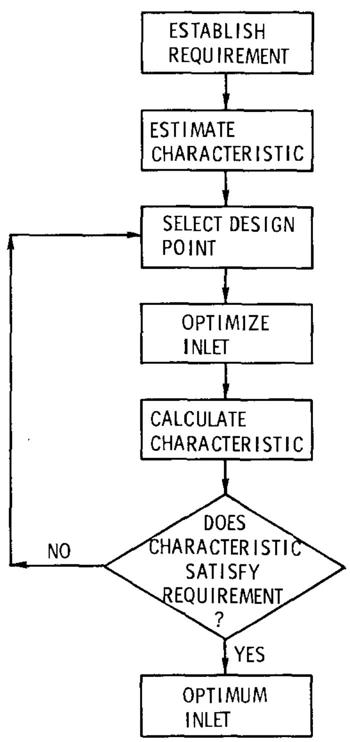



Figure 4. - Flow chart illustrating selection of design point.

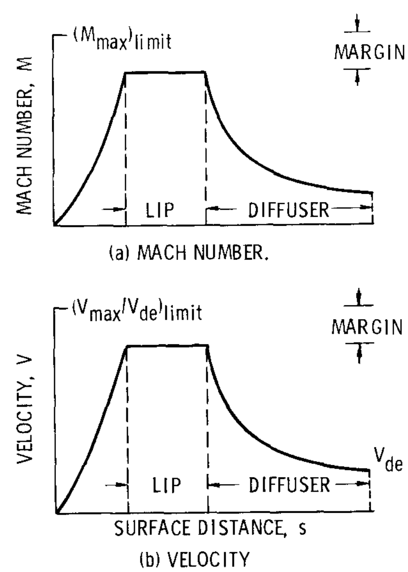
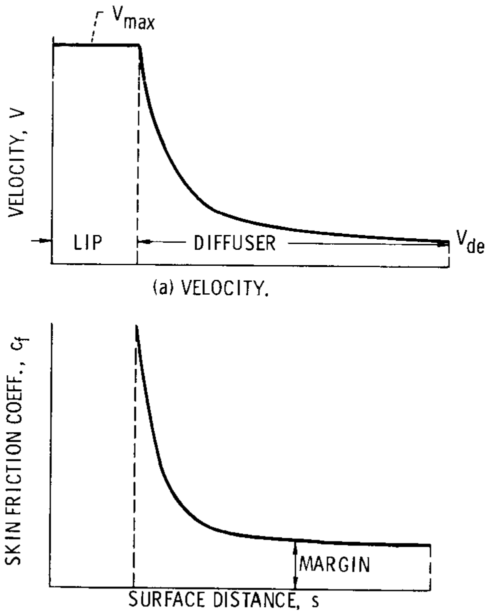



Figure 6. - Lip optimum distributions.



(a) VELOCITY.

(b) SKIN FRICTION COEFFICIENT.

Figure 7. - Diffuser optimum distributions.

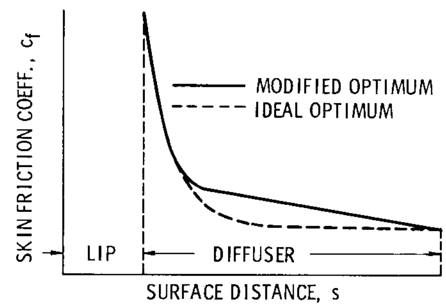


Figure 9. - Modified optimum diffuser distribution.

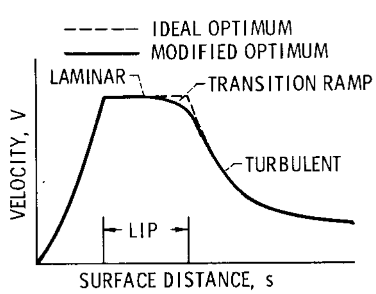
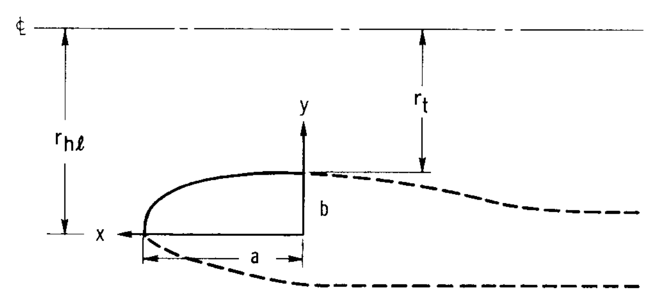


Figure 8. - Modified optimum lip distribution.

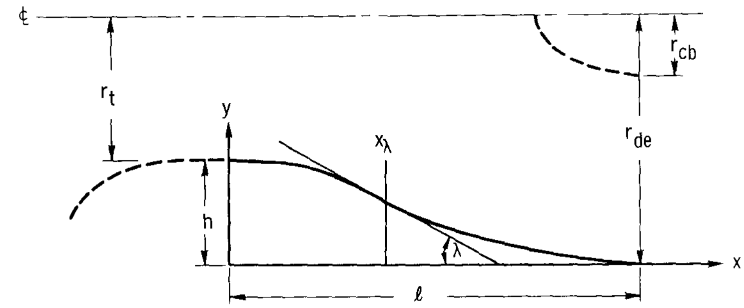


$(x/a)^p + (y/b)^q = 1.0$

FINENESS RATIO = a/b

CONTRACTION RATIO CR $= r_{h\ell}^2/r_t^2 = (r_t + b)^2/r_t^2$

Figure 10. - Bisuperellipse for lip.




$(x/\ell)^p + (y/h)^q = 1.0$

$p = p(x_\lambda, \lambda)$

$q = q(x_\lambda, \lambda)$

Figure 11. - Bisuperellipse for diffuser.

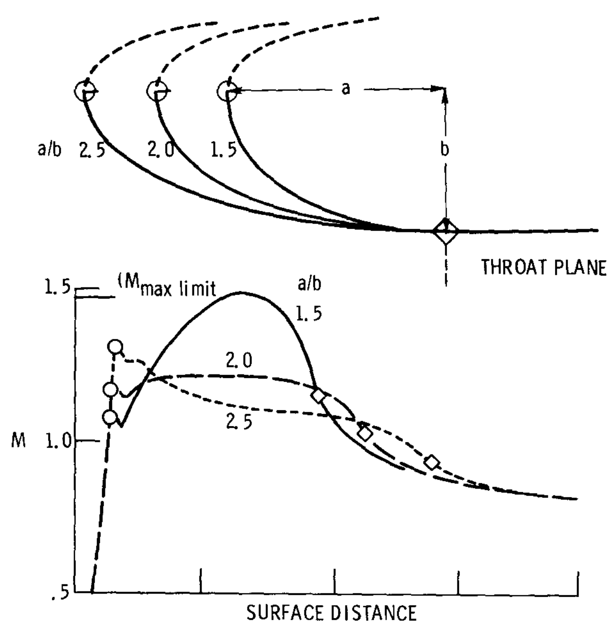



Figure 12. - Lip optimization.

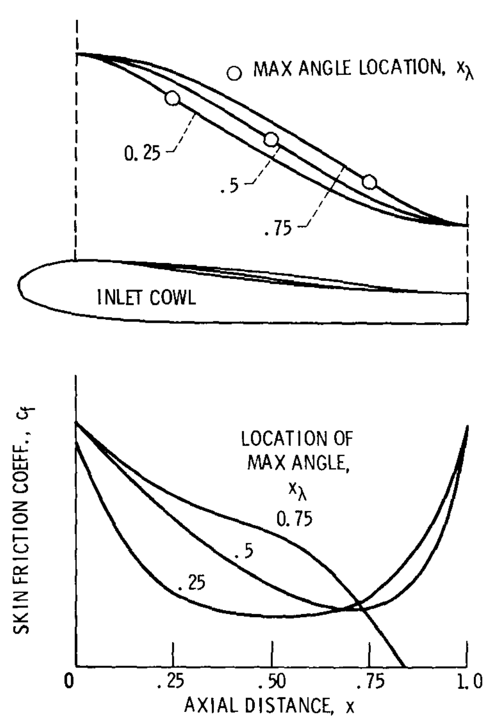



Figure 13. - Diffuser optimization.