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AERODYNAMIC ANALYSIS OF SEVERAL HIGH THROAT MACH NUMBER INLETS FOR THE QUIET CLEAN SHORT-HAUL EXPERIMENTAL ENGINE

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16. Abstract

This report presents the results of an analytical study to investigate internal and external surface Mach numbers on several inlet geometries for possible application to the nacelle of the Quiet Clean Short-Haul Experimental Engine (QCSEE). The effects of external forebody geometry and internal lip geometry were illustrated at both low-speed and cruise conditions. Boundary-layer analyses were performed on several geometries to determine if lip flow separation might exist. The results indicated that inner-surface Mach number level and gradient could be reduced with inlets at a 50° incidence angle by blunting the external forebody geometry. The external Mach numbers at cruise conditions indicated that a compromise in the external forebody bluntness might be required to satisfy both low-speed and cruise conditions. For a fixed value of bluntness parameter, no lip flow separation was indicated for the 1.46- and 1.57-area-contraction-ratio inlets at low-speed conditions. However, a lip separation condition was obtained with the 1.37-contraction-ratio inlet. The QCSEE nacelle design takeoff operating condition (incidence angle of 50° and free-stream Mach number of 0.12) resulted in higher peak surface Mach numbers than the design crosswind (incidence angle of 90° and free-stream Mach number of 0.05) or static condition.

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SUMMARY

This report presents the results of an analytical study to investigate internal and external surface Mach numbers on several inlet geometries for possible application to the nacelle of the Quiet Clean Short-Haul Experimental Engine (QCSEE). The effects of external forebody geometry and internal lip geometry were illustrated at both low-speed and cruise conditions. Boundary-layer analyses were performed on several geometries to determine if lip flow separation might exist.

The results indicated that inner-surface Mach number level and gradient could be reduced with inlets at a 50° incidence angle by blunting the external forebody geometry. The external Mach numbers at cruise conditions indicated that a compromise in the external forebody bluntness might be required to satisfy both low-speed and cruise conditions. For a fixed value of bluntness parameter, no lip flow separation was indicated for the 1.46- and 1.57-area-contraction-ratio inlets at low-speed conditions. However, a lip separation condition was obtained with the 1.37-contraction-ratio inlet. The QCSEE nacelle design takeoff operating condition (incidence angle of 50° and free-stream Mach number of 0.12) resulted in higher peak surface Mach numbers than the design crosswind (incidence angle of 90° and free-stream Mach number of 0.05) or static condition.

INTRODUCTION

A problem in the development of the engine nacelle for short-haul airplanes is the design of the inlet, which must provide low total-pressure losses and low distortion during low-speed and cruise operation. For typical short-haul aircraft missions, the engine inlet is required to operate at the large incidence angles associated with high lift coefficients at takeoff and landing and may also operate at high throat Mach numbers to provide noise suppression. In general, the designer tries to avoid flow separation on the inlet surface at all operating conditions to maintain low pressure losses and low flow distortion.

The likelihood of separation on the internal inlet surface at low speed speed can generally be reduced by minimizing the peak surface Mach number and local Mach number gradient. Also, high values of surface Mach numbers on the external forebody at cruise speed are to be avoided in order to minimize strong shocks and separation, which can lead to a premature drag rise. The designer is faced with making tradeoffs between internal and external lip geometries that give good performance at both low-speed and cruise conditions. Thus, an analytical study was initiated at the Lewis Research Center to investigate the internal and external surface Mach number on several inlet geometries applicable to operating conditions for the Quiet Clean Short-Haul Experimental Engine (QCSEE).

The QCSEE nacelle is required to operate at the following design conditions: (1) a throat Mach number of approximately 0.72 to 0.79; (2) an incidence angle up to 50° at a free-stream Mach number of 0.12 (41 m/sec; 80 knots); (3) a 90° crosswind at a free-stream Mach number of 0.05 (18 m/sec; 35 knots); (4) a cruise Mach number of approximately 0.7.

This report presents the results of an analytical study which was conducted in order to investigate the effect of inlet geometry on surface Mach number distribution. The geometric parameters varied were the internal area contraction ratio, external forebody diameter ratio, external forebody length-diameter ratio, and external forebody shape. Results are presented for these geometric variables at typical QCSEE operating conditions. Results of a boundary-layer analysis performed on several of the inlet geometries are briefly discussed. Because of the noise suppression requirement for the QCSEE nacelle, the analysis was performed at an average one-dimensional throat Mach number of 0.79.

SYMBOLS

A flow area

a major axis of internal lip (fig. 1)

b minor axis of internal lip (fig. 1)

C_f skin friction coefficient

D diameter

L length (fig. 1)

M Mach number

$\overline{M}$	one-dimensional Mach number at throat plane
N_B	bluntness parameter, $\left(\frac{y_{0.05}}{y_{0.1}}\right)\left(\frac{Y}{X}\right)\left(\frac{Y}{D_h/2}\right)$ (fig. 4)
p, q	bisuperellipse exponents
S	local surface distance from inlet highlight (fig. 1)
S_{lip}	surface distance from inlet highlight to throat (fig. 1)
S_{ref}	surface distance from inlet highlight to diffuser exit (fig. 1)
V	velocity
X	external forebody length (fig. 1)
x	axial distance from inlet highlight
Y	external forebody thickness (fig. 1)
y	radial distance from inlet highlight
α	incidence angle of inlet, angle between free-stream velocity and inlet axis (fig. 1)

Subscripts:

c	centerbody
d	diffuser
e	exit
h	highlight
max	maximum
t	throat
0	free stream

INLET CONFIGURATIONS

The principal inlet geometric parameters are illustrated in figure 1. The diffuser and lip parameters that were kept constant in this investigation are given in table I. The throat area A_t was determined for a fixed value of one-dimensional throat Mach number M_t of 0.79. The diffuser contour was cubic and had an inflection point located at 50 percent of the diffuser length. The selection of the diffuser geometry was based on the results of reference 1, which established general guidelines for the selection of a separation-free diffuser geometry.

The geometric parameters that were varied in this investigation were the internal lip and external forebody shapes. The values considered are listed in table II. All the internal lip contours were ellipses with a major-minor axis ratio a/b of 2.0. The selection of the internal lip contour was based on the results of reference 2. The values of internal lip contraction ratio $(D_h/D_t)^2$ studied were 1.37, 1.46, and 1.56 (fig. 2). This range of values was selected because it was believed that inlets within this range could tolerate the large incidence angles that can be encountered during high-lift takeoff (ref. 3).

The external forebody contours were generated with bisuperellipse curves of the form

$$\left(\frac{X - x}{X}\right)^p + \left(\frac{y}{Y}\right)^q = 1 \tag{1}$$

where X and Y are, respectively, the major and minor axes of the bisuperellipse (X and Y depend on the inlet parameters D_h/D_{max}, X/D_{max}, and D_{max}). The external forebody bluntness increases with an increase in the value of q. The bluntness is rather insensitive to the value of p. For an ellipse $p = q = 2.0$. The forebody shapes considered are shown in figure 3.

An attempt to organize the various combinations of external forebody parameters was made by defining an external forebody bluntness parameter N_B as

$$N_B = \left(\frac{y_{0.05}}{y_{0.1}}\right)\left(\frac{Y}{X}\right)\left(\frac{Y}{D_h/2}\right) \tag{2}$$

All the symbols in equation (2) are defined in figure 4. The first factor $(y_{0.05}/y_{0.1})$ is a measure of the local bluntness in the region of the highlight. It is a function only of the kind of curve chosen for the forebody contour and is independent of the actual dimensions of the forebody or the inlet (e.g., for a bisuperellipse $y_{0.05}/y_{0.1} = \left[(1 - 0.95^p)/(1 - 0.9^q)\right]^{1/q}$). The second factor (Y/X) accounts for the effect of the actual forebody dimension and is an indication of the overall external forebody bluntness. The final factor $(Y/D_h/2)$ places the lip in proportion to inlet size, by introducing the ratio of the external forebody frontal thickness to the inlet highlight radius. Each of the three factors and consequently the bluntness parameter itself increase with increasing bluntness. As indicated in table II, the variation in bluntness parameter for each value of inlet contraction ratio is obtained at constant or nearly constant values of the ratio D_{max}/D_e.

A one-dimensional area distribution for a typical inlet geometry is illustrated in figure 5. The maximum area ratio occurs at the inlet highlight and decreases to the inlet throat. The area ratio increases in the diffuser portion from the throat to the tip of the centerbody, which occurs at an x/L of 0.7. Beyond an x/L of 0.7, the annular area ratio decreases because of the presence of the centerbody. For this investigation, the ratio of overall length to exit diameter L/D_e varied from 0.97 to 1.03 (table II).

CALCULATION PROCEDURE

The distributions of inlet potential flow Mach number were obtained by using three computer programs (ref. 4). The first program, SCIRCL, established the coordinates and point spacing on the inlet surfaces. The second program, EOD, is the Douglas program for axisymmetric incompressible potential flow, for flow about inlets. It was used to obtain three basic solutions which were used as the input to a third computer program called COMBYN. This latter program combined the basic solutions and corrected the incompressible potential flow solution for compressibility. The compressibility correction used to calculate both internal and external Mach numbers is described in appendix B of reference 2.

The boundary-layer growth was obtained by use of an axisymmetric compressible finite-difference boundary-layer program (ref. 5). A discussion of the overall calculation procedure is given in reference 6. Comparisons of experimental data with this calculation procedure are given in references 7 and 8.

To illustrate the effects of external forebody geometry potential flow Mach numbers were calculated for inlets 1A, 1B, 1C, 2A, 2D, and 2E (table II) for both low-speed and cruise conditions. Potential flow and boundary-layer calculations were performed on inlets 1A, 2A, and 3A at low-speed conditions. All calculations at incidence angles were performed on the windward side of the inlet (fig. 1).

RESULTS AND DISCUSSION

The effect of external forebody shape on the internal and external surface Mach numbers is discussed first. Because of the 50° incidence angle requirement for the QCSEE nacelle, inlet area contraction ratios $(D_h/D_t)^2$ of 1.46 and 1.56 were chosen for this portion of the investigation. For each D_h/D_t three external forebody contours were considered in order to optimize the geometry for good low-speed performance. This discussion is followed by a discussion of surface Mach number distributions and boundary-layer characteristics for inlet area contraction ratios of 1.37, 1.46, and 1.56 for several low-speed flow conditions.

Effect of External Forebody Shape

The external forebody shape can affect the external forebody Mach number distribution at cruise as well as the internal Mach number distribution at low-speed conditions. Thus, a compromise shape may be required to give good performance at both low-speed and cruise conditions. The external forebody geometric parameters that were varied (table II) were diameter ratio D_h/D_{max}, length-diameter ratio X/D_{max}, and external forebody shape.

Internal surface Mach number. - The effect of external forebody bluntness on the internal surface Mach number distribution is shown in figure 6 for a free-stream Mach number of 0.12 and an incidence angle of 50°. There is a significant effect of external forebody bluntness on the peak Mach number near the inlet highlight. This effect is more severe for the 1.46 inlet (fig. 6(b)) than for the 1.56 inlet (fig. 6(a)).

The internal surface maximum Mach numbers from figure 6 are plotted in figure 7(a) against the bluntness parameter for the inlets at an incidence angle of 50°. The maximum Mach number decreases as the bluntness of the external forebody increases. The maximum Mach number was lowest for inlets 1A and 2A, which have a value of N_B of 0.0185. Unpublished results at the same inlet contraction ratios indicate that the curve of maximum Mach number as a function of bluntness parameter tends to level off for N_B greater than 0.0185. The effect of the external forebody bluntness is greater for the lower contraction ratio inlet. Thus, to obtain good low-speed performance up to an incidence angle of 50°, it appears desirable to have a high value of the bluntness parameter (0.0185 or above). However, for incidence angles below 50°, a large degree of bluntness may not be required. As shown in figure 7(b), there is little effect of external forebody bluntness on maximum Mach number for either inlet contraction ratio at an incidence angle of 30° and a free-stream Mach number of 0.18. Thus, for design maximum incidence angles of 30° or less, the external bluntness could be selected by cruise operating conditions.

External surface Mach number. - The effect of forebody bluntness on the maximum external Mach number at cruise conditions is presented in figure 8 for a free-stream Mach number of 0.75 and a one-dimensional throat Mach number of 0.79. The maximum external Mach number decreases as the bluntness parameter is increased to a value of approximately 0.015 and then increases as the bluntness is further increased. Thus, there is an optimum value of the bluntness parameter for cruise conditions. In general, the higher the cruise Mach number, the smaller the bluntness parameter. However, no analytical or experimental data are currently available to relate external nacelle drag quantitatively to the maximum external surface Mach number or to any of the specific geometric variables. Nevertheless, some compromise of the external forebody bluntness is indicated between cruise and low-speed high-incidence conditions.

Effect of Internal Lip Contraction Ratio

Potential flow calculations. - The effect of internal lip contraction ratio (fig. 2) on surface Mach number distribution is presented in figure 9 for a free-stream Mach number of 0.12 and an inlet incidence angle of 50°. The bluntness parameter for all three inlets is 0.0185. (These blunt inlets are considered most likely to satisfy the low-speed high-angle-of-attack requirement for the QCSEE inlet without too much penalty in cruise performance.) The peak Mach number decreased significantly with increasing internal lip contraction ratios from 1.37 to 1.56.

The effect of free-stream flow conditions for the three inlet lip geometries is presented in figure 10. The takeoff QCSEE conditions (incidence angle of 50° and free-stream Mach number of 0.12) result in larger peak surface Mach numbers than the crosswind (incidence angle of 90° and free-stream Mach number of 0.05) or static condition. The greatest peak Mach number and Mach number gradient on the inlet surface for the four conditions investigated occurs with an incidence angle of 44° and a free-stream Mach number of 0.18 (a possible operating condition for the QCSEE nacelle).

Boundary-layer considerations. - The surface Mach number distributions obtained from the potential flow solution were used as an input to the boundary-layer program to investigate possible boundary-layer separation on the inlet lip. Skin friction coefficients on the inlet lip are shown in figure 11. The minimum skin friction coefficient decreased with decreasing contraction ratio. For the 1.46- and 1.56-contraction-ratio inlets, there is no lip separation for the flow conditions investigated. For the 1.37-contraction-ratio inlet, lip separation occurs at a free-stream Mach number of 0.18 and an inlet incidence angle of 44° (fig. 11(b)). An inlet geometry with lip separation at or near design flow conditions is unacceptable, since large total-pressure losses and flow distortions and instabilities are generally associated with lip separation (ref. 9), and these disturbances can cause engine stall, increased blade stress, and increased noise generation. These results indicate that an inlet contraction ratio of approximately 1.46 may be required to provide separation-free inlet lip flow for the low-speed QCSEE design conditions.

SUMMARY OF RESULTS

An analytical study was performed to investigate the aerodynamics of several inlet geometries applicable to the nacelle of the Quiet Clean Short-Haul Experimental Engine (QCSEE). The principal results of the study were as follows:

1. The inlet maximum internal surface Mach number and local Mach number gradients at a free-stream Mach number of 0.12 and an incidence angle of 50° were reduced

by blunting the external forebody geometry. The most favorable surface flow conditions for these free-stream conditions were obtained for a value of a bluntness parameter equal to 0.0185. The effect of blunting was greatest for the lower contraction ratio inlet. At an incidence angle of 30°, there was little effect of external forebody bluntness on maximum internal surface Mach number.

2. For a given inlet internal lip contraction ratio, the maximum external surface Mach number at the cruise condition had a minimum value which was a function of the external forebody bluntness. Thus, a compromise of the external forebody bluntness between cruise and low-speed conditions was indicated.

3. The takeoff QCSEE condition (incidence angle of 50° and free-stream Mach number of 0.12) resulted in larger peak surface Mach numbers than the crosswind (incidence angle of 90° and free-stream Mach number of 0.05) or static condition. The greatest peak Mach number and Mach number gradient on the inlet surface occurred with an incidence angle of 44° and a free-stream Mach number of 0.18.

4. For a fixed value of the bluntness parameter of 0.0185, the peak Mach number decreased significantly with increasing internal lip contraction ratios from 1.37 to 1.56 at an incidence angle of 50°. The minimum skin friction coefficient decreased with decreasing contraction ratio for all low-speed free-stream conditions.

The results set forth in this report provide useful guidelines for designing test inlets that should satisfy the operating conditions of the QCSEE nacelle. However, experimental data are needed to confirm these analytical results.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 8, 1974,
505-01.

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TABLE I. - FIXED INLET GEOMETRIC PARAMETERS

Diffuser parameters	
Ratio of length to exit diameter, L_d/D_e	0.826
Ratio of exit flow area to throat area, A_e/A_t	1.21
Ratio of disk exit area to throat area, $A_{e,disk}/A_t$	1.44
Location of inflection point, percent of length	50
Maximum local wall angle, deg	8.7
Equivalent conical half-angle, $(\sqrt{A_e/\pi} - \sqrt{A_t/\pi})/L_d$	2.9
Contour of inlets other than 2D	cube
Contour of inlet 2D	two superellipses
Internal lip parameters	
Ratio of major to minor axis, a/b	2.0
Contour	ellipse

TABLE II. - VARIED INLET GEOMETRIC PARAMETERS

Inlet	Internal lip		External forebody					Centerbody		Overall	
	Ratio of highlight diameter to throat diameter, D_h/D_t	Inlet area contraction ratio, $(D_h/D_t)^2$	Ratio of highlight diameter to maximum diameter, D_h/D_{max}	Ratio of length to maximum diameter, X/D_{max}	Contour exponents for bisuperellipse		Bluntness parameter, N_B	Ratio of length to exit diameter, L_c/D_e	Contour exponent for superellipse	Ratio of length to exit diameter, L/D_e	Ratio of maximum diameter to exit diameter, D_{max}/D_e
					p	q					
1A	1.25	1.56	0.905	0.200	1.76	2.25	0.0185	0.75	2.0	1.03	1.148
1B	1.25	1.56	.905	.218	1.78	1.78	.0156	.75	2.0	1.03	1.148
1C	1.25	1.56	.905	.335	1.90	1.90	.0105	.48	1.5	1.03	1.148
2A	1.21	1.46	0.905	0.200	1.77	2.25	0.0185	0.75	2.0	1.0	1.111
2D	1.21	1.46	.909	.220	1.78	1.78	.0142	.75	2.0	1.0	1.107
2E	1.21	1.46	.935	.175	1.78	1.78	.0088	.75	2.0	1.0	1.077
3A	1.17	1.37	0.905	0.200	1.76	2.26	0.0185	0.75	2.0	0.97	1.075

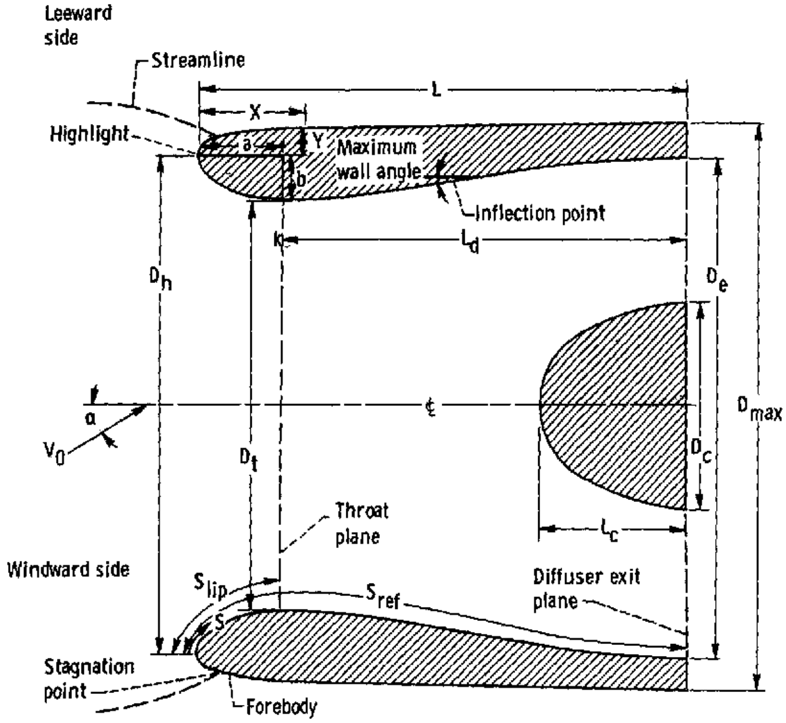


Figure 1. - Inlet geometry.

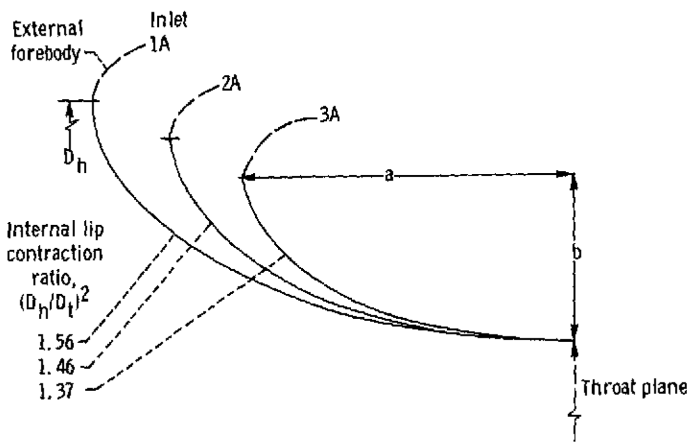
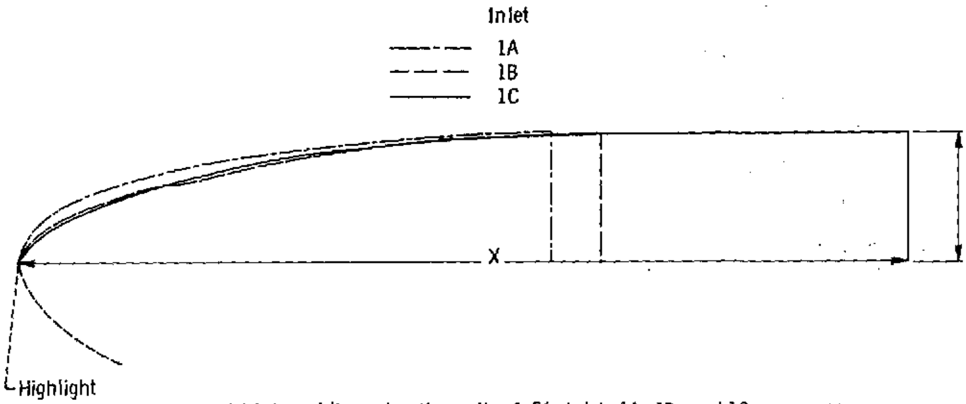
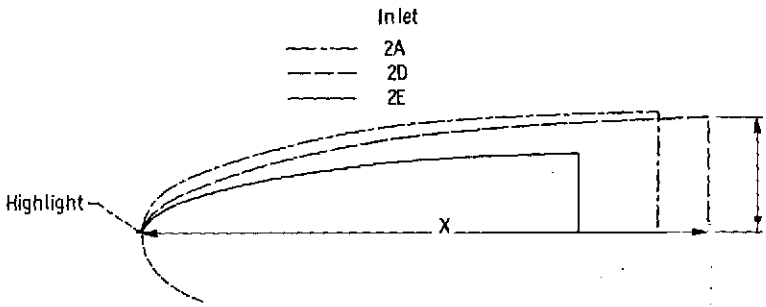


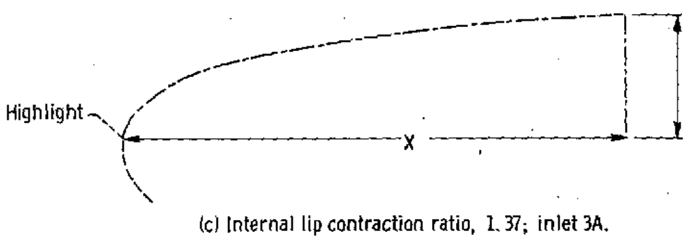
Figure 2. - Internal lip geometry.



(a) Internal lip contraction ratio, 1.56; inlets 1A, 1B, and 1C.



(b) Internal lip contraction ratio, 1.46; inlets 2A, 2D, and 2E.



(c) Internal lip contraction ratio, 1.37; inlet 3A.

Figure 3. - External forebody geometry.

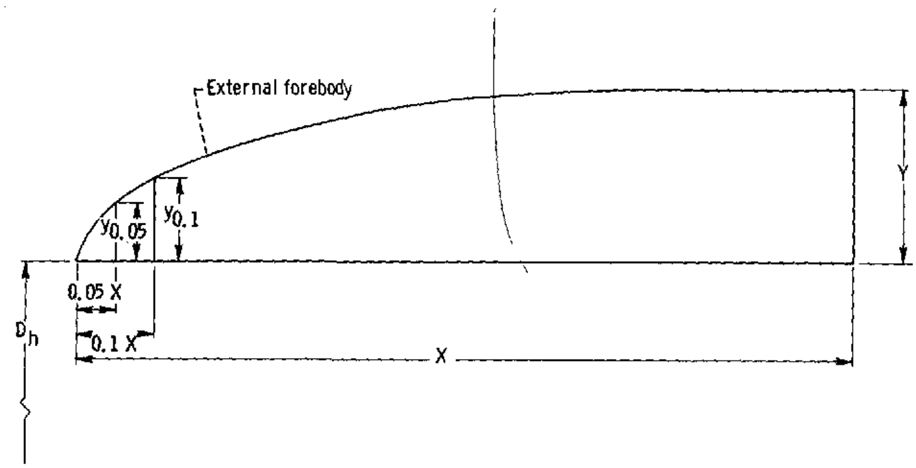


Figure 4. - External forebody bluntness parameter $N_B = (y_{0.05}/y_{0.1})(Y/X)(Y/(D_h/2))$.

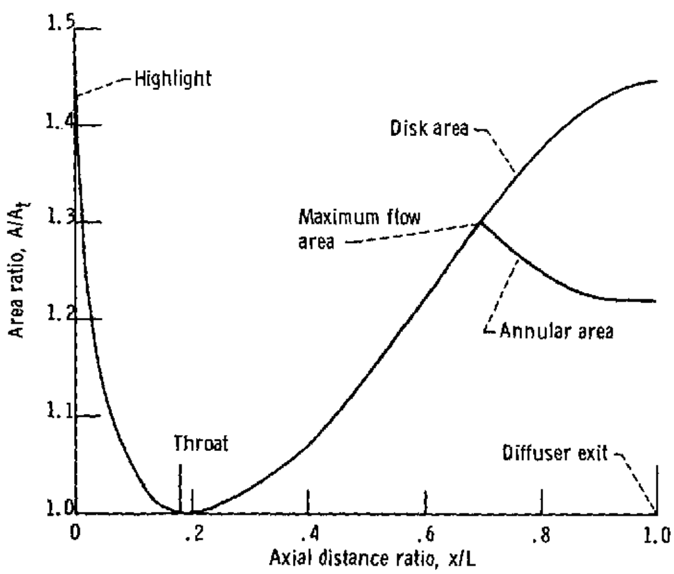
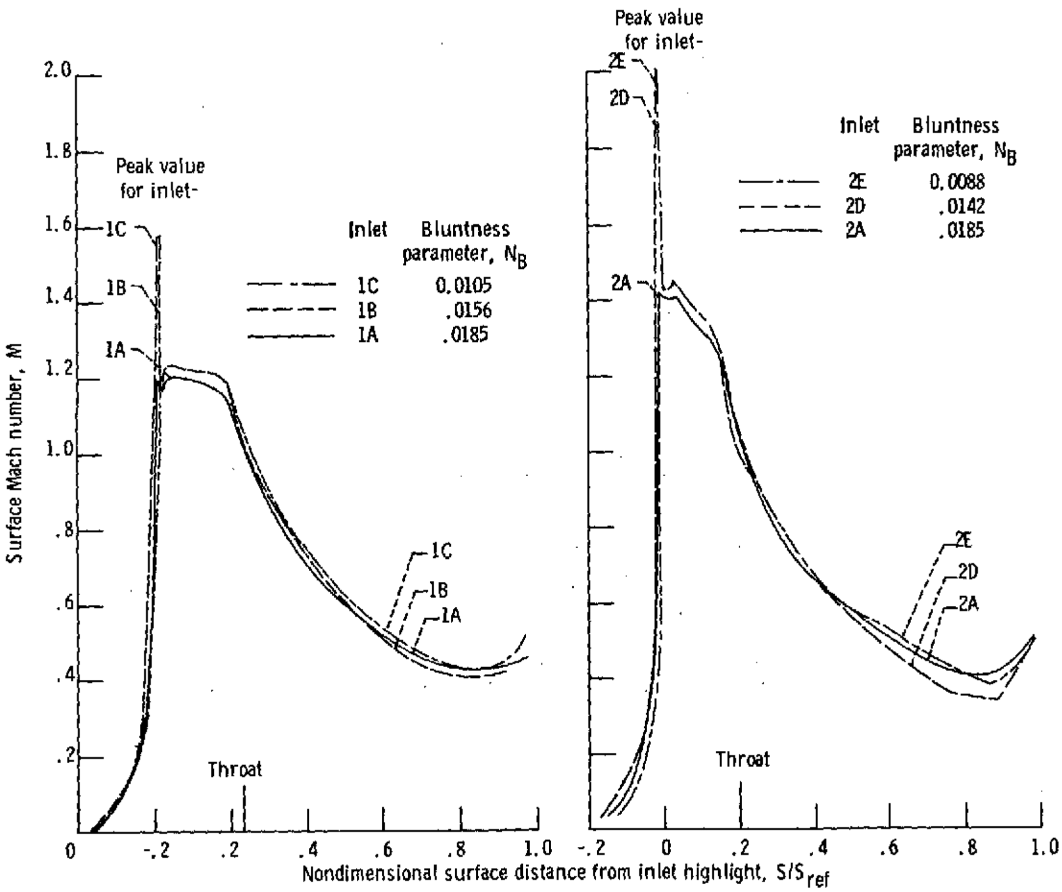


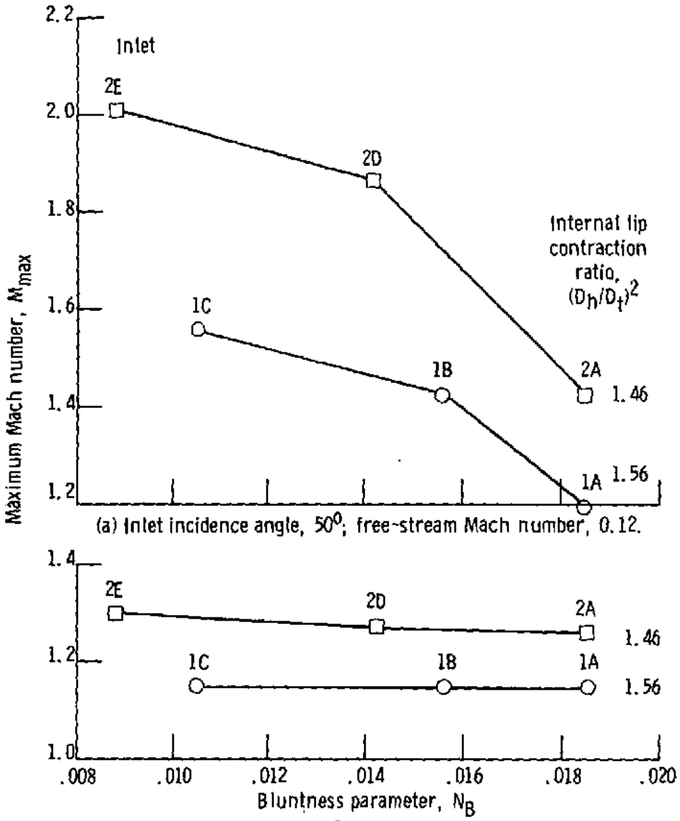
Figure 5. - Axial area distribution for typical inlet geometry (inlet 2A).



(a) Internal lip contraction ratio, 1.56.

(b) Internal lip contraction ratio, 1.46.

Figure 6. - Effect of external forebody geometry on internal surface Mach number distribution on windward side of inlet. Free-stream Mach number, 0.12; inlet incidence angle, 50°, one-dimensional throat Mach number, 0.79.



(a) Inlet incidence angle, 50°; free-stream Mach number, 0.12.

(b) Inlet incidence angle, 30°; free-stream Mach number, 0.18.

Figure 7. - Effect of external forebody bluntness parameter on maximum internal surface Mach number on windward side of inlet. One-dimensional throat Mach number, 0.79.

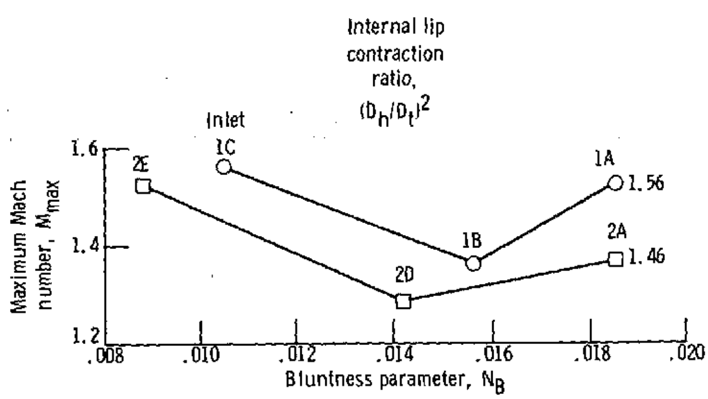


Figure 8. - Effect of external forebody bluntness on maximum external surface Mach number at cruise conditions. Inlet incidence angle, 0°; free-stream Mach number, 0.75; one-dimensional throat Mach number, 0.79.

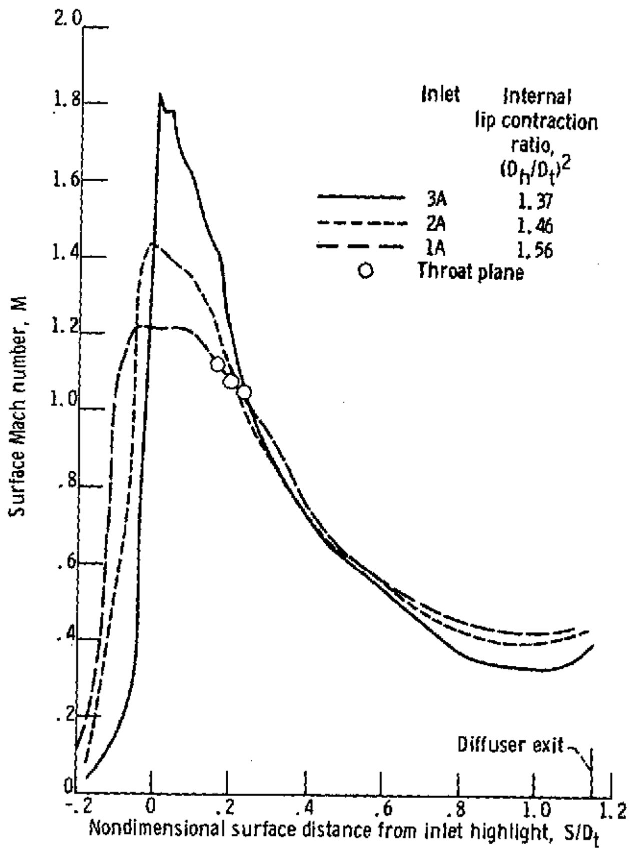


Figure 9. - Effect of internal lip contraction ratio on surface Mach number distribution on windward side of inlet. Free-stream Mach number, 0.12; inlet incidence angle, 50°; one-dimensional throat Mach number, 0.79; constant external forebody geometry (bluntness parameter, 0.0185.)

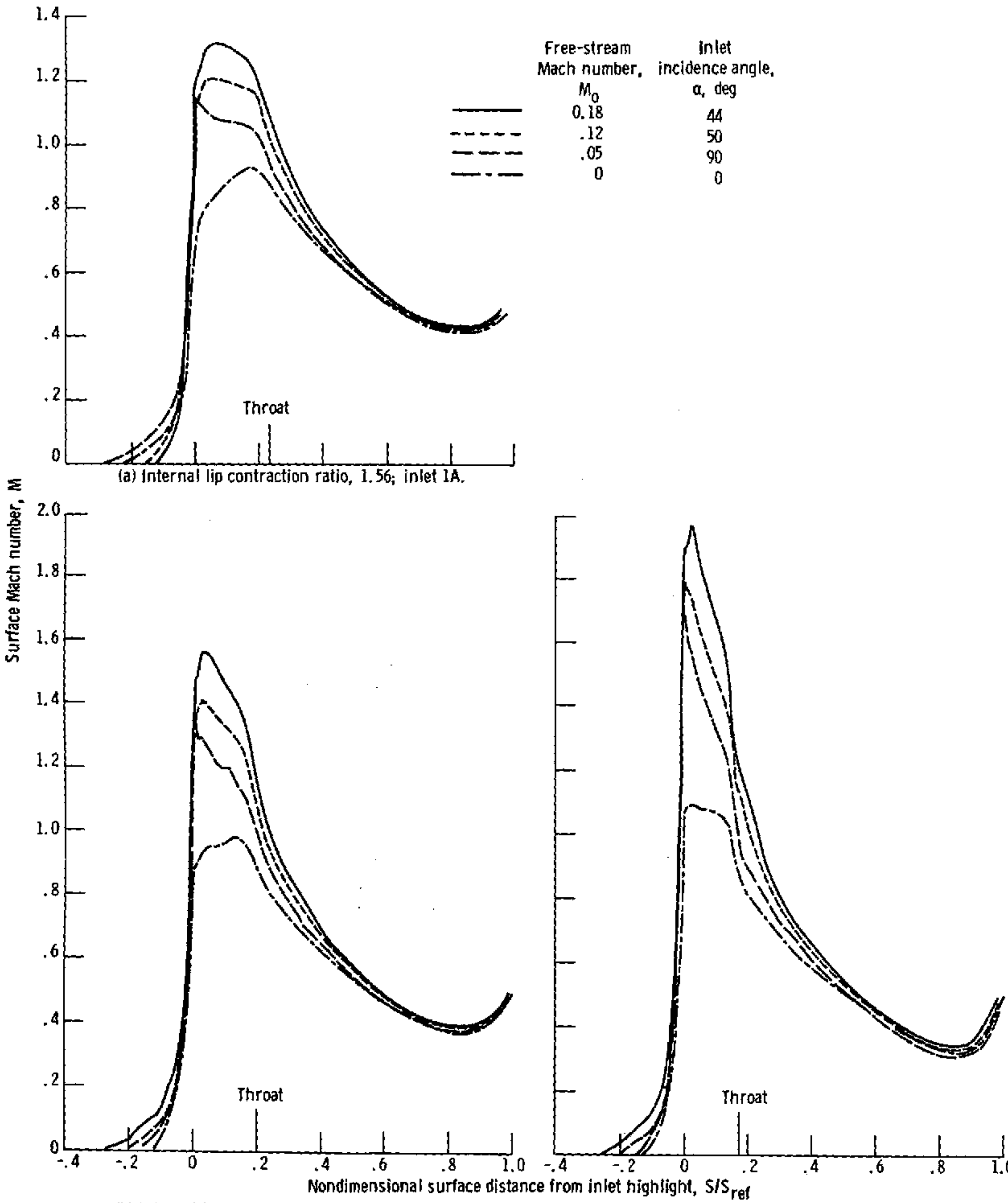


Figure 10. - Effect of free-stream flow conditions on surface Mach number distribution on windward side of inlet. One-dimensional throat Mach number, 0.79; constant external forebody geometry (bluntness parameter, 0.0185).

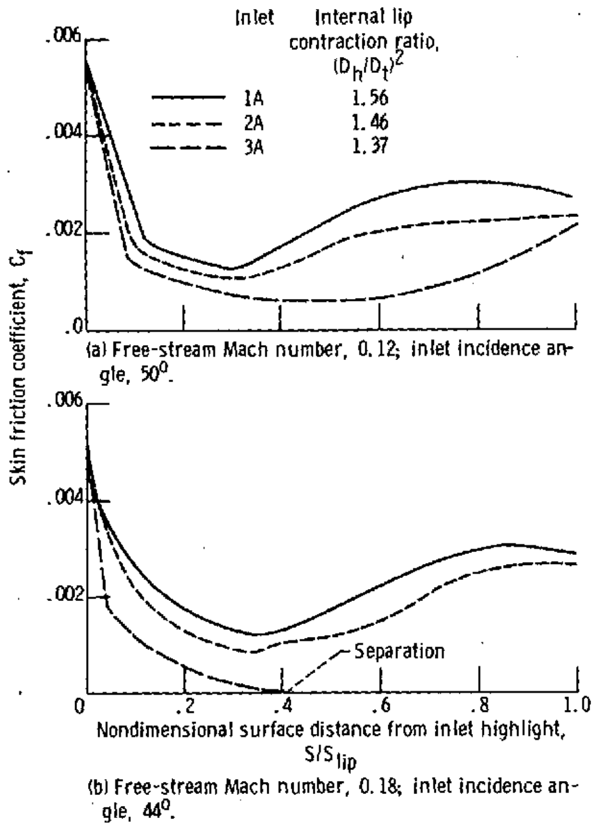


Figure 11. - Effect of internal lip contraction ratio on boundary-layer characteristics on inlet lip. One-dimensional throat Mach number, 0.79; constant external forebody geometry (bluntness parameter, 0.0185).