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# Fuselage Design for a Specified Mach-Sliced Area Distribution

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## Abstract

A procedure for designing a fuselage having a prescribed effective area distribution computed from $-90°$ Mach slices is described. This type of calculation is an essential tool in designing a complete configuration with an effective area distribution that corresponds to a desired sonic boom signature shape. Sample calculations are given for Mach 2 and Mach 3 designs. The examples include fuselages constrained to have circular cross sections and fuselages having cross sections of arbitrary shape. For a prescribed effective area distribution having sharp variations, the iterative procedure converges to a smoothed approximation to the prescribed distribution. For a smooth prescribed area distribution, the solution is not unique.


## Introduction

One approach to minimizing the effect of sonic boom noise is to attempt to design the aircraft configuration so that its ground level signature has a "low boom" shape. A class of such low-shock and low-maximum-overpressure signatures has been studied in references 1 and 2. Reference 2 also includes a systematic procedure for generating the effective area distribution for a configuration that produces the desired ground level signature along the flight ground track. This effective area distribution includes the distribution of areas of projected $-90°$ Mach slice cuts (cuts by planes swept at the Mach angle and perpendicular to the $xz$-plane) through the configuration. It also includes a significant contribution determined from the longitudinal lift distribution of the aircraft and a contribution due to nacelle-wing interference.

In order to design a configuration that has the desired effective area distribution, one procedure that has been adopted is to start with an aerodynamically feasible configuration, approximate its total effective area distribution with a low-boom distribution, then redesign the fuselage only so that the desired distribution is obtained exactly. The problem is thereby reduced to that of designing a fuselage having a prescribed effective area distribution. This problem is treated in the present investigation in a general context. The fuselage may be cambered, it may be constrained to have circular cross-section shapes, or it may be allowed to vary in cross-section shape.

## Symbols

| | |
|---|---|
| $A(x)$ | effective area distribution; area of projection on $x = 0$ plane of sector cut by $-90°$ Mach slice that intersects $z = 0$ plane at $x$ |
| $C_t$ | $z$-coordinate of fuselage camber line at terminal point |
| $l_b$ | body length |
| $l_p$ | length of prescribed area distribution |
| $M$ | flight Mach number |
| $p$ | iteration parameter |
| $r$ | body radius for bodies having circular cross sections |
| $x, y, z$ | Cartesian coordinates; $x$-axis taken through fuselage nose in flight direction |
| $\beta$ | $= \sqrt{M^2 - 1}$ |

Subscripts:

| | |
|---|---|
| $a$ | average of maximum and minimum values |
| $d$ | design |
| $i$ | iteration number |
| $s$ | slicing plane |
| 0, 1 | 0th and 1st iteration, respectively |

## Procedure and Sample Calculations

### General Considerations

For this investigation, the general approach is to gradually, by iteration, correct the fuselage shape to yield the desired effective area distribution, using a known analysis method. The fuselage equivalent area distribution calculations utilized a Langley version of a code originally written to compute wave drag from volume-effect Mach-sliced area distributions (ref. 3). The effective area associated with a particular Mach slice is assigned at the $x$-location where the slicing plane intersects the $x$-axis (see fig. 1). This effective, or projected, area is calculated by computing the coordinates of points of intersection of the slicing plane with the body shell, setting the $x$-coordinates equal to zero, and then integrating the resulting closed contour in the $x = 0$ plane. This projected area is $\frac{1}{M}$ times the actual area cut by the Mach slice.

### Circular Cross-Section Fuselage

If the fuselage is cambered, cross sections are usually defined, for the sake of convenience, in planes perpendicular to the $x$-axis ($x$ = Constant planes) rather than in planes perpendicular to the camber line. For some designs these cross-section shapes are constrained to be circular. In this case, a change in the radius at any station affects the Mach-sliced areas cut by all slicing planes that intersect that circular section (fig. 2). Thus, it is not possible to change the effective area distribution of the fuselage locally, that is, at only one point. However, if the specified area distribution is smooth with gradual variations, it is generally possible to design the corresponding fuselage while maintaining the circular cross-section constraint.

For such a fuselage, the design calculation proceeds according to the following steps.

1. Begin with an initial trial configuration having an effective area distribution that roughly approximates the desired distribution. This is usually taken to be a body that has a length

$$l_b = l_p + \beta C_t \tag{1}$$

where $l_p$ is the final value of $x$ for which the effective area is prescribed, and $C_t$ is the $z$-coordinate of the camber line at the terminal point. The radii for this initial body are then computed by the formula

$$r(x) = \sqrt{\frac{A\left(\frac{l_p x}{l_b}\right)}{\pi}} \tag{2}$$

2. Compute the actual effective area distribution $A_0$ for this initial body, and the distribution of the error

$$\Delta A(x) = A_d(x) - A_0(x) \tag{3}$$

3. For each Mach-slicing plane, determine the minimum and maximum $x$-locations of the intersection of the Mach plane with the fuselage.

4. For each input $x$-station within this interval, change the corresponding radius in such a way that the error $\Delta A$ is reduced.

5. Iterate step 4 until the desired effective area distribution is attained.

The crucial part of this procedure is step 4. As was mentioned earlier, the problem is that changing the radius at any input location changes the effective area for every Mach slice that intersects that circular cross section. For low supersonic Mach numbers—for which the slicing planes are nearly vertical—this problem is avoided if the input $x$-locations are sufficiently sparse. For higher Mach numbers, we recognize the effect of overlapping intervals but rely on iteration and smoothing to yield the desired result.

We denote the initial radius distribution in equation (2) by $r_0(x)$. The new effective area distribution $A_1(x)$ should vary approximately according to

$$\frac{r_1(x)}{r_0(x)} = \sqrt{\frac{A_1(x)}{A_0(x)}} \tag{4}$$

Now if $A_1(x)$ is taken to be the desired distribution $A_d(x)$, equation 4 should yield a radius distribution closer to the required distribution $r_0(x)$. An iteration equation is obtained from equation 4 by first subtracting 1 from both sides,

$$\frac{r_1}{r_0} - 1 = \sqrt{\frac{A_d}{A_0}} - 1 \tag{5}$$

then inserting an iteration parameter $p$, multiplying through by $r_0$, and switching to iteration indices:

$$r_i = r_{i-1}\left[1 + p\left(\sqrt{\frac{A_d}{A_{i-1}}} - 1\right)\right] \tag{6}$$

The iteration parameter $p$ is used to control the size of the step taken at each iteration. It can be permitted to vary with $x$ and/or with iteration number, but the sample calculations in this study used constant values for $p$. A large value of $p$ accelerates the iteration process, but too large a value may result in an instability in the iteration. Consequently, small values (0.025–0.1) are often used, but for some relatively low Mach number cases, values as large as 2.5 have been used effectively.

## Sample Calculations

The computer code that implements this procedure utilized iteratively the analysis procedure of reference 3. Its use is illustrated by the example shown in figure 3. Figure 3(a) shows the prescribed effective area distribution, as well as the effective area distribution for the initial shape computed from equation (2). Also shown are the results for the final design.

In all the sample calculations, there is some deviation of the effective area distribution from the specified distribution near the aft end of the fuselage. This deviation occurs because the value of $A_{i-1}$ is not permitted to fall below a certain positive value since it occurs in the denominator in equation (6), and consequently, the iteration cannot converge in this region.

Figure 3(b) shows the fuselage shape resulting from the design calculation of figure 3(a). Figure 3(c) shows the design with the vertical coordinates expanded by a factor of 6 to emphasize the variations.

To illustrate the procedure for an $M = 3$ condition, the same design distribution $A_d(x)$ was taken as for the $M = 2$ case. Figure 4(a) compares the obtained effective areas with the prescribed distribution $A_d(x)$. The resulting shape is shown in figure 4(b). Figure 4(c) shows the design with the vertical coordinates stretched by a factor of 6.

### Smoothing, Solution Existence, and Uniqueness

The computer code contains a provision for smoothing the fuselage after each iteration. However, little, if any, smoothing is actually required because the overlapping of intervals cut by different Mach slices results in an inherent smoothing. This overlapping increases with Mach number, and so the converged area distribution will be quite smooth. Consequently, greater smoothness in $A_d(x)$ is required at the higher Mach numbers. In fact, if $A_d(x)$ contains corners or regions of very high curvature, the iteration cannot converge to $A_d(x)$. In this case, the design calculation results in a smoothed approximation to $A_d(x)$.

In an attempt to obtain effective area distributions with regions of high curvature, a slightly different procedure was used. Instead of altering all the radii intercepted by a Mach slice, only the radii aft of the intersection of the Mach slice with the camber line were altered. This technique eliminated part of the overlap, and consequently the iteration converged rapidly except at very near the aft end.

However, for the same input variables as for the previous example, the fuselage had a different shape—one with cyclic radii variations (fig. 5). This waviness occurs because the modified downstream fraction of the interval cut by each Mach slice, in attempting to correct for the entire interval, exaggerates the correction locally. For example, if a particular Mach-sliced area is considerably less than that specified, the radii for the downstream part of the Mach-sliced interval would be increased significantly, because no contribution to the increase comes from the upstream radii. Now, however, downstream Mach slices that intersect this greatly enlarged part of the body have too great an effective area. The required decrease is accomplished by decreasing the downstream radii in an exaggerated manner, and so this cyclic behavior is propagated downstream. However, the desired effective area distribution is obtained.

Thus, it is seen that, at least for some cases, the fuselage corresponding to a given effective area distribution is not unique.

### Arbitrary Cross-Section Fuselages

When the cross section of the fuselage is not constrained to be circular, a similar iterative procedure is used, but the design procedure is more straightforward. In theory, one needs only to adjust the coordinates along each Mach slice in order to correct the effective area for that slice. However, the discrete input coordinates are located on $x =$ Constant stations and not along Mach slice sections. Interpolation could be used to compute the changes at each of these coordinate points. However, since the calculation must be iterated in any case, a simpler method was used. The intersection of the Mach slice with each lofting line was located, and the coordinates were adjusted at the input point on the lofting line that was nearest this intersection. (The $j$th lofting line connects the $j$th points on each of the cross sections.)

The $z$-coordinates are adjusted relative to the central value of $z$

$$z_a(x) = \frac{z_{\max}(x) + z_{\min}(x)}{2} \tag{7}$$

These values of $z_a(x)$ represent, to a close approximation, the fuselage camber line. The iteration equation (6) is now replaced by two equations:

$$z_i(x) = z_a(x) + (z_i(x) - z_a(x)) \left[1 + p\left(\sqrt{\frac{A_d}{A_{i-1}(x)}} - 1\right)\right] \tag{8a}$$

$$y_i(x) = y_{i-1}(x) \left[1 + p\left(\sqrt{\frac{A_d(x)}{A_{i-1}(x)}} - 1\right)\right] \tag{8b}$$

This iteration converges more rapidly than the circular cross-section calculation. A sample calculation is shown in figure 6 for an $M = 2$ body.

One problem that can arise with the use of equation (8a) is that the maximum and minimum $z$-coordinates at each $x$-station are gradually changed in the design process. Consequently, their average $z_a$ is changed, and the redesigned fuselage has a camber line that is slightly different from that of the original fuselage. This variation is normally slight and in most cases does not represent a problem.

However, the problem is avoided altogether if the $z$-coordinates are held constant and only the $y$-coordinates are iterated (eq. (8b)). Figure 7 shows the results of a calculation carried out in this way. Comparing this fuselage with that of figure 6 reveals somewhat greater lateral variation of the lofting lines.

## Concluding Remarks

A procedure for designing a fuselage having a prescribed effective area distribution computed from $-90°$ Mach slices has been described. This type of calculation is an essential tool in designing a complete configuration with an effective area distribution that corresponds to a desired sonic boom signature shape. Sample calculations were given for Mach 2 and Mach 3 designs. Examples included fuselages constrained to have circular cross sections and fuselages having cross sections of arbitrary shape. For a prescribed effective area distribution having sharp variations, the iterative procedure converges to a smoothed approximation to the prescribed distribution. For a smooth prescribed area distribution, the solution is not unique. That is, more than one fuselage shape may have the prescribed effective area distribution. This lack of uniqueness may permit some freedom in allowing for other design constraints, such as minimizing wave drag.

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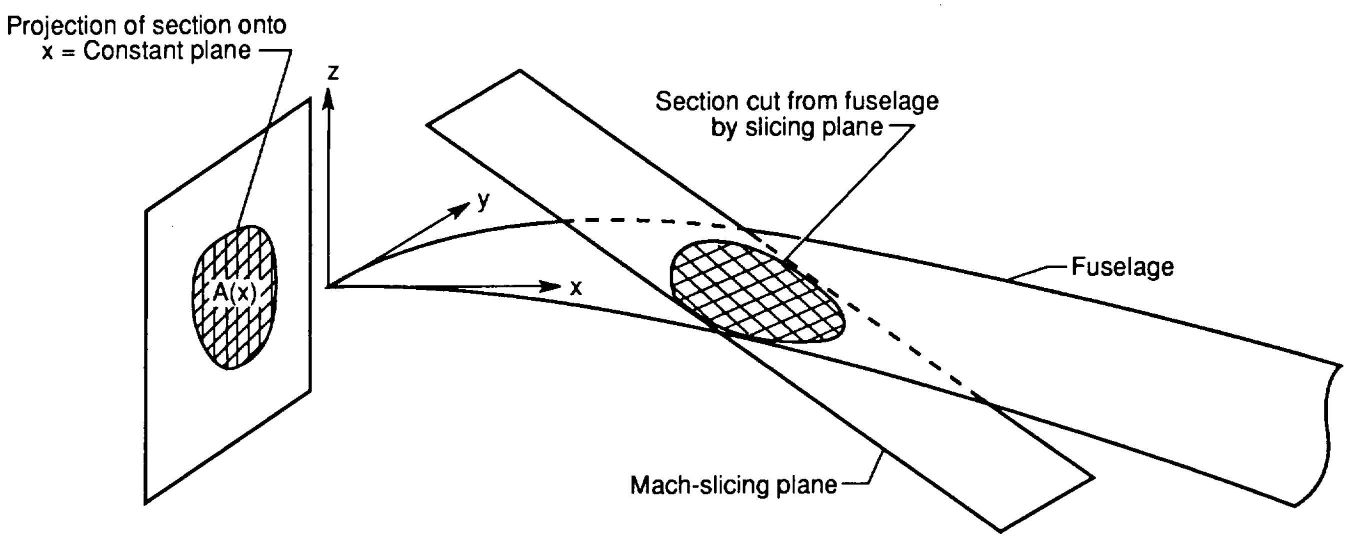



Figure 1. Diagram to illustrate definition of effective area $A(x)$.

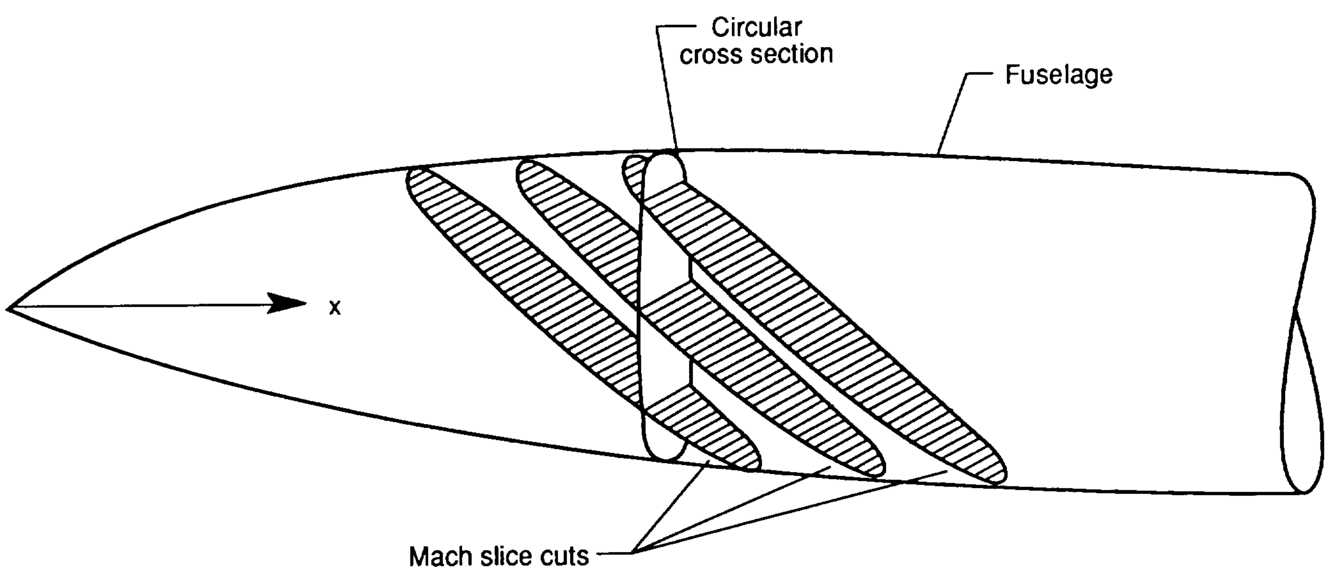
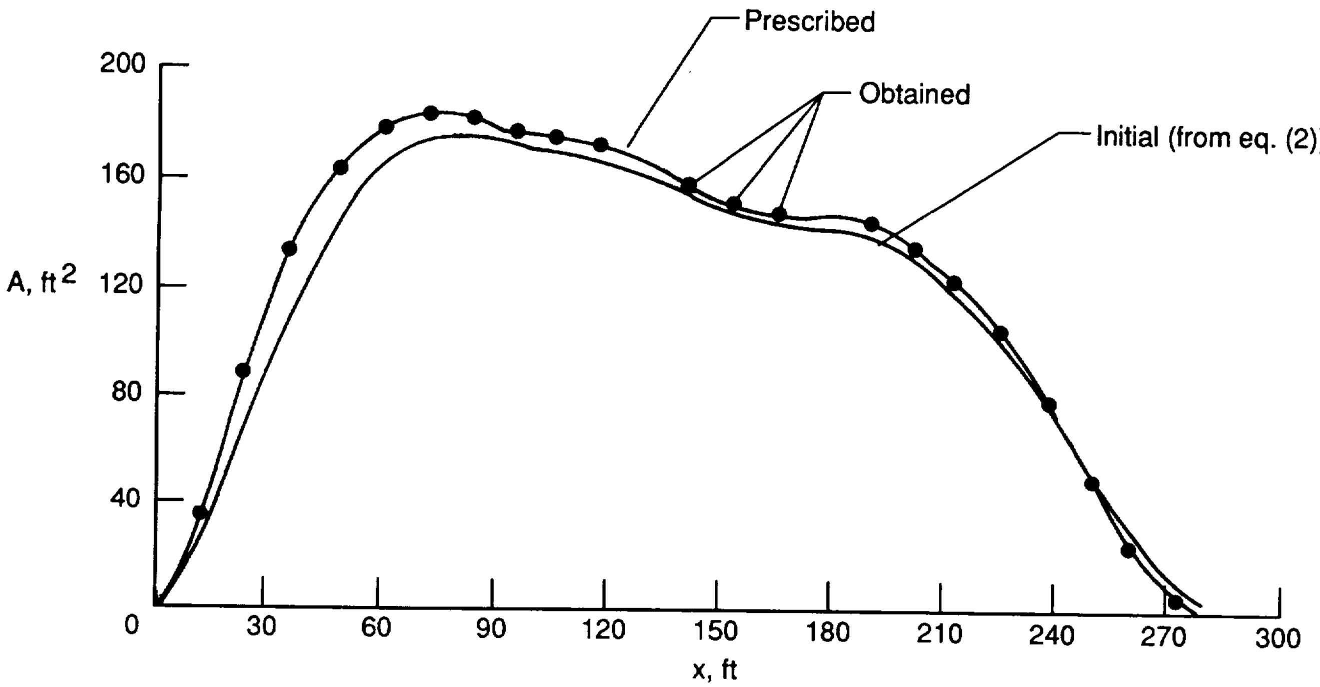
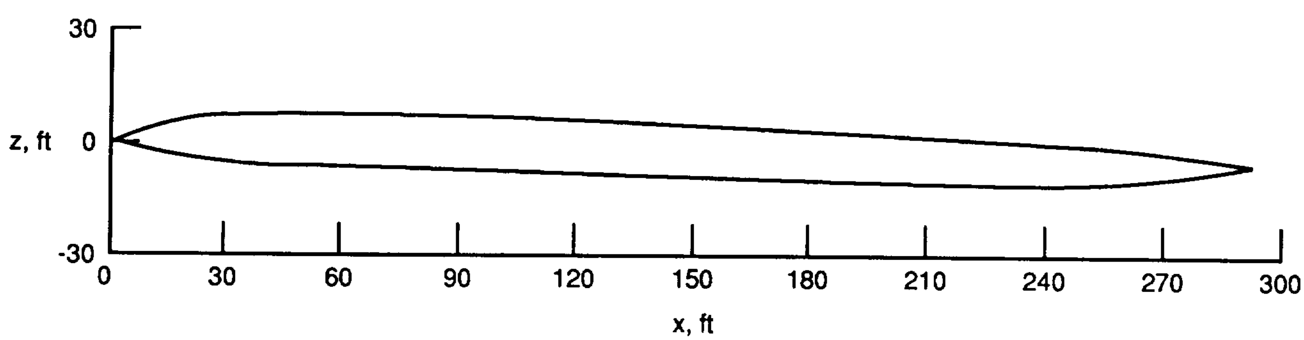



Figure 2. Overlapping of Mach slices that cut a single cross section.

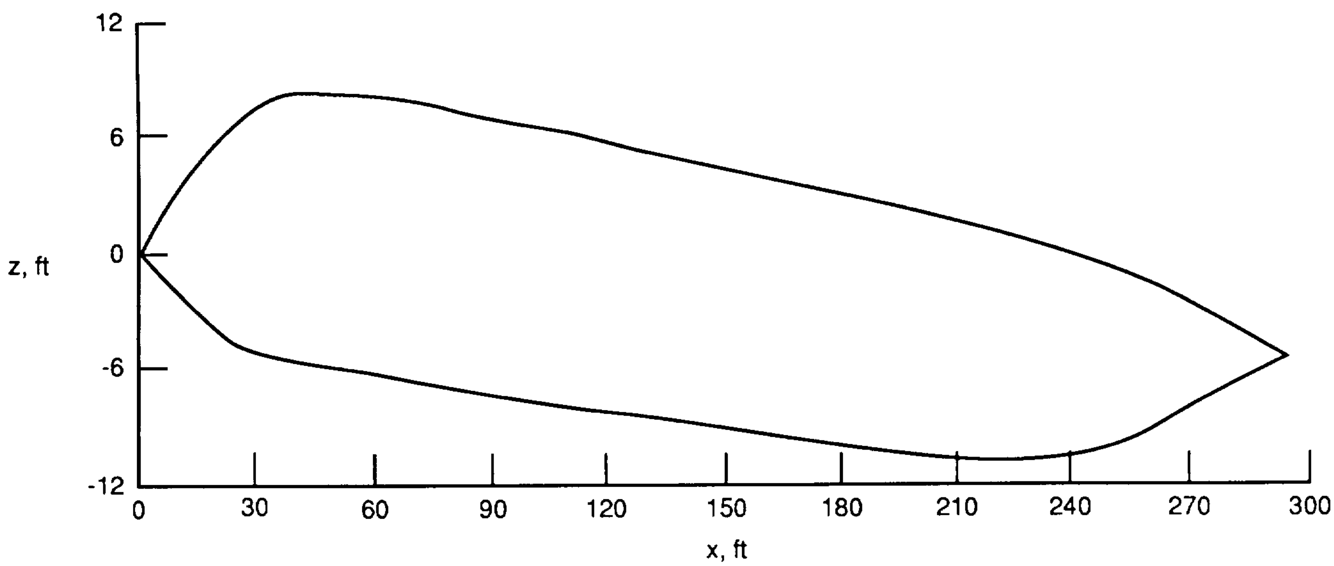



(a) Effective area distributions.



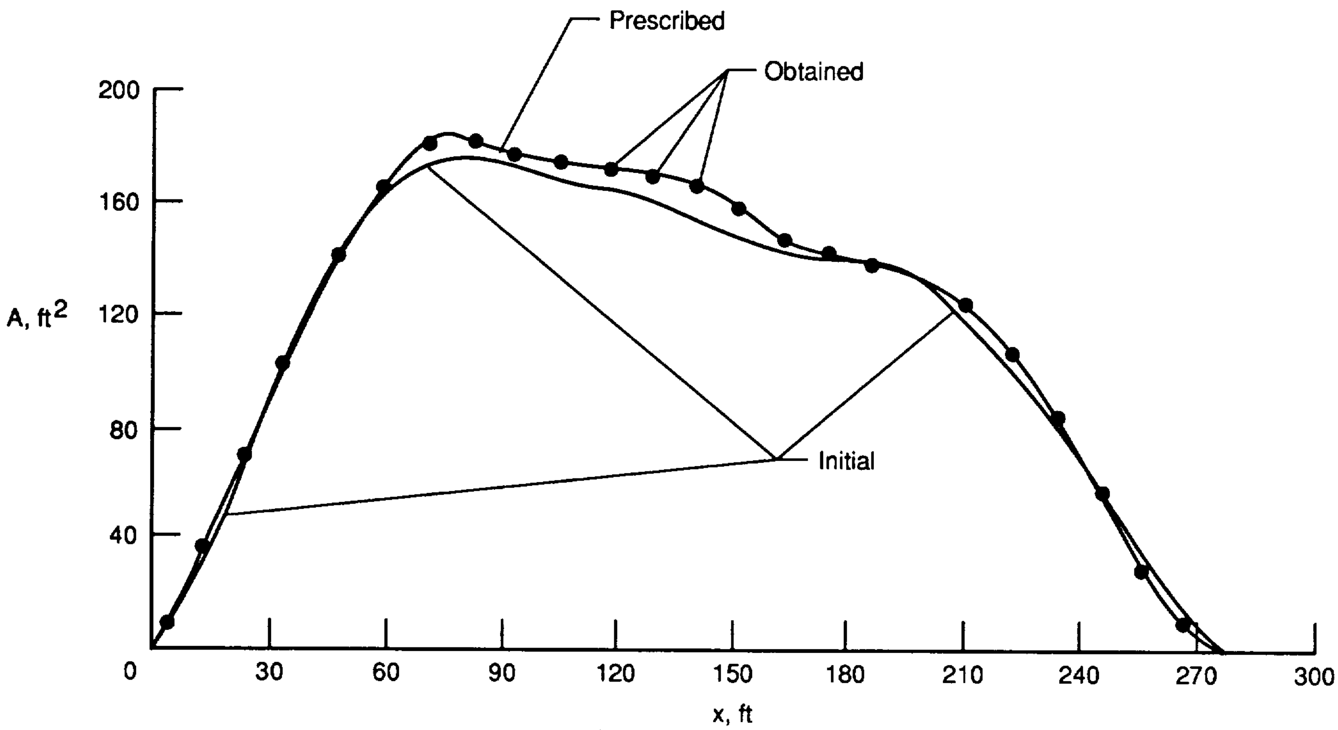

(b) Designed circular cross-section fuselage.

Figure 3. Example calculation; $M = 2$ design.

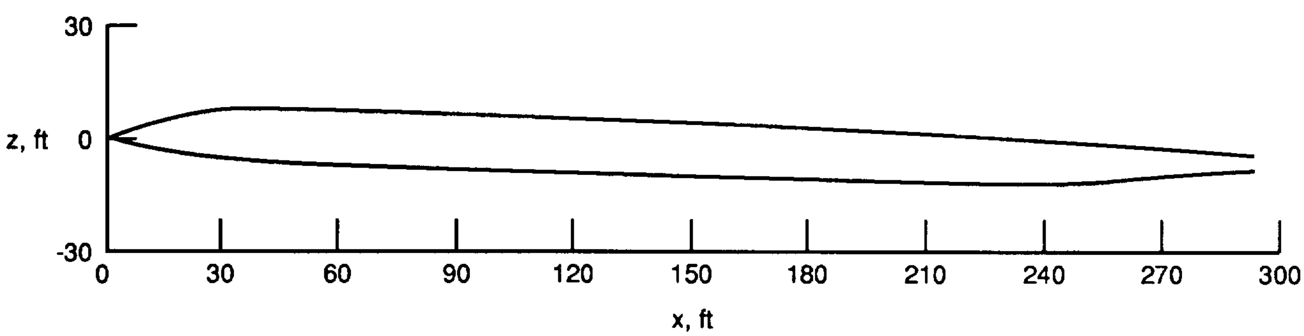



(c) Designed fuselage with vertical coordinates expanded to emphasize variation.

Figure 3. Concluded.

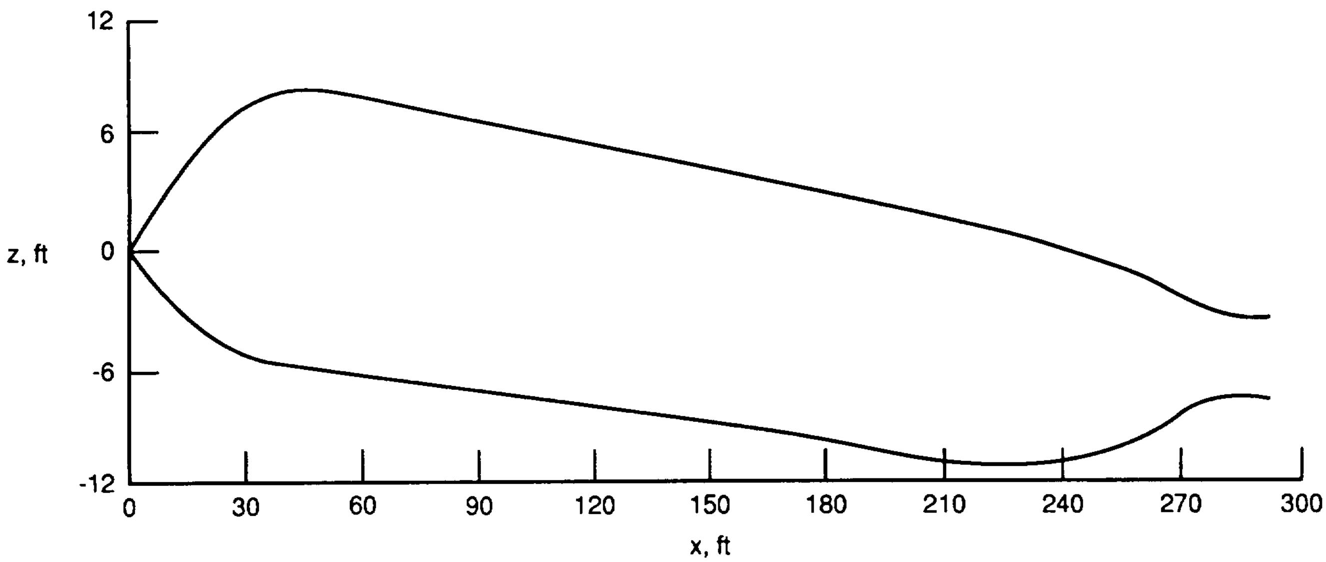



(a) Effective area distributions.



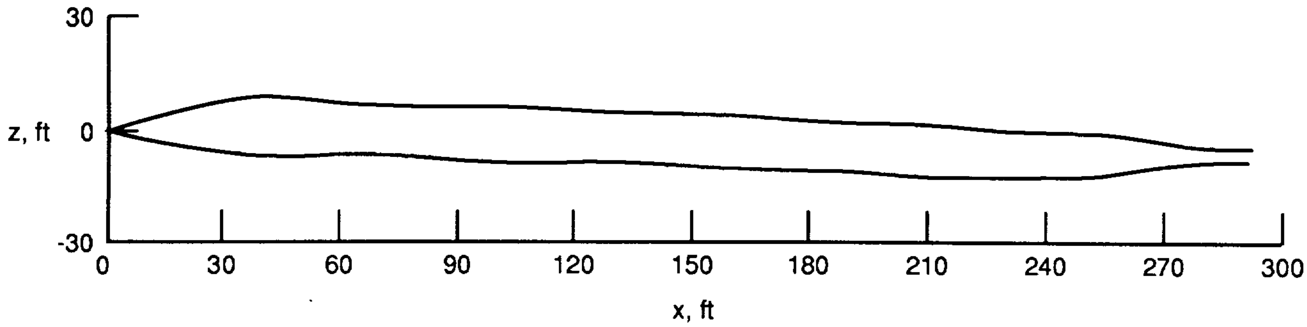

(b) Designed circular cross-section fuselage.

Figure 4. Example calculations; $M = 3$ design.

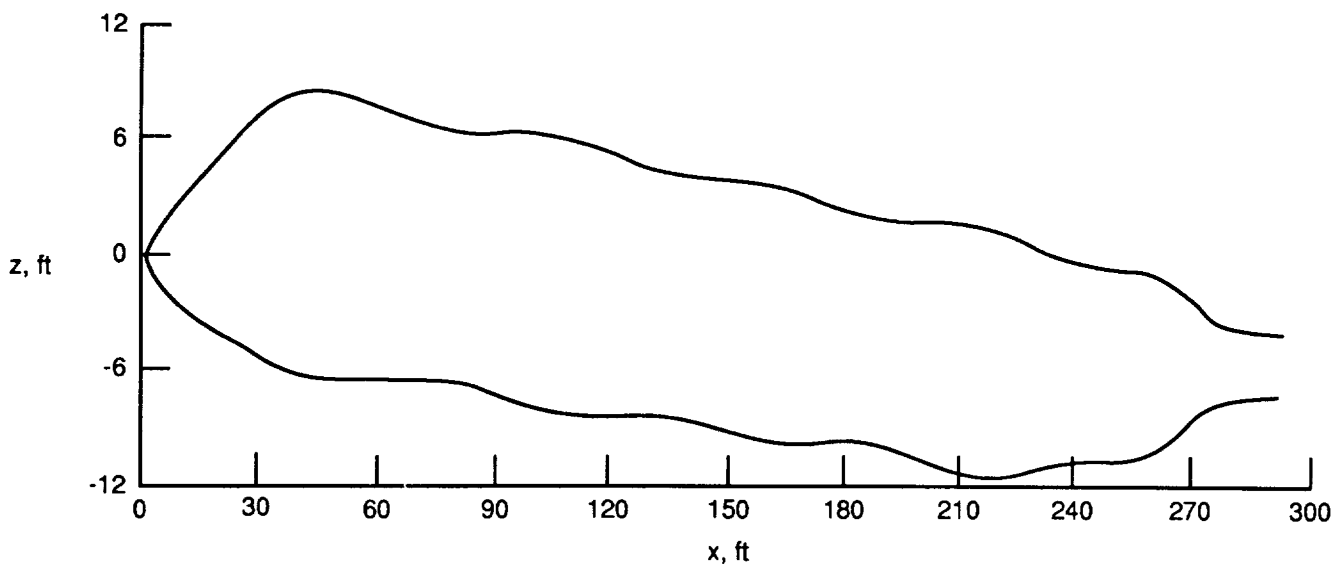



(c) Designed fuselage with expanded $z$-scale.

Figure 4. Concluded.

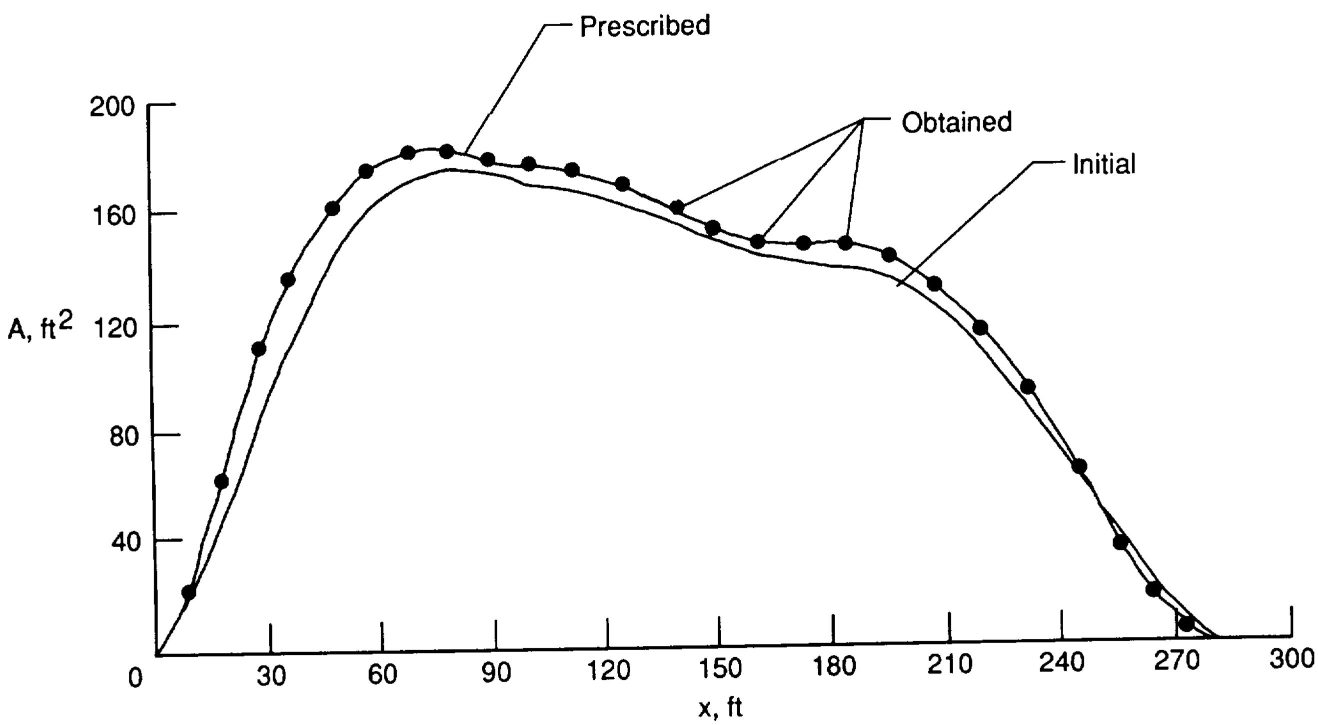



(a) Actual scale.

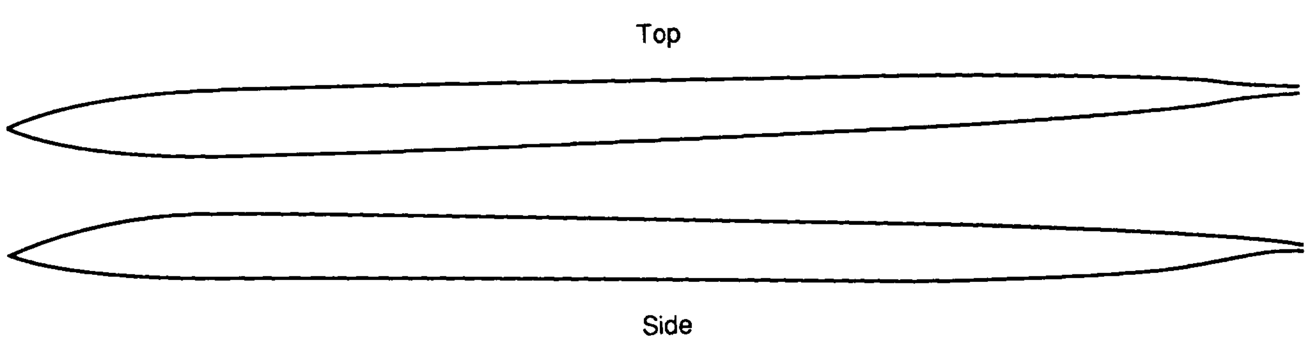



(b) Expanded $z$-scale.

Figure 5. Fuselage designed for same conditions as in figure 4 but with different iterative modification technique.

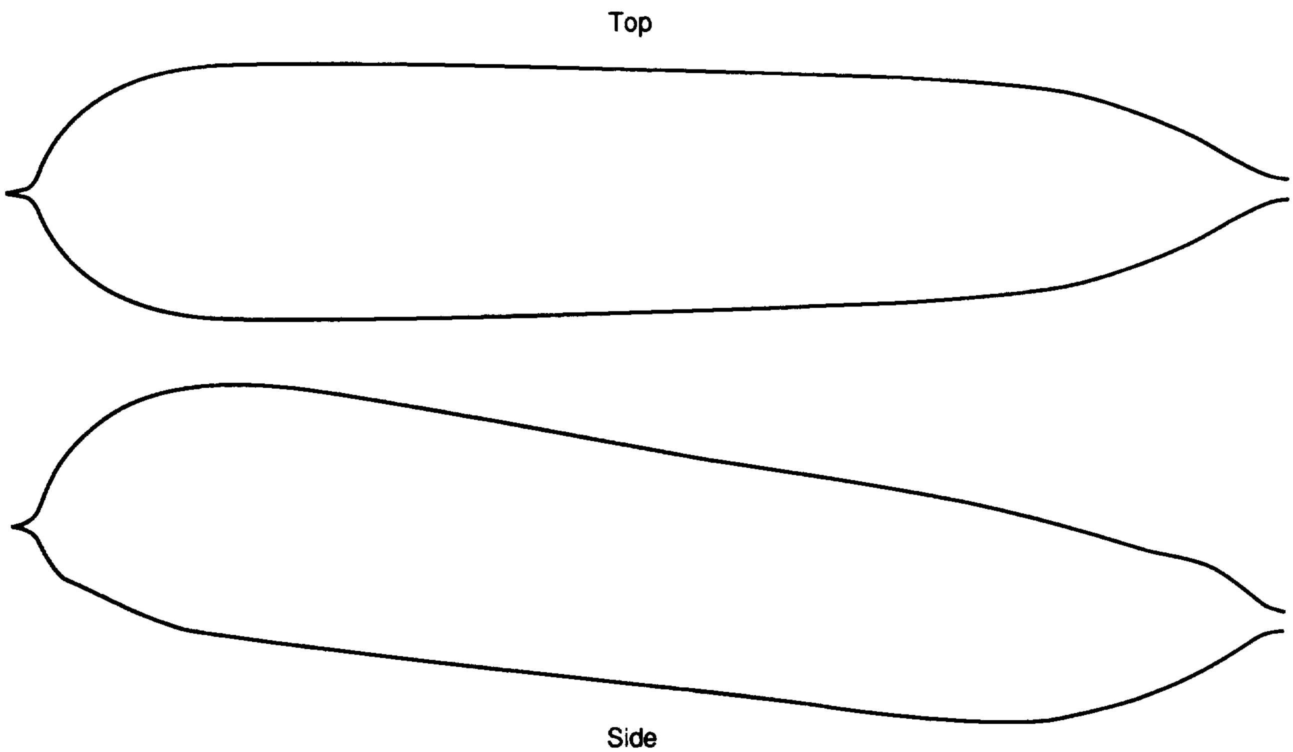



(a) Effective area distributions.



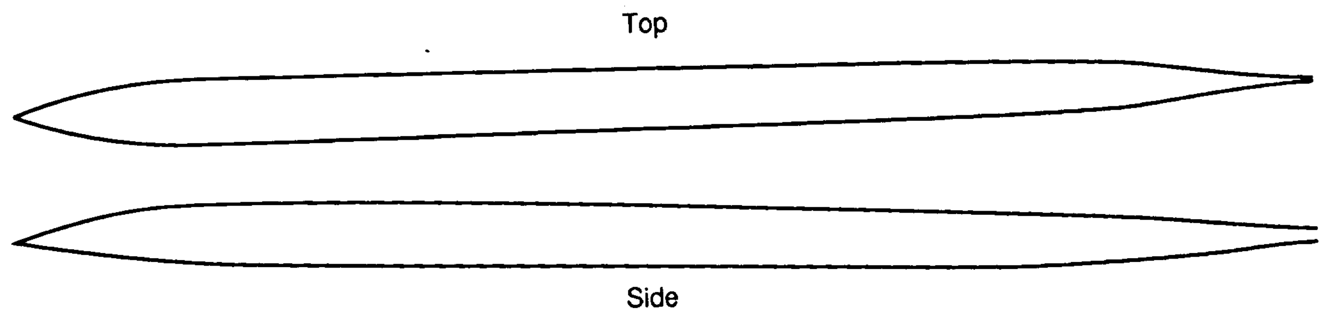

(b) Fuselage design, actual scale.

Figure 6. Arbitrary cross-section fuselage; $M = 2$ design.

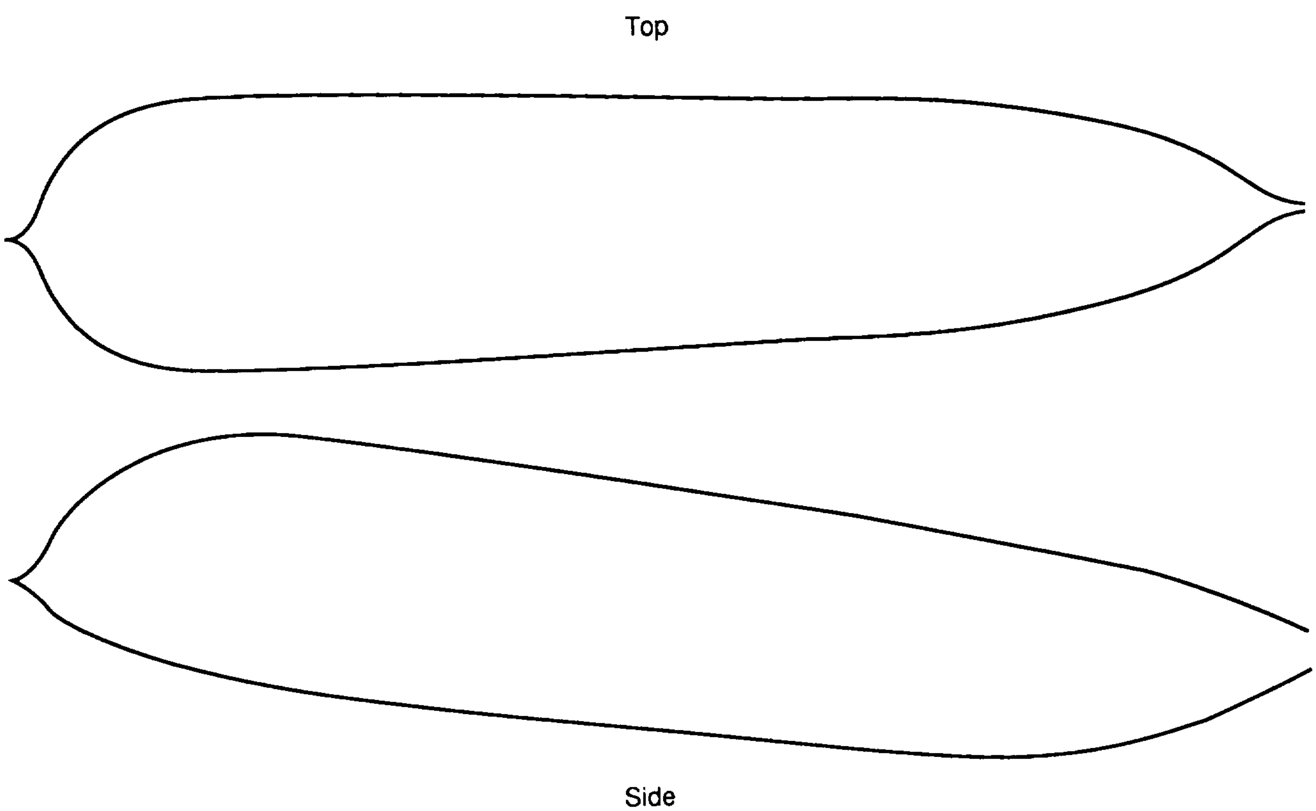



(c) Fuselage design, expanded $y$- and $z$-scales.

Figure 6. Concluded.




(a) Actual scale.




(b) Expanded $y$- and $z$-scales.

Figure 7. Fuselage designed for same conditions as for figure 6 but with $y$-variation only.

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16. Abstract

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