Technical Memorandum 4228

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# A Semiempirical Method for Obtaining Fuselage Normal Areas From Fuselage Mach Sliced Areas

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## Summary

An aircraft designed to meet low-sonic-boom or shaped ground-overpressure signature requirements has a volume and lift equivalent-area distribution that is in good agreement with the equivalent areas of a desired theoretical curve. Final-stage design modifications of the aircraft geometry to meet this requirement are usually made through adjustments to the fuselage normal cross-section areas that are derived from the corresponding fuselage equivalent areas by iterative methods. The time required to obtain good agreement between the desired low-boom-area distribution and the conceptual-aircraft total-area distribution can be reduced by using a semiempirical method that eliminates much of the final trial-and-error iteration previously employed. Fuselages from conceptual aircraft designed to generate low-sonic-boom ground overpressures at cruise Mach numbers of 2.0 and 3.0 were used as examples to examine the capabilities and limitations of the method. Results indicate that, as a design tool, the method has merit consistent with other linear-theory methods.

## Introduction

An aircraft designed to meet low-sonic-boom requirements and specified mission requirements must have its components shaped and integrated such that its total (volume and lift) equivalent areas are in good agreement with a desired, theoretical low-boom curve. These volume and lift equivalent areas are obtained, using the methods of references 1 to 3, from a mathematical analysis of the aircraft component geometry as they are iteratively blended and integrated to achieve aerodynamic efficiency, structural integrity, and low-boom potential. During the final stages of aircraft design and component integration, the agreement between the equivalent area of the desired low-boom curve and the equivalent area of the conceptual aircraft can reach the condition shown in figure 1, where only small area increments separate the two area-distribution curves. A corresponding comparison of ground overpressure signatures computed from these two area distributions with the signatures is shown in figure 2. The overall agreement is fairly good, but it could be much better if small but strategic geometry adjustments were made on the aircraft.

A change in the wing planform would require a new camber surface and more computation time and effort with new problems of integrating wing, fuselage, engines, fins, etc., to be resolved. The simplest and most convenient solution is, in most cases, to add all the required equivalent area to the fuselage. (See fig. 3.) This strategy is based on the assumptions that the required adjustments do not prevent the fuselage from being used as originally planned, and that the fuselage can be represented as a cambered body of revolution when calculating the projected Mach plane area slices in the wave-drag code of reference 1. Thus, the general problem of obtaining fuselage normal area from fuselage equivalent areas is made more tractable.

Because trial-and-error fuselage modifications can be tedious and time consuming, a computer-implemented method would be of help during this design phase. A semiempirical method, based on slender-body and area-rule cone theories, has been devised and encoded. It generates fuselage normal areas that meet low-boom-area agreement conditions with a reasonable degree of accuracy. Another approach, iterative in methodology, is discussed in reference 4. The renewed interest in conducting research that could lead to a second-generation supersonic-cruise commercial transport has provided the stimulus to develop a design tool for adjusting the fuselage areas to match those needed for obtaining desired low-boom equivalent-area distributions.

## Symbols

| | |
|---|---|
| $A$ | fuselage cross-sectional area normal to fuselage camber line $z(x)$, ft$^2$ |
| $A_E$ | equivalent ("Mach sliced") areas, ft$^2$ |
| $h$ | aircraft altitude, ft |
| $K_c$ | fuselage camber factor (see fig. 6) |
| $K_s$ | fuselage surface slope factor (see fig. 7) |
| $l$ | fuselage length, ft |
| $l_E$ | fuselage effective length, $l + \beta z(l)$, ft |
| $M$ | Mach number |
| $\Delta p$ | incremental pressure measured from free-stream static pressure |
| $r$ | fuselage radius derived from equivalent areas, $\sqrt{A_E/\pi}$, ft |
| $\hat{r}$ | fuselage radius derived from normal areas, $\sqrt{A/\pi}$, ft |
| $x$ | distance along longitudinal coordinate axis, ft |
| $x_E$ | effective distance along longitudinal coordinate axis, $x + \beta z(x)$, ft |
| $z$ | fuselage camber ordinate, ft |
| $\beta$ | Mach number parameter, $\sqrt{M^2 - 1.0}$ |

$\Delta$ small increment

$\epsilon$ fuselage camber-line slope, $\tan^{-1}(\Delta z/\Delta x)$, deg (see fig. 6)

$\eta$ surface slope, $\Delta\hat{r}/\Delta x$ at $x$ (see fig. 7(b))

$\mu$ Mach angle, $\sin^{-1}(1.0/M)$, deg

Subscripts:

0,1 area or radius notation (see fig. 7(b))

## Method Description

The empirical method used to compute fuselage normal areas from fuselage equivalent areas consists of three elements shown schematically in figure 4. A change of equivalent-area position from the effective-length line to the fuselage camber line is the first element. A fuselage camber slope correction and a fuselage surface slope correction are the second and third elements; these elements are applied to the repositioned equivalent area to estimate the normal area.

The first element is described with the aid of figure 5. At a distance along the fuselage longitudinal axis $x$ an effective distance $x_E$ is computed as follows:

$$x_E = x + \beta z(x) \tag{1}$$

A corresponding equivalent area $A_E$ is found and an uncorrected normal-area estimate at distance $x$ is calculated as follows:

$$A(x) = A_E(x_E) \tag{2}$$

The second element, a fuselage camber slope factor $K_c$, is calculated as follows:

$$K_c = \sin[\mu + \tan^{-1}(\Delta z(x)/\Delta x)]/\sin\mu \tag{3}$$

This element corrects, approximately, for local fuselage camber slope effects. Figure 6 shows the derivation of equation (3). A cylinder of area $A_0$ is superimposed on the fuselage section at distance $x$; the axis is tangent to the fuselage camber line and the diameter is the same as the fuselage station diameter. Geometric projection of the cylinder (fuselage) normal area $A_0$ to the Mach plane and then to a plane normal to the free-stream direction gives an effective area $A_E$. In the reverse sense, cylindrical area $A_0$ can be found from $A_E$ by using the factor $K_c$ given by equation (3).

The third element, a fuselage surface slope factor $K_s$, is obtained from an approximation to local cone theory. In figure 7, the essentials of this approximation are sketched. The fuselage camber is excluded, because this effect is accounted for by the factor $K_c$. The normal radius $\hat{r}$ and the local surface slope $\eta$ are estimated from the equivalent areas, since these quantities are initially known (fig. 7(a)). A truncated cone that is Mach line bound is calculated from $\mu$, $\eta$ and $r$ so as to obtain values of $x_0$ and $x_1$. Surface slope is obtained from

$$\tan\eta \approx (\hat{r}_1 - \hat{r}_0)/(x_1 - x_0) \tag{4a}$$

as shown in figure 7(b) and is iterated from

$$\tan\eta = (1 - \beta^2\tan^2\eta)^{3/4}\,\Delta r/\Delta x_E \tag{4b}$$

The local slope factor $K_s$ is then obtained as follows:

$$K_s = (1 - \beta^2\tan^2\eta)^{3/2} \tag{5}$$

Combining these three elements provides an estimate of the fuselage normal area at $x$ from

$$A(x) = K_c K_s A_E(x_E) \tag{6}$$

This method of obtaining fuselage normal areas from equivalent areas is very accurate when the fuselage is cylindrical or nearly cylindrical, since

$$K_s = 1.0 \tag{7a}$$

$$A(x) = A_E(x_E)\sin(\mu + \epsilon)/\sin\mu \tag{7b}$$

It is based on the same linearized theory and slender-body theory that is used in other analysis codes; thus, it has the same limitations and applicability. The following examples illustrate the applicability of this empirical method, and the results demonstrate its capabilities and limitations.

## Examples and Results

The following two examples demonstrate the method in its intended mode of application: determining fuselage normal areas for the design of conceptual aircraft to meet low-sonic-boom requirements. The aircraft design has progressed to the point (fig. 8) where it satisfies mission requirements. At this stage, the wing planform shape, camber and twist, and airfoil thickness have been set; the fuselage volume and camber hold the required crew, passengers, and baggage, and position the control surfaces; and the engine and inlet-nozzle nacelles are designed and integrated with the airframe. Aircraft total-equivalent areas are close to, but not in adequate agreement with, the theoretical areas required for an acceptable sonic-boom signature shape. The most convenient way of solving this problem is to add all the remaining equivalent-area increments to the fuselage and then calculate a normal-area distribution that has the desired, accumulated equivalent-area distribution.

Example 1 was a Mach 2.0 conceptual aircraft (fig. 8) that had small differences between its designed and its desired low-boom equivalent areas (fig. 9(a)). These incremental areas were added to the fuselage equivalent areas, so that the empirical method could be used to obtain corrected fuselage normal areas. Figure 9(b) shows a comparison between the initial fuselage equivalent areas, the low-boom-required fuselage equivalent areas, and the wave-drag program-calculated "Mach sliced" fuselage areas obtained from fuselage normal areas supplied by the empirical method code. The relatively good agreement between the required and the calculated equivalent fuselage areas indicates that this step was successfully completed. As a check on how well the new fuselage areas blended with the other aircraft components to meet low-boom requirements and generate a low-boom ground signature, the combined volume and lift equivalent areas were used as input data in a sonic-boom propagation code (ref. 5). A comparison of overpressure signatures from the low-boom conceptual aircraft (before and after modification) and the minimum overpressure prediction code is shown in figure 9(c). Since the signature shape is sensitive to trends in the second derivative of area, the fairly good agreement between the desired overpressure and low-boom constrained aircraft signatures indicates that the empirical-fuselage normal-area predictions closely matched those that met low-boom requirements at a Mach number of 2.0.

Example 2 was similar to the design described in example 1, but with a design Mach number of 3.0 instead of 2.0. A comparison of initial areas, low-boom-required equivalent areas, and predicted Mach sliced fuselage areas from the empirical-method code are shown in figure 10(a). The agreement in area magnitudes and trends is fairly good overall. However, near regions of rapid area change, the agreement in magnitude is not as good as at a Mach number of 2.0. In figure 10(b), where overpressure signatures are compared, the effects of area differences are readily seen. The nose shock is 10 percent stronger than desired, the required ramp-like compression and expansion is replaced by two small but finite-strength shocks that sandwich a hump-like cluster of minishocks, and the tail shock is, like the nose shock, stronger than desired.

With additional trial-and-error area trimming, this signature shape can be brought closer to the desired shape. Thus, the fuselage normal-area distribution calculated by the empirical method can be a major first step toward a final, satisfactory solution. As such, it can indicate whether an exact solution is worth pursuing by providing a zero-lift wave-drag estimate and a predicted ground-overpressure signature shape.

## Concluding Remarks

An aircraft designed to meet low-sonic-boom or shaped ground-overpressure signature constraints has a volume and lift equivalent of a theoretical constraint curve. Final-stage design modifications of the aircraft geometry to meet this requirement are usually made through adjustments to the fuselage normal cross-section areas that are derived from the corresponding fuselage equivalent areas by iterative methods. However, the time required to obtain a good agreement between the desired, low-boom-area distribution and the conceptual-aircraft total-area distribution can be reduced by using a semi-empirical method that eliminates much of the final trial-and-error iteration previously used. Fuselages from conceptual aircraft designed to generate low-sonic-boom ground overpressures at cruise Mach numbers of 2.0 and 3.0 were used as examples to examine the capabilities and limitations of the method. Results indicated that the method has merit as a design tool consistent with other linear-theory methods.

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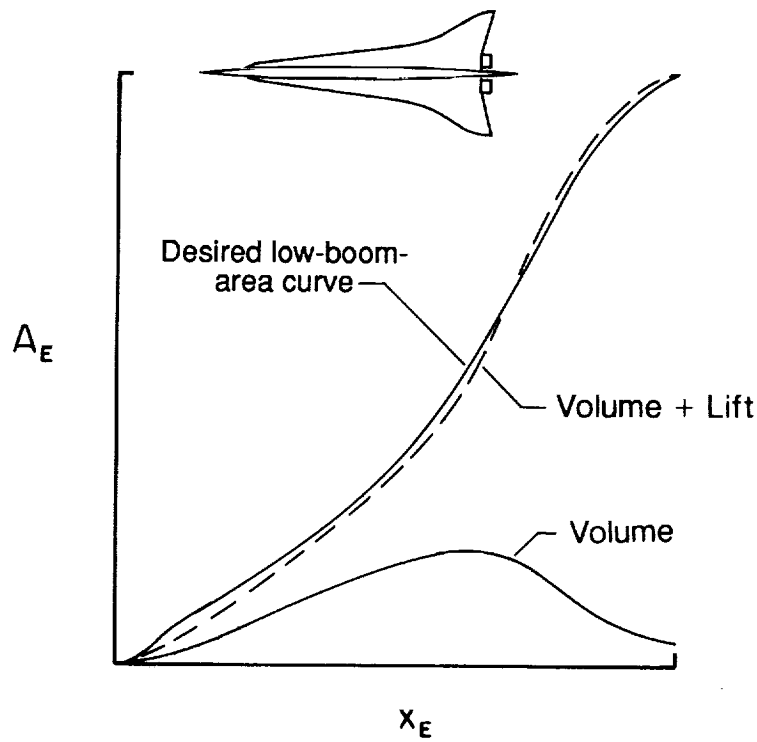



Figure 1. Comparison of equivalent areas from conceptual aircraft with desired low-boom-area curve near final stages of geometry definition.

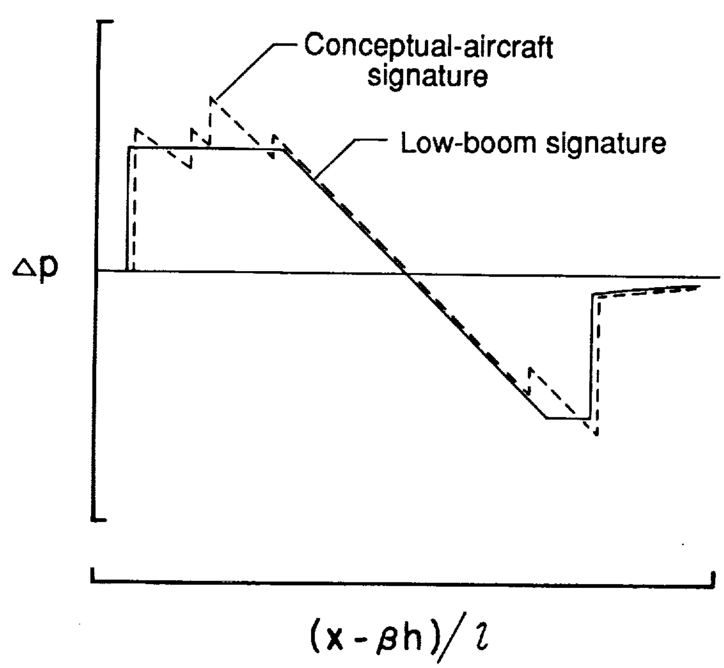



Figure 2. Comparison of overpressure signatures from conceptual aircraft with low-boom equivalent areas.

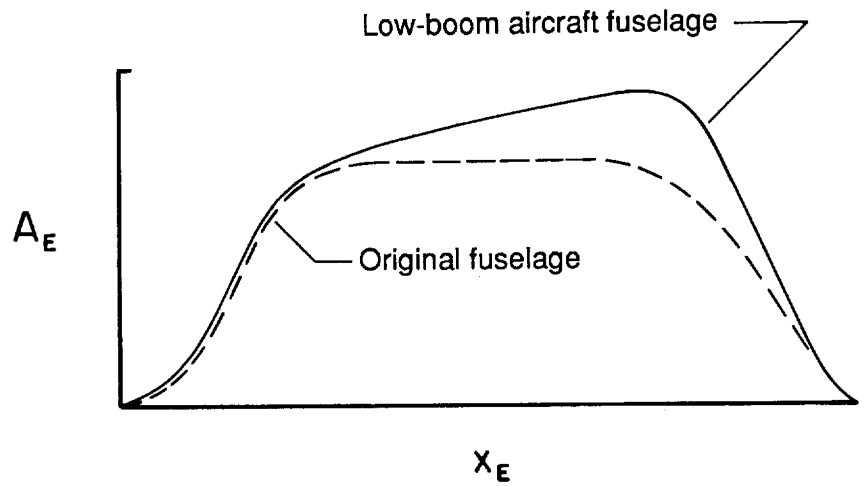



Figure 3. Comparison of fuselage areas to show modifications needed to meet desired low-boom requirements.

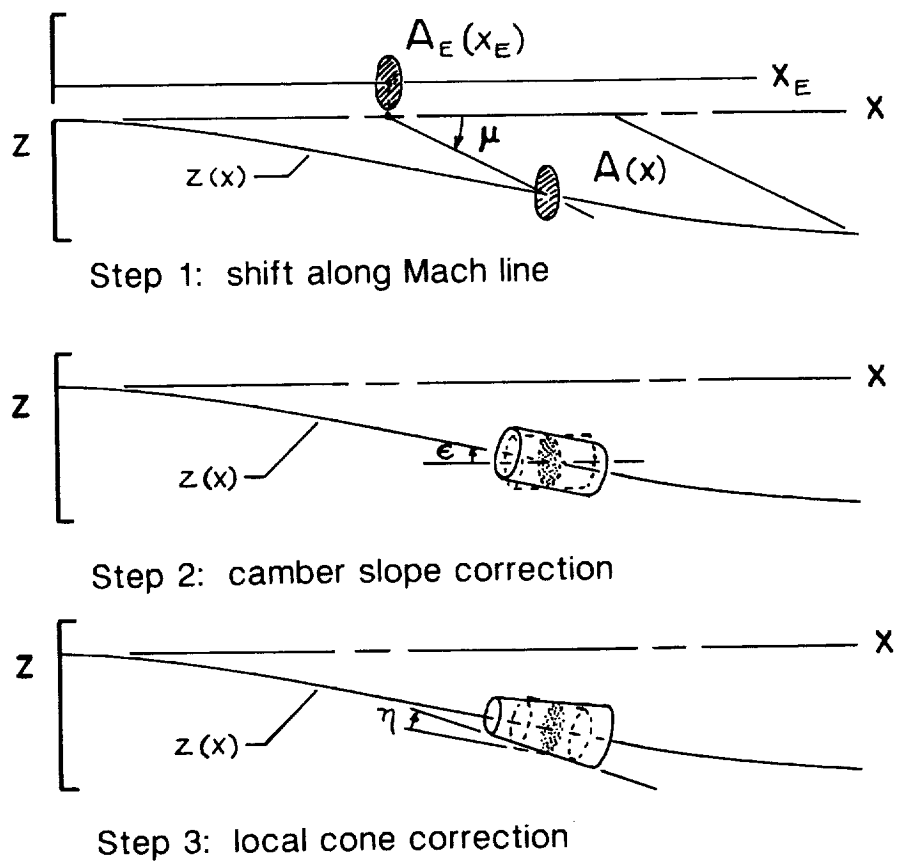



Figure 4. Schematic description of empirical method.

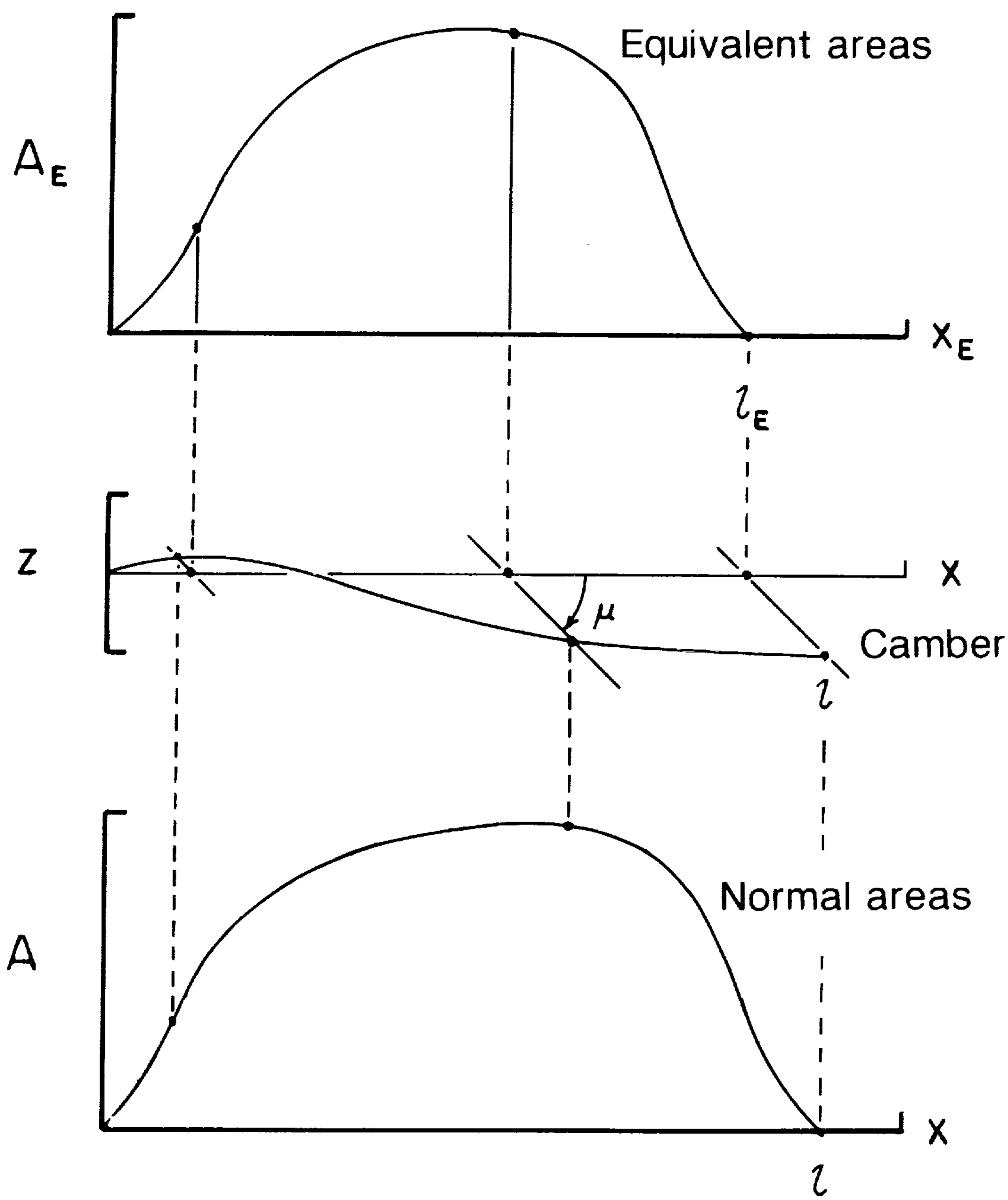
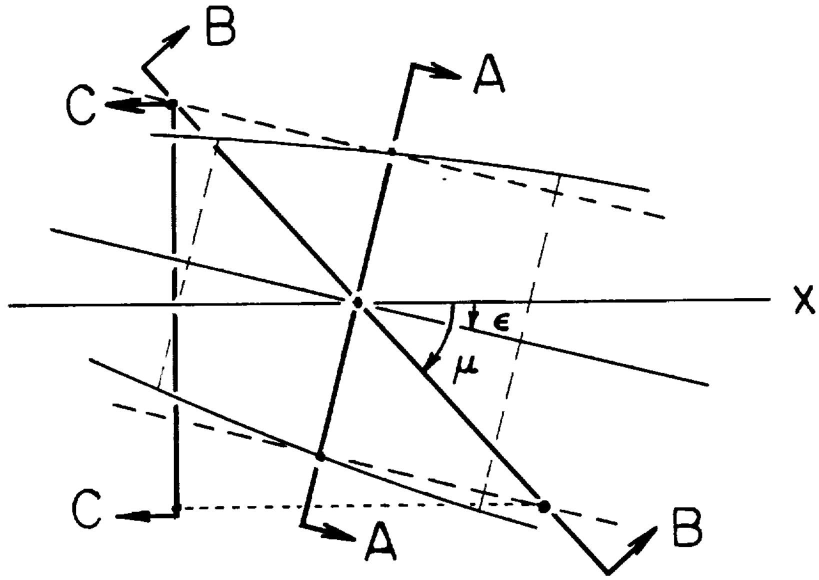



Figure 5. Mach line shift of areas $A_E(x_E)$ for $A(x) \approx A_E(x_E)$ (uncorrected first estimate).




$A_0$ = Area across section A-A

$A_1$ = Area across section B-B

$A_E$ = Area across section C-C

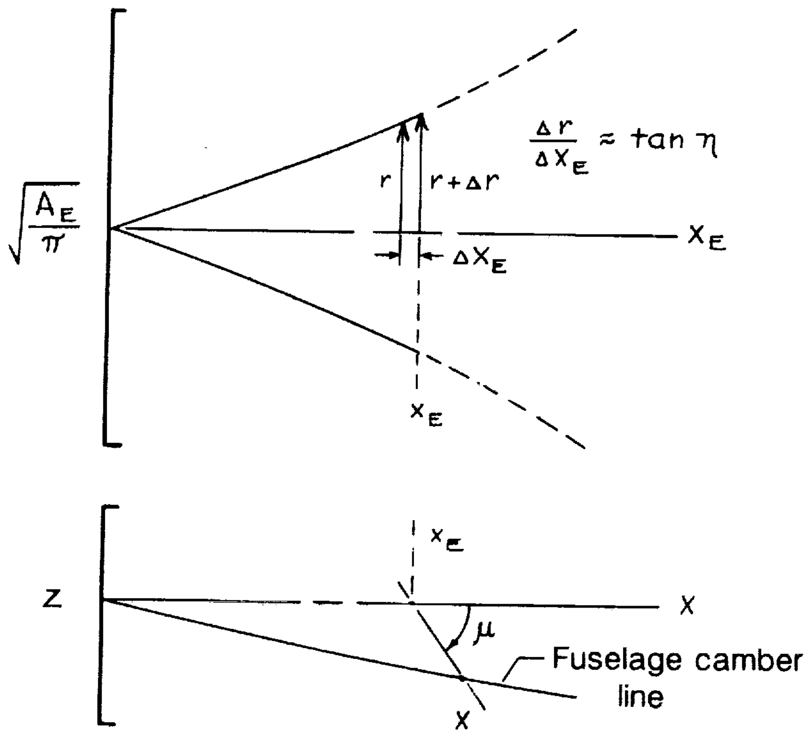
$$A_1 = A_0 / \sin(\mu + \epsilon)$$

$$A_E = A_1 \sin \mu$$

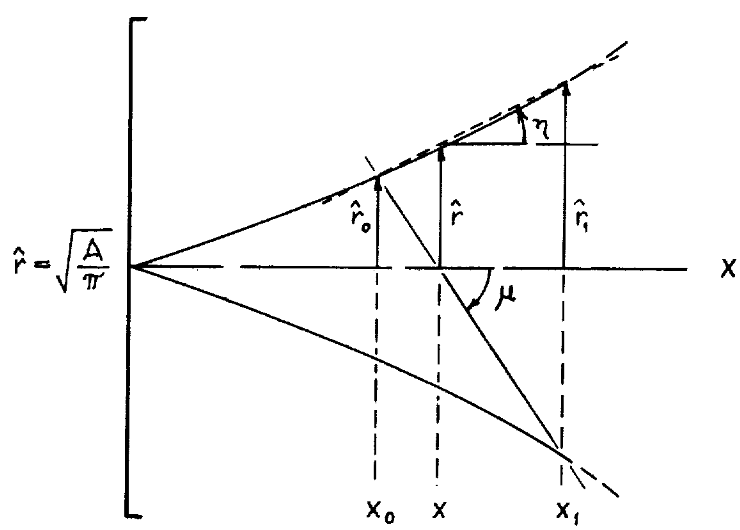
$$A_0 = A_E \sin(\mu + \epsilon) / \sin \mu = K_C A_E$$

$$K_C = \frac{\sin(\mu + \epsilon)}{\sin \mu}$$

Figure 6. Derivation of fuselage camber slope factor $K_C$.




(a) Initial surface slope estimation.

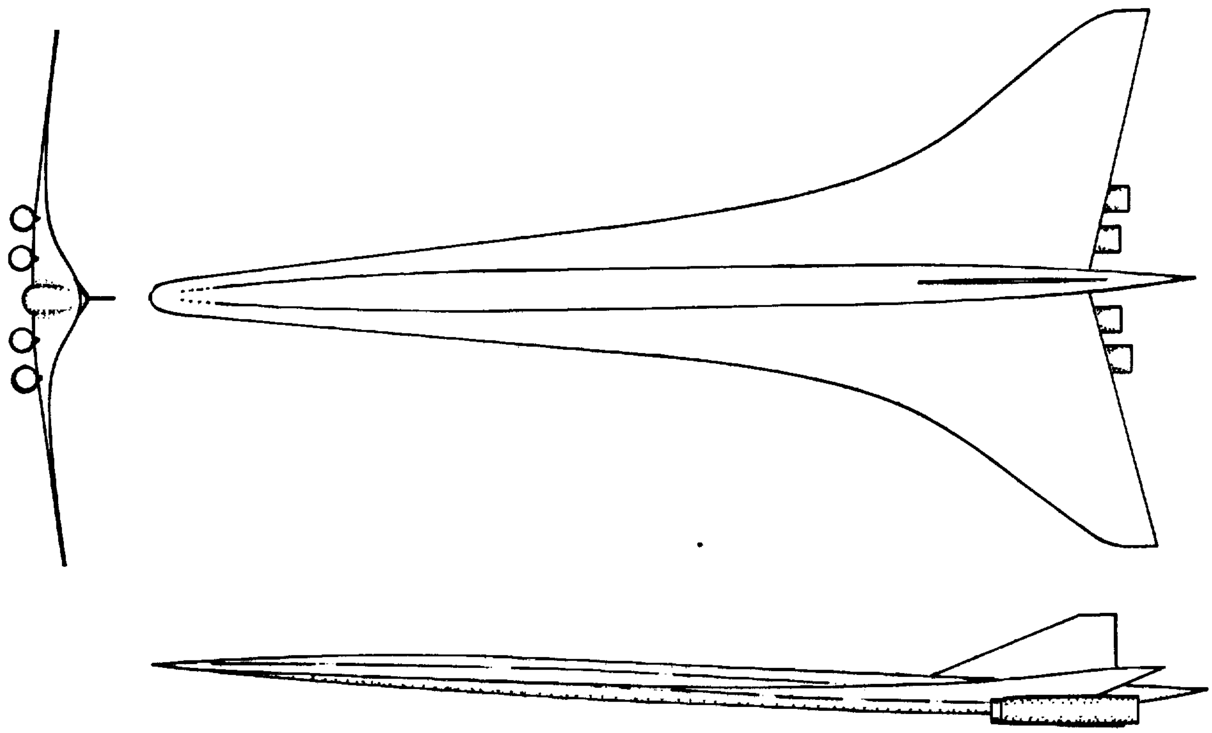



$$\tan \eta \approx \frac{\hat{r}_1 - \hat{r}_0}{x_1 - x_0} = \left(1 - \beta^2 \tan^2 \eta\right)^{\frac{3}{4}} \left(\frac{\Delta r}{\Delta X_E}\right)$$

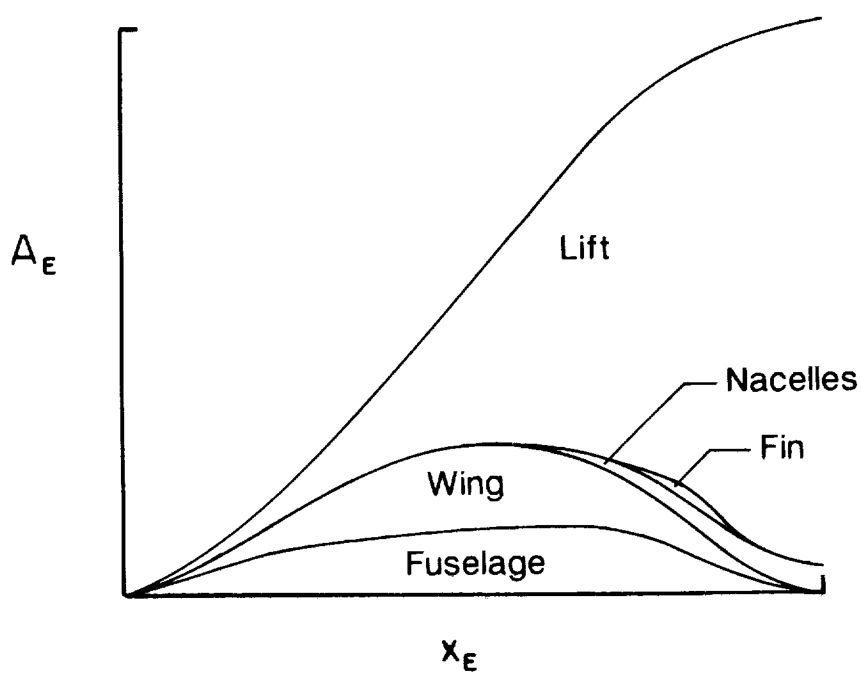
$$K_S = \frac{A_{cone}}{A_{E,cone}} = \left(1 - \beta^2 \tan^2 \eta\right)^{\frac{3}{2}}$$

(b) Corrected surface slope calculation.

Figure 7. Derivation of fuselage slope factor $K_s$.

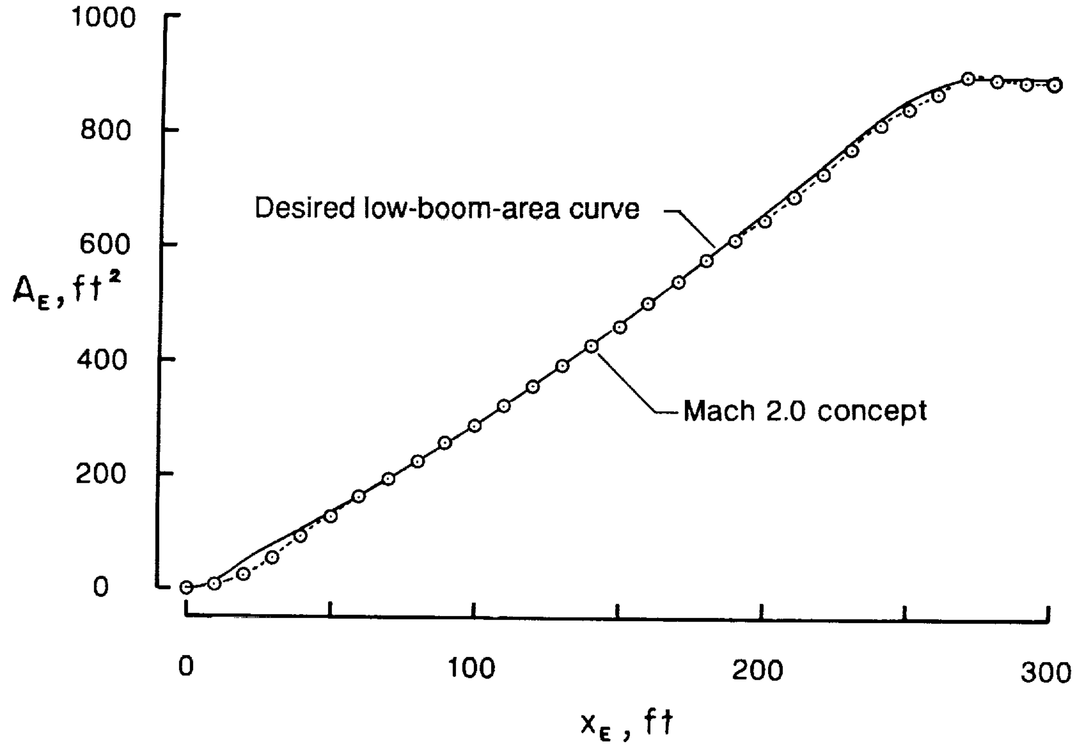


(a) Three-view schematic.

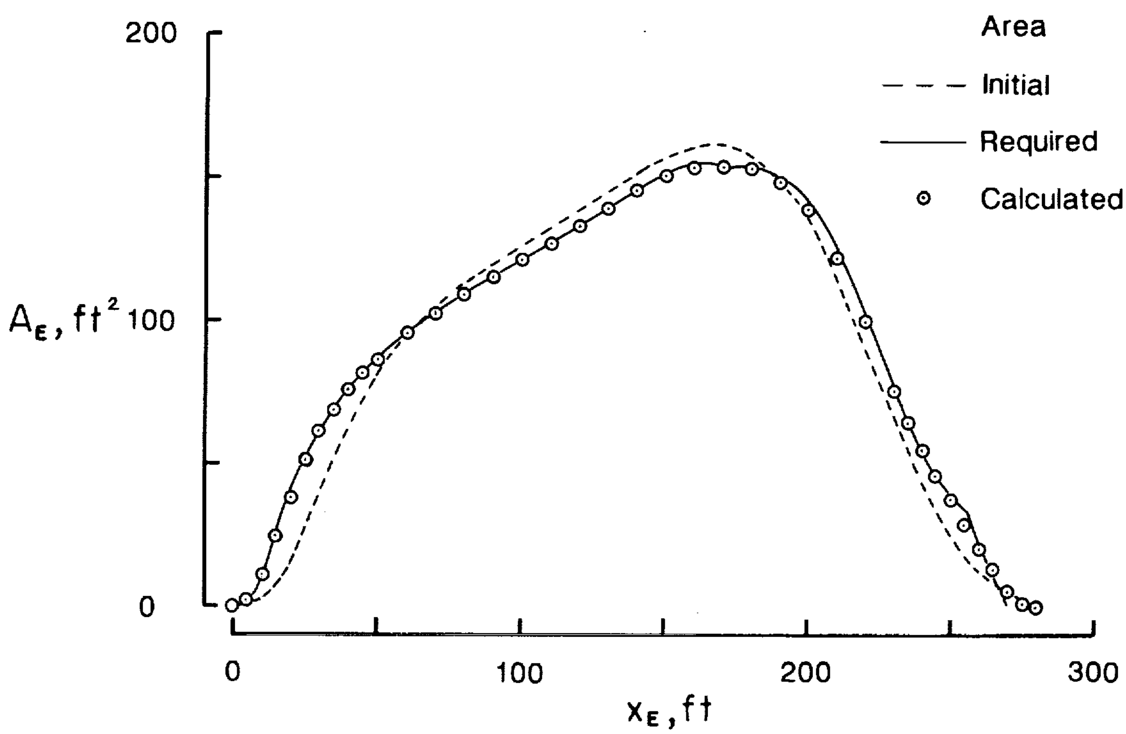



(b) Equivalent areas.

Figure 8. Conceptual aircraft nearing final definition.

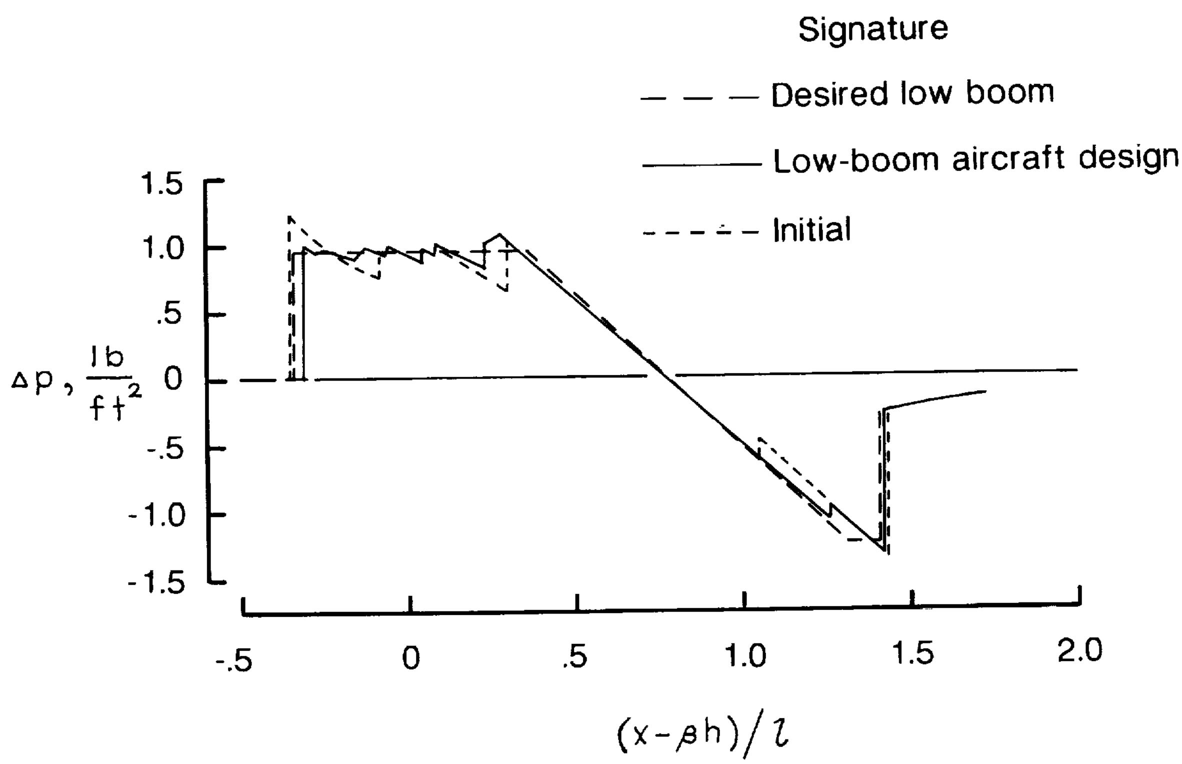



(a) Equivalent-area comparison.



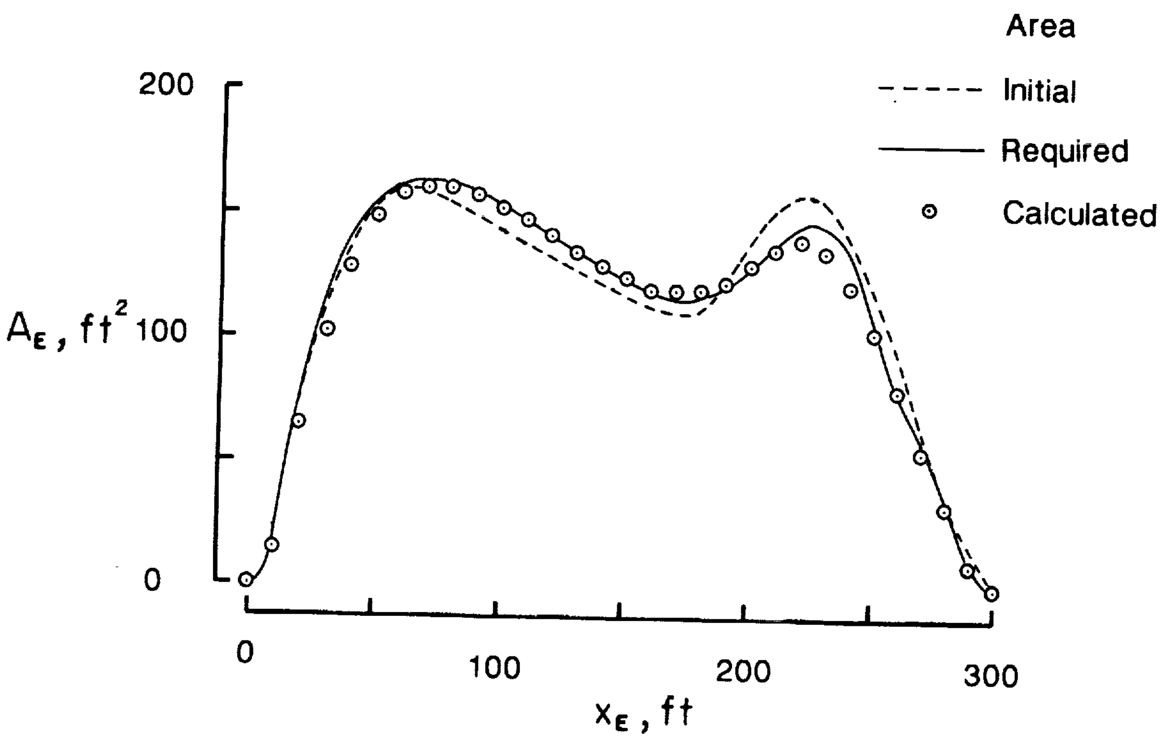

(b) Fuselage area comparisons.

Figure 9. Mach 2.0 low-boom aircraft.

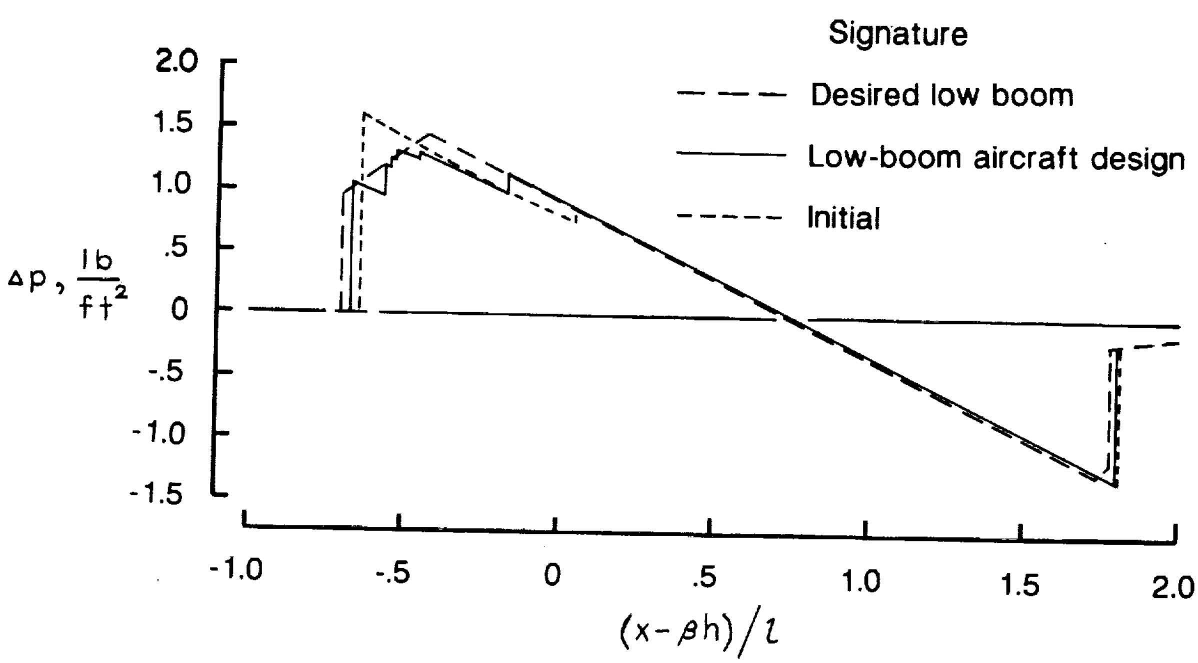



(c) Comparison of pressure signature at $h = 55\,000$ ft.

Figure 9. Concluded.




(a) Fuselage area comparisons.




(b) Comparison of pressure signature at $h = 65\,000$ ft.

Figure 10. Mach 3.0 low-boom aircraft.

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15. Supplementary Notes

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16. Abstract

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