CURRENT RESEARCH IN SONIC-BOOM MINIMIZATION

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SUMMARY

A review is given of several questions as yet unanswered in the area of sonic-boom research. Efforts, both here at Langley and elsewhere, in the area of minimization, human response, design techniques and in developing higher order propagation methods are discussed. In addition, a wind-tunnel test program being conducted to assess the validity of minimization methods based on a forward spike in the F-function is described.

INTRODUCTION

Much progress has been made in the understanding of sonic-boom phenomena in the past two decades – especially in the areas of generation and propagation. Many advances have also been made in the area of sonic-boom minimization. With scheduled flights of the Concorde and the TU144 having begun in recent months, the era of commercial supersonic flight is here. Even so, restrictions on such flights because of noise and especially because of the sonic boom reduce their economic viability. Route structures must be planned to limit supersonic operation to water or desert areas. Designers of second-generation transports which cruise supersonically must be concerned with the sonic-boom problem if the economic outlook is to improve.

There are still many unanswered questions in sonic-boom research. The most important question (since the ultimate aim is overland supersonic flight) concerns the level of sonic boom which would prove acceptable for regularly scheduled flights conducted over a long period of time. Consideration here must be given to the response of humans and animals, both indoors and out, and to the response of building structures. Studies of such responses in both simulation tests and actual flight tests have been made and published in recent years but as of yet no acceptable levels have been established. These studies have shown, however, that the shock level of the pressure signature seems to be the most disturbing feature of the signature for outside exposure and the impulse most disturbing for indoor exposure. Since indoor and outdoor disturbances are seemingly controlled by two different parameters of the signature, the question then is, what parameter of the pressure signature should be minimized? Knowledge of how to minimize certain familiar parameters of the pressure signature already exists. The capabilities of the sonic-boom minimization program developed here at Langley and some results of this program are discussed.

Because economics of supersonic flight are of fundamental concern, avoidance of excessive penalties to the efficiency of airplane designs which attempt to minimize the sonic boom must also be a primary concern. Contrary to earlier beliefs, it has been found that improved efficiency and lower boom characteristics do not always go hand in hand. Extensive trade-off studies are needed to determine just how much efficiency must suffer to meet acceptable boom levels. Application of the previously mentioned minimization program in the conduct of one phase of these trade-off studies is illustrated.

Atmospheric turbulence and the necessary accelerations and maneuvers of supersonic aircraft cause an intersection of rays forming a phenomena known as a caustic. Linearized theory fails to make predictions of the "superboom" that occurs at a caustic, and questions still remain about the validity of other methods advanced to make these predictions. Caustics do at times reach the ground and thus make this condition a critical point in sonic-boom research.

Restrictions on the sizes of wind-tunnel models because of limitations of current propagation and extrapolation methods point out the need for propagation methods which include asymmetric effects. Such methods would allow larger, better defined models, more accurate measurements, and improved overall results. Consideration of flights at higher Mach numbers and altitudes have also led to a need for propagation methods which include second-order effects. Efforts at New York University to develop methods such as these will be discussed.

With the addition of sonic boom as a design constraint, current methods of design have been found to be inadequate. More direct analytical methods are needed to replace the iterative procedures of design which will be described in this paper.

Previous wind-tunnel experiments have verified in principal the validity of earlier less sophisticated design methods applicable to boom reduction at transonic acceleration conditions. A new experimental investigation to assess the applicability of the newer methods to cruise conditions at Mach numbers up to 2.7 is now underway. The design concepts employed, the scope of the test program, and the goals of the research are discussed.

SYMBOLS

Although results have been shown in both the International System of Units and U.S. Customary Units, primary calculations were made in U.S. Customary Units;

hence, the peculiar values presented for parameters.

A	equivalent area
C_D	drag coefficient
F	Whitham F-function
h	altitude
I	impulse
l	length
M	Mach number
t	time
W	weight
x	axial distance
y_f	nose length or balance point of front shock in F-function
Δp	overpressure or shock level
α	cone half-angle
μ	Mach angle
τ	rise time

Subscript:

r	reference conditions
max	maximum

REVIEW OF PREDICTION AND MINIMIZATION METHODS

The sonic-boom pressure field as generated by an aircraft in supersonic flight is briefly reviewed in figure 1. The complete field of disturbance of the aircraft is confined to a generally conical region extending back from the nose of the aircraft. The entire region of ground disturbance is defined by the intersection of the "Mach cone" and the ground. Supersonic aircraft of today produce far-field N-wave signatures in this region. For a more detailed review of sonic-boom generation, see reference 1.

Prediction methods in sonic-boom theory have been to a large extent based on methods developed by Whitham, Walkden, and Hayes (refs. 2 to 4), and on geometric acoustics. An outline of the basic procedure is illustrated in figure 2. From the complex airplane an equivalent area distribution is defined by passing Mach cuts through its volume and lift distribution. A mathematical expression is then used to define the "Whitham F-function" from the second derivative of the area distribution. This F-function represents the source distribution which causes the same disturbances as the aircraft at large distances from the aircraft. Because the linear pressure signal propagates at the local speed of sound and each point of the signal advances according to its amplitude, the signal is distorted at the ground and could theoretically be multivalued. The physically unrealistic multiple values of pressure in the ground signal are, however, eliminated by the introduction of shocks. Shock location, based on the observation that for weak disturbances the shock bisects the angle between two merging characteristics lines, is determined by a balancing of the signature area within loops on either side of the shocks.

Historically, sonic-boom minimization has been based on finding the minimizing form of the F-function and then inversely defining the equivalent area distribution. The first minimization efforts were aimed at the far-field N-wave (refs. 5 and 6). With the observation that it might indeed be the mid-field wave which intersected the ground (refs. 7 and 8) advances were made in minimizing first the bow shock (refs. 9 and 10) and then both shocks of the pressure signature (refs. 11 and 12). All the minimums were found to require an F-function characterized by a delta function at $x = 0$.

A sonic-boom minimization program employed here at Langley and illustrated in figure 3 is based on theories developed by Seebass and George at Cornell University. With their method, it is possible to minimize either the initial shock of the signature or the overpressure (ref. 13). Their analysis was applied to propagation through an isothermal atmosphere and the minimizing F-function utilized the characteristic delta function at $x = 0$. The version of this program developed at Langley was modified to provide for propagation in the real atmosphere (refs. 14 and 15) and to allow for relaxation of the delta function to a spike of finite width (ref. 16). It has been found that by adding a finite width to the spike of the F-function, the extreme bluntness called for by the delta function can be relaxed to a conical nose shape. Defining parameters for this signature are Δp, the initial shock; Δp_{max}, the maximum level of overpressure; τ, the rise time between Δp and Δp_{max}; and I, the impulse or the area of the positive portion of the signature. For this example, the initial shock has been minimized. If the overpressure had been minimized for the same set of conditions, the resulting signature would be a "flat top" signature with no rise time.

The input to this computer program consists of the flight conditions of Mach number, altitude, length, and weight. In addition, the parameter to be minimized in the pressure signature must be specified as well as the base width of the F-function spike. The algorithm then specifies the minimizing F-function for these conditions, the accompanying ground pressure signature, and the equivalent area distribution of the aircraft.

Although the question of what should be minimized in a pressure signature is unanswered, it is felt that experience gained in minimizing the familiar parameters will be valuable if a new parameter or combination of parameters is found which better describes the total disturbance of the pressure signature.

APPLICATION TO LOW-BOOM AIRCRAFT DESIGN

To obtain maximum benefit from the results of a program such as this, one needs methods for producing airplane designs which match the resulting equivalent area. Let us briefly review the methods used for designing aircraft for boom minimization as outlined in figure 4. After deciding upon the design cruise condition, the type of signature desired, and an intermediate spike width or in other terms the extent of nose blunting, these values are used in the program to generate the equivalent area distribution. Initial designs of planform, fuselage, horizontal and vertical tails, nacelles, etc. are made and the area distribution (or volume contribution) is calculated by using the wave drag program (ref. 17) and the lift distribution is calculated by using the linearized wing theory program (ref. 18). From these two distributions a total equivalent area is generated and compared with the ideal area. Through an iterative process configurations are found which match reasonably well the ideal area. It should be noted here that there is a need for better analytical methods in this design process. Even neglecting the fact that this manual iteration is a very cumbersome process, it is nearly impossible to match areas exactly in this way and slight differences are quite significant since the relationship between the area and the resulting pressure signature is through the second derivative.

APPLICATION TO STUDY OF MINIMIZATION PARAMETERS

Application of sonic-boom minimization concepts to the design of models for a wind-tunnel test program to assess their validity is discussed later. Now it might be more appropriate to consider program results which serve to establish design goal levels of sonic-boom parameters and to show their variation with the significant airplane and operational parameters. Shown in figure 5 is the variation of the overpressure and impulse of the pressure signature with the airplane parameters of length and weight. These results are for minimum overpressure- "flat-top" signatures for which the F-function is characterized by a delta function at $x = 0$. For convenience, all variables have been non-dimensionalized with respect to the cruise conditions shown. The reference overpressure and impulse are the values obtained for these parameters at the reference flight conditions. Note that, as expected, an increase in both overpressure and impulse with the weight of the aircraft and a decrease in both of these parameters with the length occur.

The variation of the parameters with the operating conditions of Mach number and altitude is shown in figure 6. Here it is seen that there is an increase in the overpressure level with Mach number but a decrease in the impulse. Recalling that each of these parameters is a measure of a different type of disturbance from the pressure signature, this opposite variation highlights clearly the problem of selecting the parameter of the signature to be minimized. With altitude, an increase in impulse for the range shown as well as an increase in overpressure for most of the range occurs. The minimum value shown on the overpressure plot occurs approximately at the beginning of the stratosphere. Although flights at this altitude would seem to be attractive for boom considerations, drag and range penalties would be quite severe.

BOOM — DRAG TRADE-OFF

Researchers earlier thought that those factors which improved the efficiency of an aircraft would also tend to lower the sonic boom; however, it has now been found that this is not necessarily so. To explain this somewhat paradoxical situation, figure 7 shows a comparison of the wave pattern propagating to the ground. The low boom aircraft is seen to have an extremely blunt nose and special shaping so that even though there is a high shock level at the aircraft, and thus a high drag level, the pattern of propagation is such that no further coalesence of shocks occurs. There, in fact, are no other shocks behind the bow shock; there is only an expansion field. Because of this, the shock at ground level is greatly attenuated. The drag configured, sharp-nosed aircraft, on the other hand, had a comparatively lower shock at the aircraft, but because of shock coalesence the ground signature has a relatively higher level shock.

To answer the question of how much aircraft efficiency must suffer in order to meet boom requirements, extensive trade-off studies must be conducted by design teams. The ability to vary the width of the spike in the F-function which, in turn, adds a cusp-like nose region of the equivalent area distribution makes the previously described minimization program valuable as an important part of such studies. As a rough idea of such a trade-off study, drag levels, overpressure,and impulse are shown as a function of nose length, y_f/l in figure 8. As the nose length is increased, levels of drag decrease as expected, but there is a corresponding increase in the levels of overpressure and impulse. This study was made with bodies of revolution being used to get approximate drag increments. The important point, however, is not the result of this example, but the new capabilities for meaningful design studies now provided.

RELATED WORK

There is no work going on at Langley concerning the acceptable level of sonic boom or concerning the parameter which should be minimized. However, some work in this area, which in fact stems from our minimization studies, is being conducted at the University of Toronto Institute for Aerospace Studies (ref. 19). A series of pressure signatures such as that shown in figure 9 are being prepared for reproduction in acoustically sealed chambers so that studies may be made of their effects on humans. Although each of these signatures is distinctly different, they all represent the same flight conditions. For reference, the equivalent area distribution corresponding to each signature is shown, with the area distribution for the N-wave repeated on the others as a dashed line for comparison. Note that for the large shock difference occurring between the N-wave and the flat-top signature, there is only a small redistribution of equivalent area needed.

Testing methods in sonic-boom research have progressed from the use of 1-inch models when only far-field theories were available to roughly 6-inch models with the currently used mid-field theory. Model sizes are limited today because currently used propagation methods require nearly axisymmetric input, and thus readings must be taken far enough away to reduce significantly the error produced by the nonsymmetry of volume and lift. This restriction in size makes it difficult to incorporate with sufficient accuracy such features as camber and twist to define more realistic models.

Propagation methods being developed at New York University under a NASA Grant promise to improve this experimental situation. A computer program which accounts for the nonsymmetry in the linear lift distribution (ref. 20) is now operable and work is currently being done, Lu Ting being the primary investigator, to include the effects of nonsymmetry in spanwise volume and lift. Such programs allow larger models to be used – roughly 30 to 45 cm (12 to 18 in.) in length. In addition to allowing more accuracy, larger models will also allow some wind-tunnel tailoring of models as a means of compensation for inaccuracies in some of the presently used minimization theories.

A comparison of currently used propagation methods (refs. 21 and 22) with recent methods developed at New York University is shown in figure 10. Note that at this fairly high Mach number, significant differences occur in the results when second-order effects and entropy variation are included. A smaller difference occurs when asymmetric effects of the linear lift distribution are included.

There is no active research here at Langley concerning the predictions of overpressure levels occurring at a caustic. Descriptions of recent efforts in this area may be found in references 23 to 25.

EXPERIMENTAL PROGRAM

To test the validity of minimization methods described, an experimental program incorporating five models and tests at two different Mach numbers is being conducted. Two of the models, one with a conventional delta-wing planform and the other with a familiar arrow wing planform, are to be tested to provide a basis for comparison with the overpressure levels and signature shapes obtained with sonic-boom optimized models. The low-boom models were designed along conceptual lines put forth in references 26 and 27, although in this case some of the aircraft features such as vertical- and horizontal-tail surfaces, nacelles, etc, were omitted for the sake of simplicity and because of limitations of tunnel testing methods.

The low-boom wind-tunnel models were 1/600-scale versions of a wing-body configuration which met the following specifications:

1) Cruise Mach number of 1.5 and 2.7
2) Beginning cruise weight of 272 155 kg (600 000 lb)
3) Cruise altitude of 15 240 m (60 000 ft)
4) Seating room for at least 200 passengers
5) Aircraft length of 91.44 m (300 ft)
6) Maximum overpressure of 41.03 Pa (0.857/lb/ft^2) and 50 Pa (1.044 lb/ft^2)

Special features included in the design and shown in figure 11 are:

1) A boom-contoured nose section
2) A highly swept wing leading edge
3) Varying thickness ratio from wing root to wing top
4) Positive wing dihedral for an effective length of 91.44 m (300 ft)
5) An area-ruled fuselage
6) A long lift-tailored wing planform

The five models for the test program are shown in their proper relative sizes in figure 12. For the three low boom models, a modified arrow planform was chosen for a configuration designed to cruise at Mach 2.7, a low notch ratio arrow wing was employed in a configuration optimized for a cruise Mach number of 1.5, and a special blunt apex and low notch ratio arrow-wing planform was used to represent an advanced blended wing fuselage configuration designed for $M = 2.7$. These models and tests will be used to explore the applicability of the Seebass and George method at a low supersonic Mach number where small disturbance linearized theory methods are generally valid and at a relatively high Mach number where the applicability of linearized theory is questionable.

In figure 13 the theoretical predictions for the two base line model configurations and for the modified arrow designed for Mach 2.7 cruise are shown. For the low-boom configuration the difference between the signatures produced by the ideal area and the designed area again emphasize the sensitivity of the design process.

CONCLUDING REMARKS

A review has been made of some of the questions as yet unanswered in sonic-boom research. Current efforts here at Langley and elsewhere in minimization, human response, higher order asymmetric propagation methods and current techniques of design with sonic-boom constraints have been discussed. In addition, a wind-tunnel test program now being conducted to assess the applicability of minimization methods based on a forward spike in the F-function has been described.

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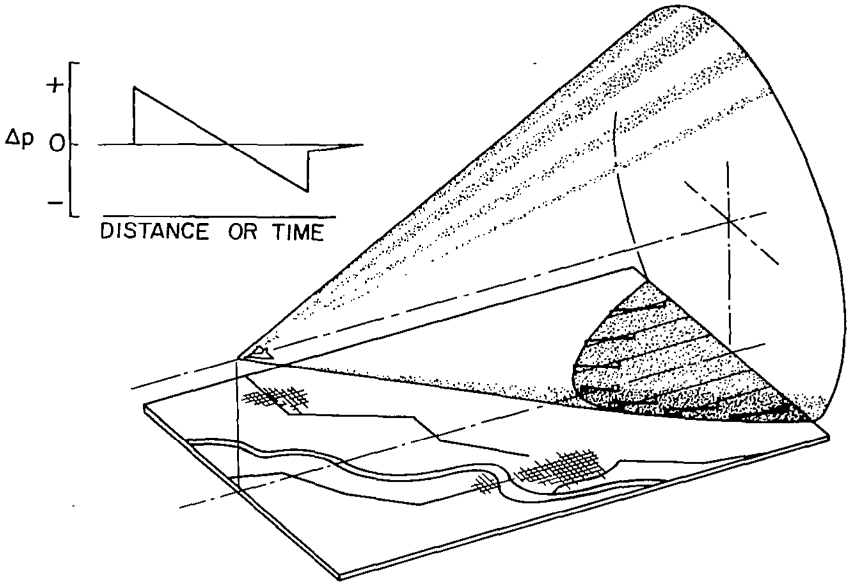

Figure 1.- The sonic boom pressure field.

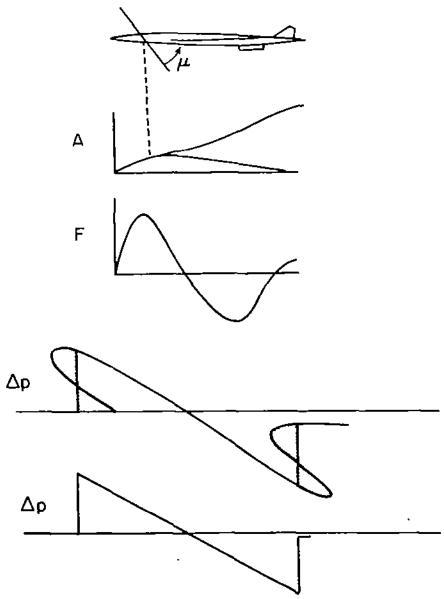

Figure 2.- Prediction methods.

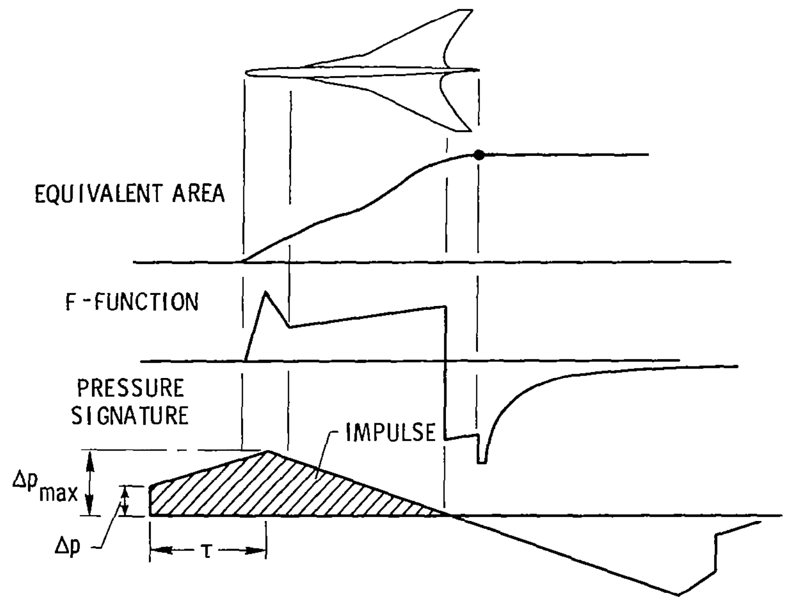

Figure 3.- Sonic-boom minimization concepts.

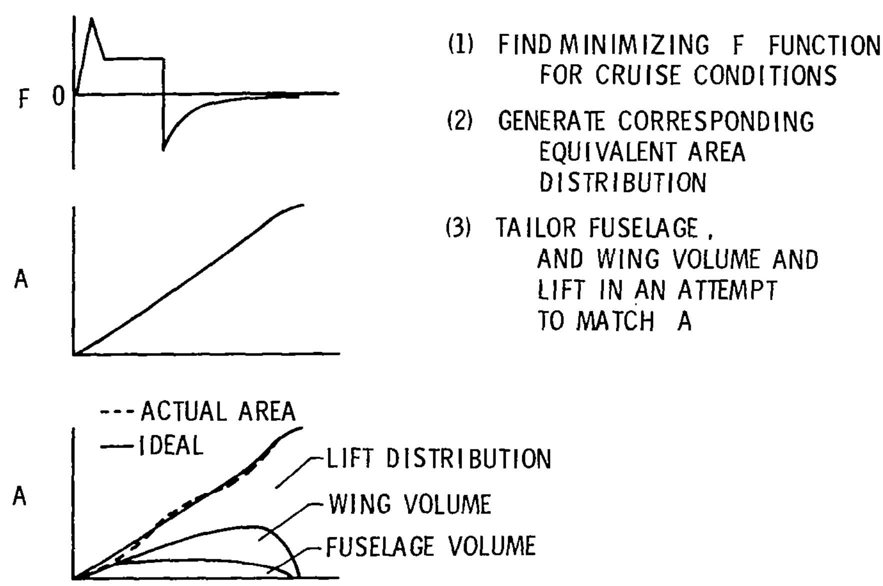

Figure 4.- Minimizing techniques and design methods.

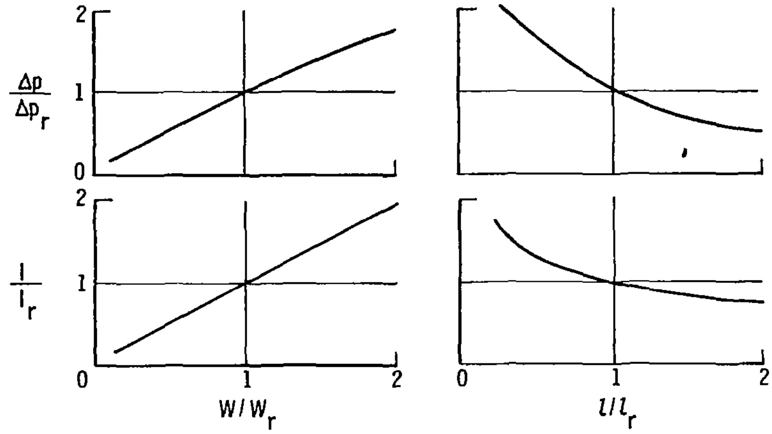

Figure 5.- Sonic-boom variation with airplane parameters. Optimized configuration: M = 2.7; h = 18 288 m (60 000 ft); W_r = 272 155 kg (600 000 lb); l_r = 91.44 m (300 ft); Δp_r = 45.51 Pa (0.951 lb/ft^2); I_r = 6.48 Pa-sec (0.135 lb-sec/ft^2).

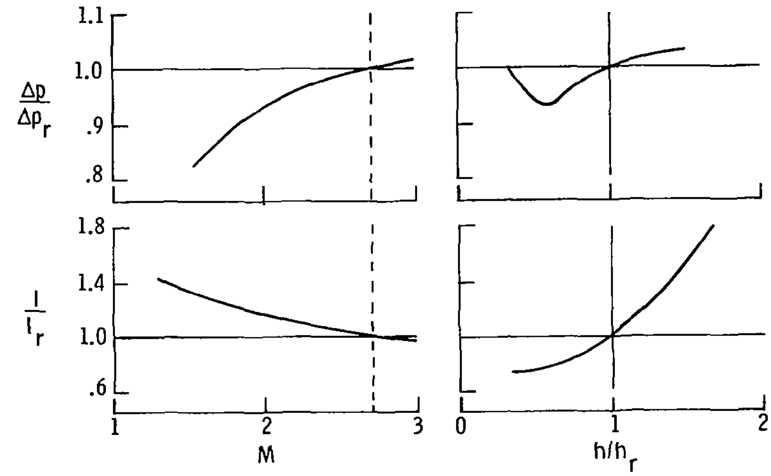

Figure 6.- Sonic-boom variation with operational parameters. Optimized configuration: W = 272 155 kg (600 000 lb); l = 91.44 m (300 ft); h_r = 18 288 m (60 000 ft); M = 2.7; Δp_r = 45.51 Pa (0.951 lb/ft^2); I_r = 6.48 Pa-sec (0.135 lb-sec/ft^2).

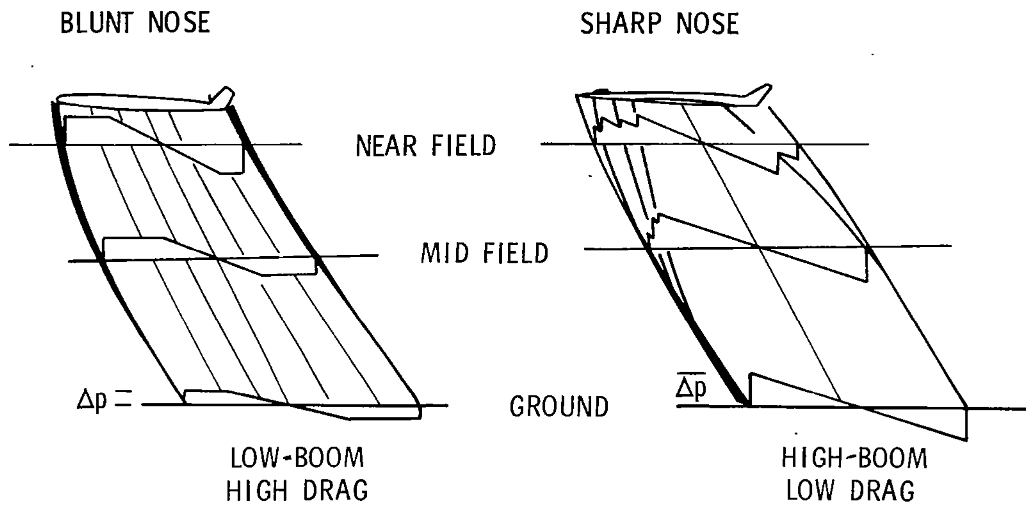

Figure 7.- Drag-boom paradox.

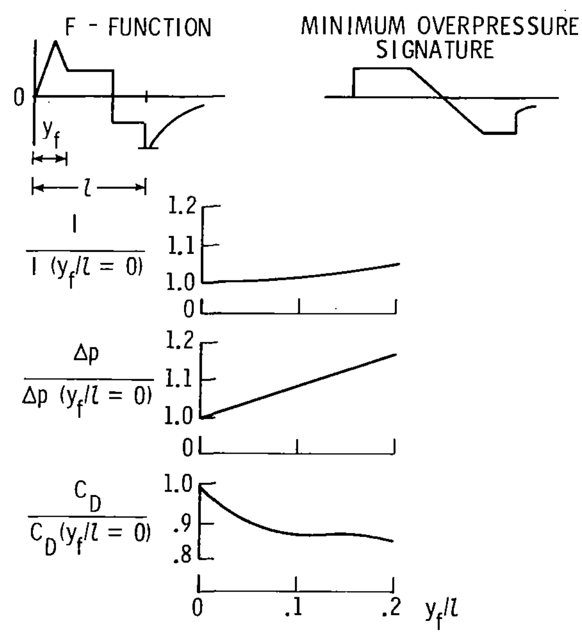

Figure 8.- Estimated drag increments in minimization.

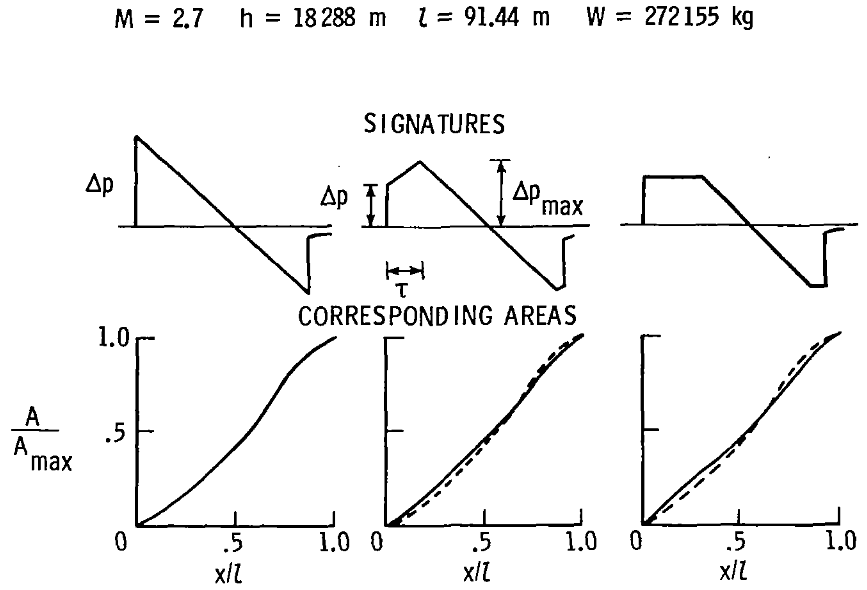

Figure 9.- Human response studies at the University of Toronto Institute for Aerospace Studies.

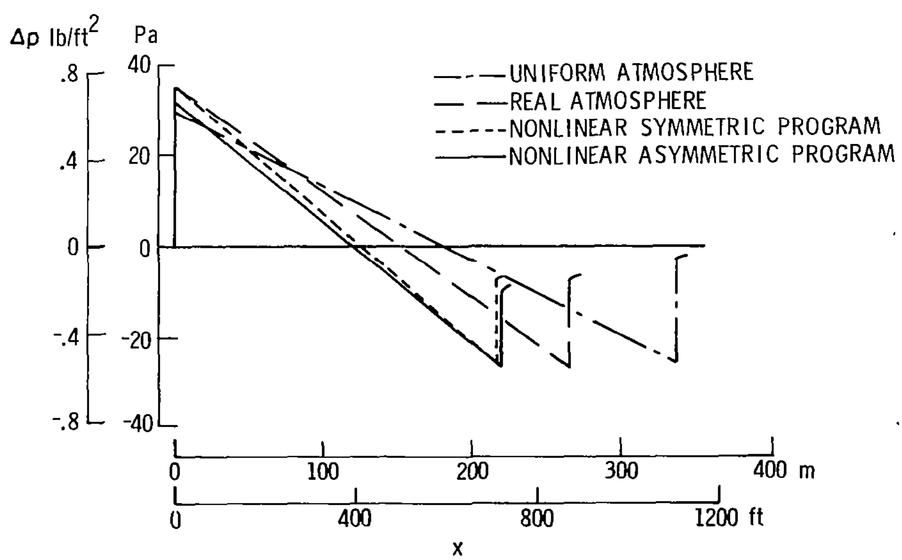

Figure 10.- Higher order propagation methods. $M = 4.0$; $h = 24\ 384$ m (80 000 ft); $\alpha = 5$.

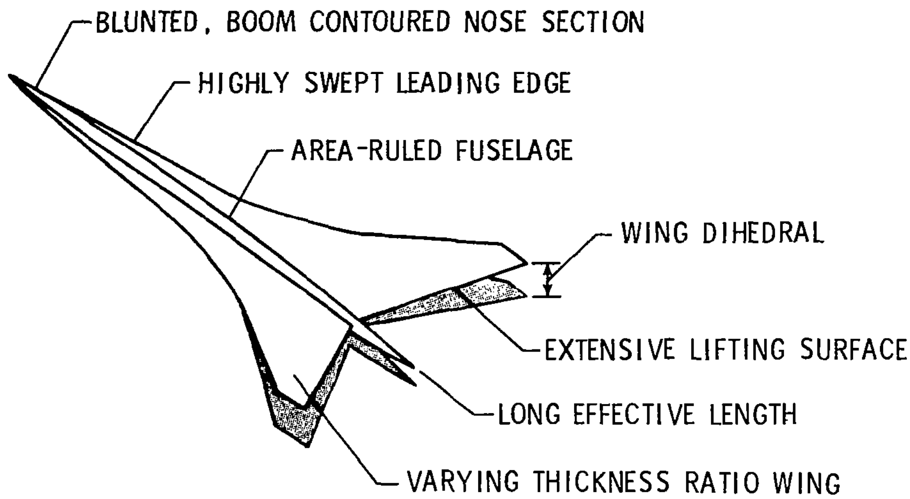

Figure 11.- Features of low-boom study models.

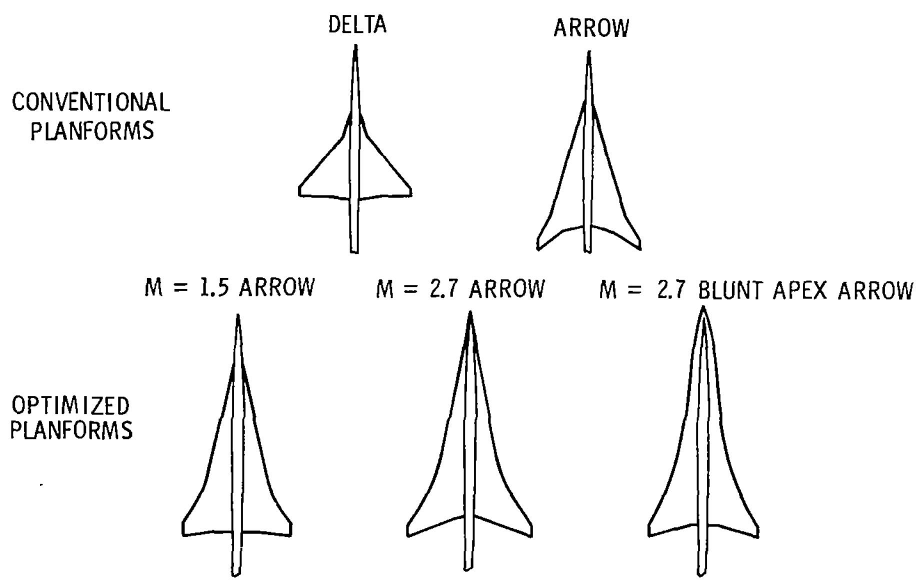

Figure 12.- Planforms for an experimental study of optimization.

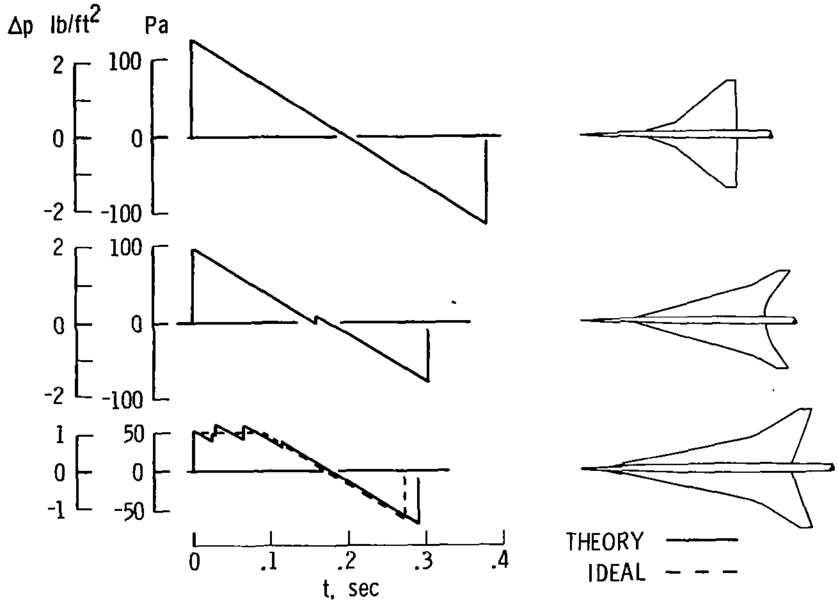

Figure 13.- Ground pressure signatures of models.