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SUMMARY

Existing theoretical methods of sonic-boom estimation have been used to determine the sonic-boom profiles of representative supersonic and hypersonic airplanes of the future. The sonic-boom characteristics of these future airplanes have been related to the sonic-boom characteristics of current supersonic airplanes. In the supersonic climb and cruise phases of flight, where the sonic-boom overpressure and impulse levels are relatively high, the use of near-field effects to modify the sonic-boom disturbance of these large future airplanes has been considered. The near-field investigation indicates that some reduction in overpressure and impulse might be possible.

INTRODUCTION

Consideration was given to the aerodynamic drag problem associated with the pressure disturbances about a supersonic airplane in reference 1. As the pressure disturbances generated beneath the airplane propagate to the ground they give rise to another problem - the problem of sonic boom. The noise and structural excitations which can result from sonic boom have raised serious questions as to the acceptability of routine flights of future supersonic and hypersonic airplanes over populated areas. Since these routine flights would be desirable from an economic standpoint, sonic boom has thus become a major consideration in the design and projected operation of these proposed airplanes.

During the course of research on the sonic-boom problem, theoretical methods have been developed which can be used to relate the sonic-boom disturbance to the characteristics of the airplane (refs. 2 to 5). These methods are based on the equivalent-body principles discussed in reference 1. Procedures have also been developed to account for the propagation of the sonic-boom disturbance from the airplane to the ground (ref. 6.). The purpose of the present paper is to utilize these existing methods to relate the predicted sonic-boom characteristics of the large, heavy supersonic and hypersonic airplanes of the future to those of currently operational supersonic airplanes. Another purpose is to explore some means which might be used to modify the sonic-boom disturbances associated with these proposed airplanes.

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[1]Presented at the classified "Conference on Aircraft Aerodynamics," Langley Research Center, May 23-25, 1966, and published in NASA SP-124.

SYMBOLS

A_e	effective cross-sectional area due to a combination of volume and lift
C_L	lift coefficient
h	airplane altitude or perpendicular distance from model to measuring probe
I	positive impulse of pressure signature, $\int \Delta p \, dt$
l	length of airplane or model
M	Mach number
p	reference pressure
Δp	incremental pressure due to flow field of airplane or model
Δp_{max}	maximum positive value of Δp
t	time
t_r	time required for pressure disturbance to rise from zero overpressure ($\Delta p = 0$) to maximum overpressure ($\Delta p = \Delta p_{max}$) (see fig. 1)
W	airplane weight
x	distance measured along longitudinal axis of airplane or model
Δx	distance measured parallel to longitudinal axis of model from point in undisturbed stream to point on pressure signature
$\propto$	varies as

DISCUSSION

Some Aspects of the Sonic-Boom Problem

A number of factors characterize the sonic-boom ground pressure disturbance. Figure 1 can be used to illustrate some of these factors which are considered in the present paper.

General signature characteristics.- Some important general characteristics of the ground pressure signature are illustrated in the upper portion of figure 1. In the signature at the upper left, which is drawn for the case of no atmospheric distortion, Δp_{max} is the maximum rise in ground pressure due to the flow field of the airplane. Impulse is the time integral of the positive overpressure as indicated by the shaded portion of the signature. In some manner, both of these signature characteristics influence the response of people and structures to sonic boom. During the early phases of the supersonic transport competition, concern over sonic boom led to the establishment of tentative upper limits on Δp_{max} of 2.0 pounds per square foot in climb and 1.5 pounds per square foot in cruise.

The possible effects of random atmospheric disturbances on the sonic-boom signature are illustrated in the upper right portion of figure 1. As indicated, these atmospheric disturbances can either spike the signature and lead to higher values of overpressure than expected or round the signature and lead to lower values of overpressure than expected. In this paper only the nominal or averaged values of overpressure are considered, with the realization that random atmospheric distortions can lead to overpressures above and below the nominal.

Specific signature characteristics.- Some specific signature characteristics which may be important are illustrated in the lower portion of figure 1. A typical far-field N-wave is shown in the lower left of the figure. A far-field condition is said to exist when shocks from the individual airplane components have merged at the ground and have formed this N-wave pattern.

For some normal operating conditions of a large supersonic airplane, the ground pressure disturbance retains some features of the shock pattern from individual airplane components (ref. 7). In this near-field situation, the character of the pressure signature depends directly on the effective shape of the airplane. A typical twin-peaked near-field signature is illustrated in the lower center of figure 1.

Because of the dependence of the near-field pressure signature on the arrangement and operating condition of the airplane, a variety of near-field signatures is possible. Two near-field signatures discussed in this paper are the plateau signature and the signature with finite rise time, which are illustrated in the lower right of figure 1. It can be noted that the finite rise-time signature is characterized by a gradual buildup in overpressure. If the buildup in overpressure can be extended over an appreciable rise time t_r on the order of 10 to 15 milliseconds, the sonic-boom disturbance might be more acceptable than the typical disturbance which has an instantaneous pressure jump.

Although not an extremely important sonic-boom consideration, it can be noted that the pressures at the tail-shock portion of the signatures of figure 1 do not return to ambient conditions within the time shown in the figure. This feature of the sonic-boom disturbance is characteristic of the general solution of sonic-boom theory and has been observed in flight investigations.

The aspects of the sonic-boom problem which are illustrated in figure 1 do not represent all the factors which characterize the sonic-boom disturbance. Such factors as the energy spectrum of the pressure wave are also important. As yet, research has not conclusively established which of the several characteristics of the ground pressure disturbance governs human and structural response to sonic boom.

Sonic-Boom Characteristics of Current Supersonic Airplanes

Flights of operational supersonic airplanes have provided valuable information for preliminary assessment of the sonic-boom problem of future airplanes. In addition to public- and structural-response data, these flights have provided a means for evaluating sonic-boom prediction methods. Correlations of measured and theoretical sonic-boom characteristics are presented in figure 2 for three current supersonic airplanes, the F-104 fighter, the medium B-58 bomber, and the large, heavy B-70 bomber. On the left side of the figure, the variation of maximum ground overpressure with altitude is shown for the three airplanes. The impulse characteristics are similarly shown on the right side of the figure. For both overpressure and impulse the theoretical predictions are represented as a band of values to account for differences in operating weight and Mach number at a given altitude. As indicated in the figure, the larger and more flexible the airplane, the wider the band of possible values of overpressure and impulse.

Three important points can be made with the results presented in figure 2. First, existing theoretical estimation methods provide a good assessment of the nominal overpressure and impulse characteristics of these three airplanes, which vary widely in size and general arrangement. Secondly, there are substantial increases in overpressure and impulse with increased airplane size. These increases in overpressure and impulse are due principally to increased weight, which varies from 27 000 pounds for the F-104 to approximately 100 000 pounds for the B-58 and to about 450 000 pounds for the B-70 airplane. The third important indication of the results presented in figure 2 is the near-field influence on the overpressure characteristics of the large B-70, as represented by the shaded band in the upper left of the figure. In the operating region where these near-field effects are present, the maximum ground overpressures of the B-70 are not much greater than those of the smaller B-58 airplane.

Selected ground pressure signatures from the large B-70 airplane can be used to illustrate the types of sonic-boom disturbance that can be expected from future supersonic and hypersonic airplanes. These signatures, which have minimal atmospheric distortions, are presented in figure 3. The measured and theoretical ground pressure signatures at the top of the figure illustrate the natural near-field tendencies of a large supersonic airplane which is operating at relatively low altitude, in this case, at an altitude of 31 000 feet. A typical near-field signature such as this would be expected during the early supersonic climb stages of flight of the large supersonic and hypersonic airplanes of the future.

The measured and theoretical B-70 ground pressure signatures at the bottom of figure 3, which are for a Mach number of 2.6 and a flight altitude of 66 000 feet, approach the typical far-field N-wave pattern. This type of ground pressure disturbance would be expected during the cruise flight of future supersonic airplanes and during the midclimb and cruise flight of future hypersonic vehicles.

For both flight conditions illustrated in figure 3, the major disagreement between theory and flight measurements is in the tail-shock portion of the signature where the wake conditions and engine exhaust plume are difficult to define.

Sonic-Boom Characteristics of Future Supersonic and Hypersonic Airplanes

Correlations such as those shown in figures 2 and 3 give some confidence that current theoretical methods can be used to analyze the sonic-boom characteristics of future airplanes in the supersonic speed regime. The scarcity of sonic-boom information at extremely high speeds gives somewhat less assurance as to the applicability of these methods at hypersonic speeds. On the basis of some preliminary studies of hypersonic configurations, however, it is believed that the present methods are adequate to illustrate the trends of sonic boom at hypersonic speeds.

The predicted sonic-boom overpressure and impulse characteristics of two research configurations, which have been chosen to illustrate the sonic-boom problem of proposed supersonic and hypersonic airplanes, are presented in figure 4. The supersonic configuration, represented by the solid curve, has a cruise Mach number of 2.7 and a design range of 3480 nautical miles. The hypersonic airplane, represented by the dashed curve, has a cruise Mach number of 6.0 and a design range of 5000 nautical miles. The predicted maximum ground overpressure and impulse of the two configurations are shown as they vary with range or distance from take-off.

The sonic-boom profiles indicate that both airplanes would generate relatively high ground overpressure and impulse during the early climb and acceleration phases of flight. In this flight regime, the natural near-field characteristics of these large airplanes serve to reduce the overpressures some 10 to 15 percent below the levels which would be expected on the basis of the far-field assumptions of sonic-boom theory. At cruise conditions, which are represented by the flat portions of the profiles, the overpressure and impulse would be at reduced levels. The cruise values would be expected to lie between the levels measured during high-altitude flights of the current B-58 and B-70 airplanes. As the two airplanes approach their destination and descend toward the ground, the overpressure and impulse would be expected to increase from the cruise values. In this descent phase of flight the near-field effects would also be present.

The basic factor which leads to the relatively high values of overpressure and impulse in the early stages of the two flight profiles shown in figure 4 is the initiation of supersonic climb and acceleration at relatively low altitudes. This low-altitude initiation of supersonic flight is an economic consideration based on the desire for minimum block time and for minimum propulsion-system and airplane weight. Although other configurations might produce variations from the sonic-boom profiles used in this illustration, the economic factors would tend to dictate similar trends in sonic-boom characteristics.

As indicated in figure 4, the regions of relatively high overpressure and impulse are limited in range to some 200 to 400 nautical miles in climb and to some similar range in descent. Although this range of relatively high sonic-boom exposure is limited, it might be desirable to alter the shape and magnitude of the sonic-boom disturbance in these flight regimes. The rest of the present paper considers the possibility of such an alteration.

Near-Field Considerations

A possible means for altering the shape and magnitude of the sonic-boom disturbance from a large airplane is to make use of the natural near-field characteristics of such an airplane. Two important factors which influence the near-field characteristics are the area distribution of the airplane due to combined volume and lift effects and the length of the airplane. The supersonic airplane considered in figure 4 is used to illustrate these area and length effects.

The influence of effective area distributions A_e on the character of the sonic-boom disturbance is illustrated in figure 5(a). The effective area distribution and predicted ground-track pressure signature corresponding to a typical climb condition of the original design are shown at the top of the figure. The predicted sonic-boom disturbance is a twin-peaked near-field signature. A modification of the original effective area distribution to the shape shown in the lower right of figure 5(a) would theoretically alter the pressure disturbance to the plateau shape at the bottom of the figure with considerably reduced overpressures.

The effect of airplane length on near-field characteristics is illustrated in figure 5(b). The area distribution at the upper right of the figure corresponds to the original area distribution with the length increased from 230 to 280 feet. This extension of length induces more near-field effects in the signature and reduces the maximum overpressure. The effective area distribution and signature at the bottom of figure 5(b) show the combined effects of increased length and area modification on the near-field signature. For this illustrative example, the resultant maximum overpressure is less than half of the original value. Although no attempt has been made to modify the tail shock, note that, for this particular application, the pressure jump at the aft portion of the signature is no greater than the modified bow pressure rise.

Airplane modification for plateau pressure.- If the near-field characteristics of the original and modified area distributions are determined for a number of airplane lengths, the design requirements for a plateau pressure signature of a given maximum overpressure can be established.

Figure 6 presents the results of such a study for a typical supersonic airplane climb condition of $M = 1.4$, $W = 400\ 000$ pounds, and $h = 40\ 000$ feet. In this figure the circular symbol represents the maximum overpressure of approximately 2.2 pounds per square foot for the original design area distribution and design length of 230 feet. The curves indicate the variation of maximum ground overpressure with airplane length for the original effective area distribution (dashed curve) and for a modified area distribution which varies as $x^{3/2}$ to provide a plateau pressure distribution (solid curve). The manner in which the original and modified pressure signatures vary with length is indicated by the inset sketches.

The obvious point to be made from the results is that, for this typical climb condition, modification of the airplane effective area distribution can lead to substantial reductions in maximum overpressure both within the airplane design length of 230 feet and at greater lengths. At a given airplane length, the area modification also resulted in a 6- to 7-percent decrease in impulse. Airplane weight, of course, influences the overpressure levels shown. For example, an increase in climb weight from 400 000 to 500 000 pounds would require a 25- to 30-foot extension in length to maintain a given overpressure level.

At altitudes and Mach numbers associated with the cruise conditions of a large supersonic airplane, the design requirements for near-field effects would be more stringent than at climb conditions. The higher altitudes and Mach numbers increase the lift contribution to the effective area distribution which leads to a more rapid approach to far-field conditions. These factors are illustrated in figure 7 for a typical cruise Mach number of 2.7, a weight of 350 000 pounds, and an altitude of 65 000 feet. For these conditions, the predicted ground pressure disturbance for the original design condition of the supersonic airplane (represented by the circular symbol) would be a typical far-field N-wave with a maximum overpressure of about 1.55 pounds per square foot. As indicated in the figure, within the original design length of 230 feet, for these cruise conditions, the plateau pressure disturbance cannot be generated. As airplane length is increased, however, near-field effects are induced in the original configuration, as indicated by the inset pressure signatures. At airplane lengths greater than about 260 feet, it is once again possible to modify the configuration so as to produce a plateau pressure disturbance with reduced maximum overpressure and impulse.

Wind-tunnel investigation of airplane modification for plateau pressure.- To investigate the applicability of the plateau pressure modification previously discussed, small 4-inch complete models of the original and modified supersonic configuration have been tested in the Langley 4- by 4-foot supersonic pressure tunnel. The airplane models were designed to simulate the typical climb condition considered in figure 6. Some results of the wind-tunnel investigation are presented in figure 8.

Plan views of the original and modified configurations are presented at the top of the figure. The rather modest changes in effective area distribution which were theoretically required to produce the plateau pressure disturbance can best be seen in the effective area distribution plots in the middle of the figure. The purpose of the area modification was to smooth the original distribution and reduce the rate of change of area with longitudinal distance.

The measured and theoretical signatures at the bottom of figure 8, which correspond to a station 10 body lengths below the models, indicate that the desired effect of replacing the twin-peaked signature of the original configuration with a plateau pressure disturbance was essentially accomplished. Differences between the measured and theoretical signatures of the modified model could be attributed to slight differences between the actual and specified models.

It should be pointed out that the sonic-boom disturbance along the ground track of a supersonic airplane depends only on a particular effective area distribution. The wave drag, on the other hand, depends on the averaged contributions of a number of equivalent bodies corresponding to all orientations of the airplane. (See ref. 1.) Consideration of the near-field modification discussed would depend on a complete analysis of the consequences of the modification on other aspects of the airplane performance. For the particular modification considered in this figure, the wave drag of the configuration was reduced at the climb Mach number of 1.4 with little or no penalty for other flight conditions. This effect would not necessarily hold for some other configuration.

Airplane modification for finite rise time.- As mentioned earlier, a sonic-boom disturbance with an appreciable rise time might be more desirable than the typical disturbance which has an instantaneous pressure rise. Accordingly, a near-field investigation of the supersonic airplane of the previous discussion was made to determine the design requirements for such a finite rise-time signature. This design requirement would increase the chances for a substantial rise time. Small rise times have been measured during flights of current airplanes.

The results of the rise-time investigation for a typical supersonic climb condition are shown in figure 9. The variation of maximum overpressure with length of the original configuration is once again represented by the dashed curve. The area development $x^{5/2}$, which is one requirement for finite rise time, is represented by the solid curve. The results indicate that even for this climb condition some extension in airplane length is required to generate the signature with gradual pressure rise and that some increases in maximum overpressure and impulse appear to be necessary to achieve this type of pressure disturbance. With lengths above about 260 feet, however, appreciable rise times appear to be possible. The variation of rise time from the cutoff point to the maximum length is from 0 to 160 milliseconds.

Figure 10 shows the results of a similar analysis of the finite rise-time signature for typical supersonic cruise conditions. The results indicate that the design requirements for gradual pressure rise in this cruise speed regime are too stringent to be met within practical airplane lengths and weights.

The foregoing near-field analyses of a large supersonic airplane suggest that substantial modifications of the shape and magnitude of the sonic-boom disturbances may be possible at typical climb conditions. Less substantial, but perhaps important modifications can be made in the sonic-boom signatures of long airplanes at supersonic cruise flight conditions. Similar analyses of a typical hypersonic configuration show similar possibilities for signature modification in these flight regimes. At hypersonic speeds, however, near-field effects are not to be expected.

CONCLUDING REMARKS

Existing theoretical methods of sonic-boom estimation have been used to determine the sonic-boom profiles of representative supersonic and hypersonic airplanes of the future. The sonic-boom characteristics of these future airplanes have been related to the sonic-boom characteristics of current supersonic airplanes. In the supersonic climb and cruise phases of flight, where the sonic-boom overpressure and impulse levels are relatively high, the use of near-field effects to modify the sonic-boom disturbance of these large future airplanes has been considered. The near-field investigation indicates that some reduction in overpressure and impulse might be possible.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., May 25, 1966,
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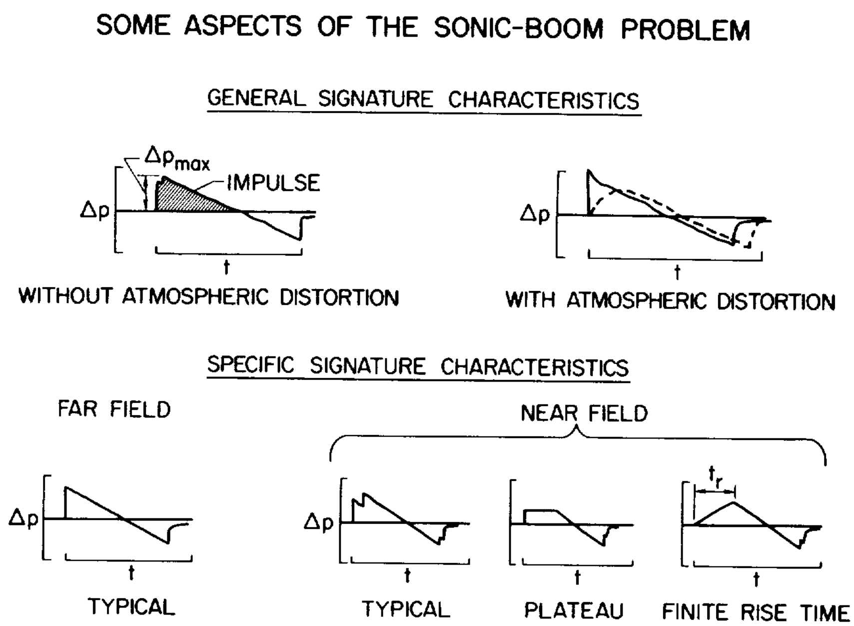

Figure 1

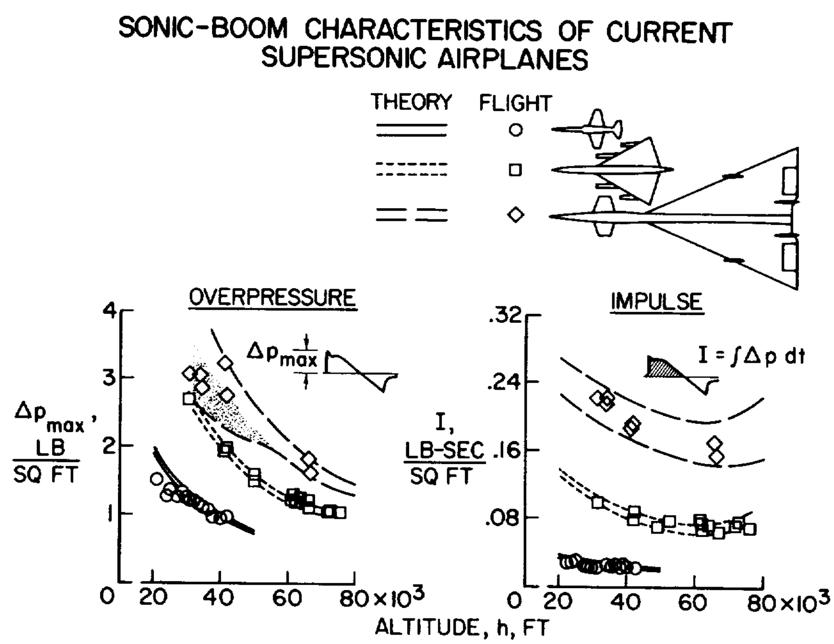

Figure 2

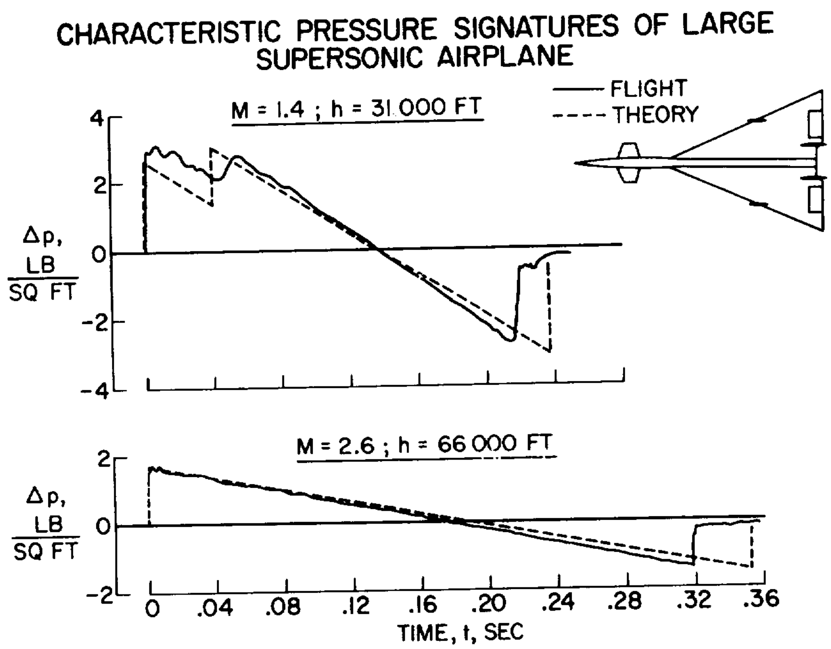

Figure 3

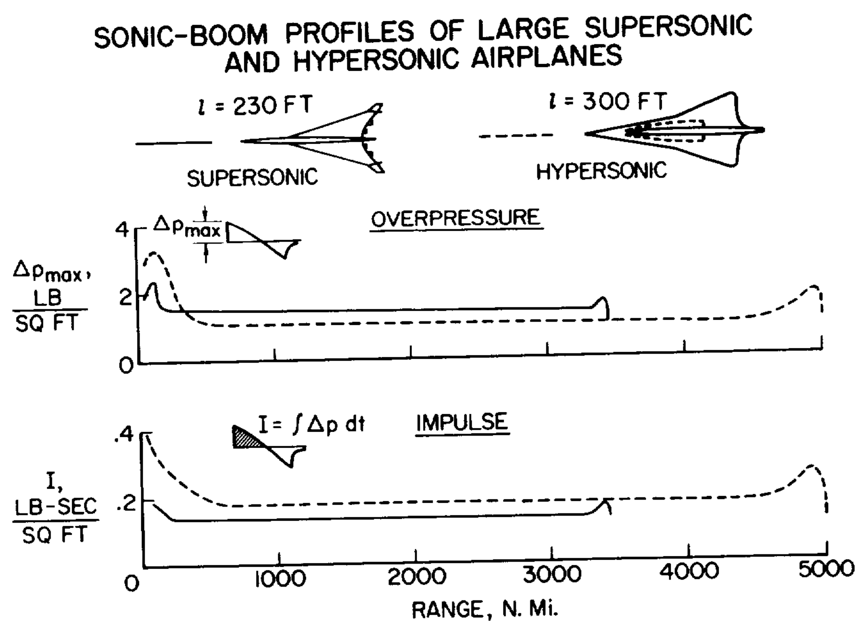

Figure 4

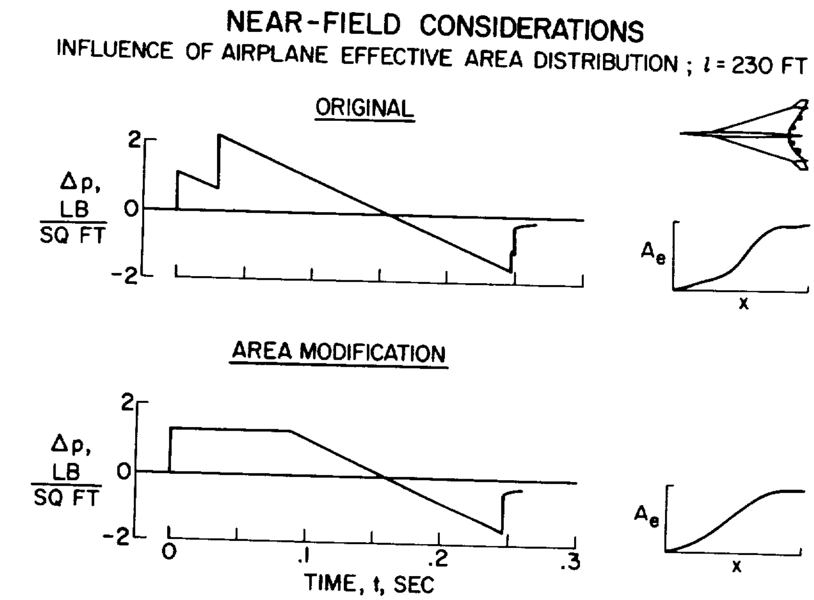

Figure 5(a)

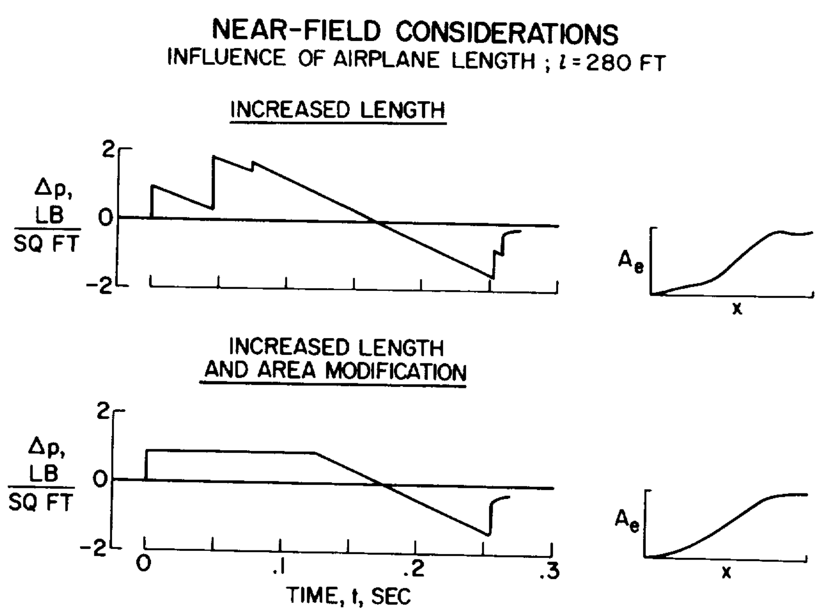

Figure 5(b)

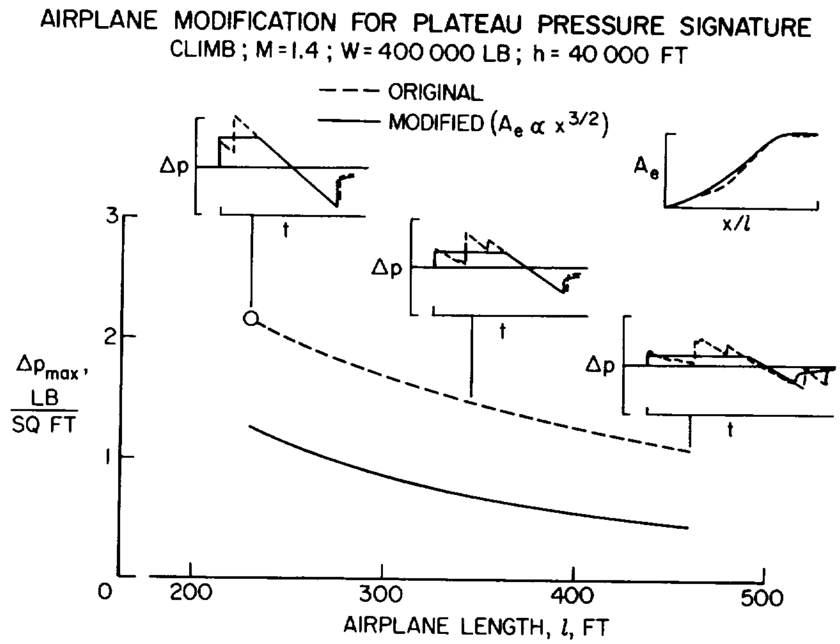

Figure 6

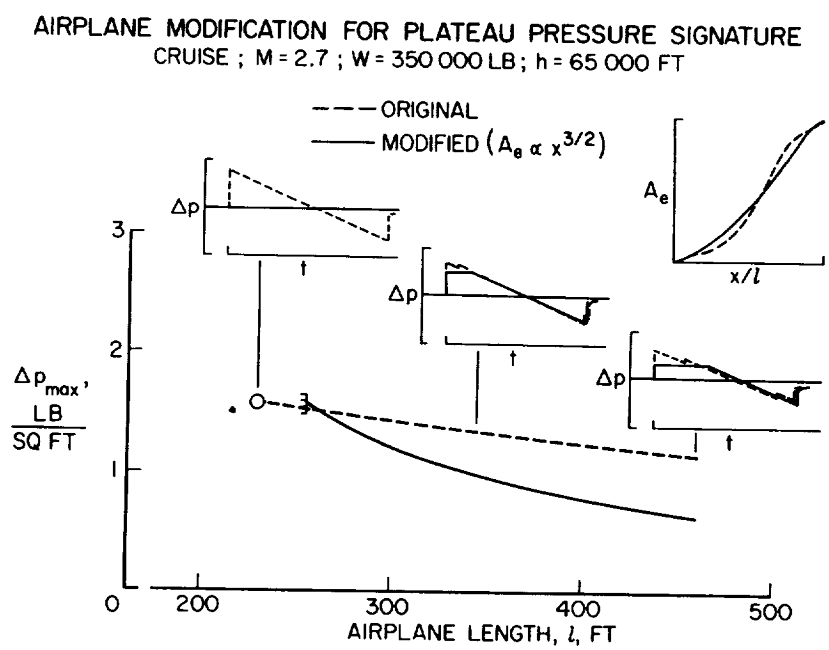

Figure 7

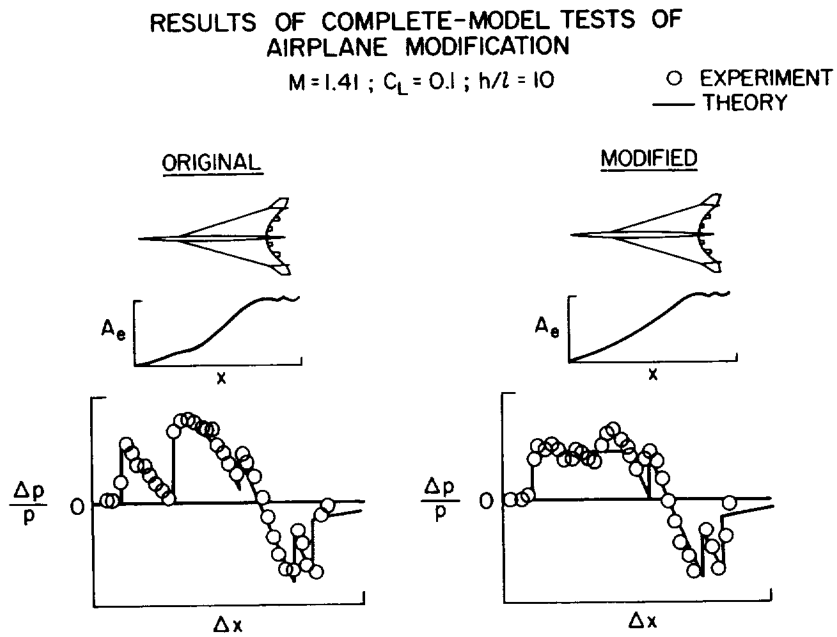

Figure 8

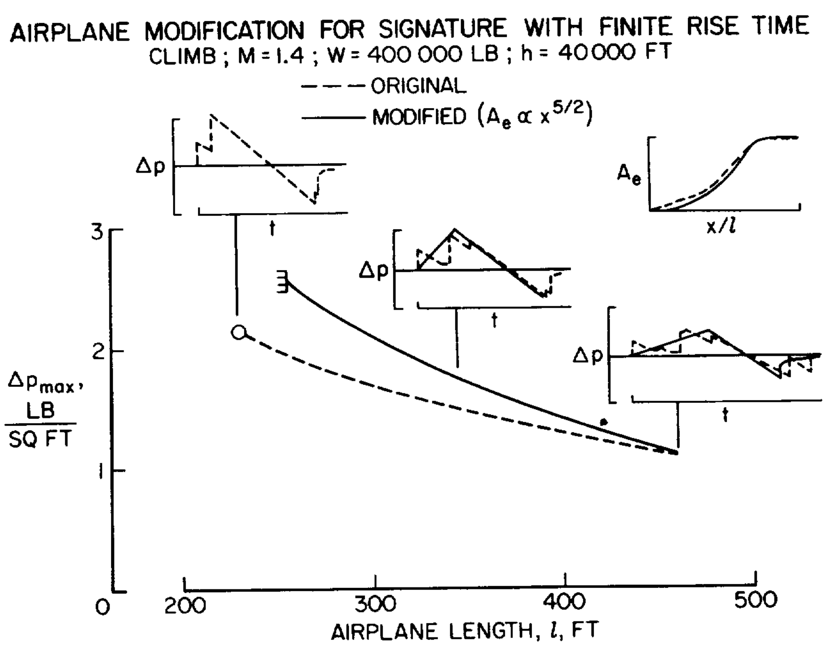

Figure 9

AIRPLANE MODIFICATION FOR SIGNATURE WITH FINITE RISE TIME
CRUISE ; M = 2.7 ; W = 350 000 LB; h = 65 000 FT

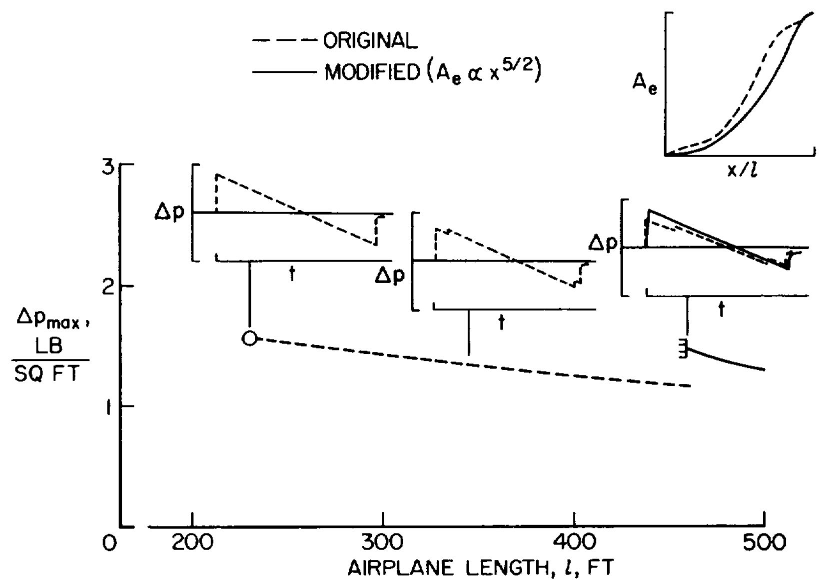

Figure 10