DESIGN METHODS FOR MINIMIZATION OF SONIC-BOOM PRESSURE-FIELD DISTURBANCES

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ABSTRACT

This paper will review theoretically based techniques for minimization of sonic-boom pressure-field energy and overpressure through detailed consideration of airplane configuration. The discussion will include consideration of the recently discovered potential for overpressure minimization for large slender airplanes with extended near-field characteristics. Use of the latter method will be illustrated with correlations of theory and wind-tunnel measurements.

INTRODUCTION

Sonic-boom estimation methods have been developed which adequately describe the nominal pressure disturbances generated by a complex airplane in supersonic flight.[1] The principal factors which influence the estimation of sonic boom naturally form the basis for methods which can be used to minimize or suppress certain aspects of the pressure disturbance. The attenuating effect of increased distance from the source to the disturbance, for example, suggests higher airplane operating altitudes as a means for reducing sonic-boom overpressure. The dependence of sonic-boom estimates of overpressure and impulse on an accurate description of airplane geometry and lift condition would suggest favorable component arrangement as a means for reducing these important pressure-field characteristics.

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Studies of airplane configuration effects with the far-field solutions of sonic-boom theory have led to the definition of an equivalent body shape which would produce an "N" wave pressure disturbance with lower bound overpressure and impulse.[2,3] Although the airplane design required to attain this lower bound effective area distribution was not practical from other considerations, the associated research pointed out some important effects of configuration arrangement on sonic-boom characteristics.[4] More recent investigations of the sonic-boom minimization problem have indicated that the far-field solutions are not applicable for some normal operating conditions of a large slender airplane.[5] For these conditions, which include the critical climb portion of the supersonic transport flight path, the ground pressure disturbance is not an "N" wave but has a near-field shape which depends on the detailed geometry of the airplane. These near-field concepts introduce the possibility that configuration oriented changes in the shape of the pressure signature may be used to reduce sonic-boom overpressure.

The purpose of the present paper is to review some of the results of these research efforts to find means to minimize or suppress the sonic-boom disturbance. Particular emphasis will be given to the results as they apply to the sonic-boom problem of the supersonic transport. The theoretical methods discussed in the previous paper[1] were used to calculate the sonic-boom disturbances presented herein. The method of Friedman, Kane, and Sigalla[6] was used to account for the propagation of the generated sonic-boom disturbances through a standard atmosphere from the airplane to the ground.

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, $\int \Delta p \, dt$
K_r	reflection factor
l	airplane or model length
M	Mach number
p	reference pressure
Δp	incremental pressure due to airplane or model flow field
Δp_{MAX}	maximum positive value of Δp
t	time
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.

FAR-FIELD SONIC-BOOM MINIMIZATION

Altitude Attenuation

Far-field estimates of the nominal pressure-field characteristics of current supersonic airplanes have correlated well with data obtained during flight.[1] The analytical estimates and measured flight data for these relatively light airplanes have shown a predominant attenuative effect of increased operating altitude on sonic-boom overpressure.[1] In the case of a large heavy airplane such as the supersonic transport the attenuative effect of altitude would be somewhat counterbalanced by an intensification of the sonic-boom disturbance due to lift or weight effects. These counterbalancing effects of weight on the calculated far-field ground overpressures of a representative supersonic transport are illustrated in figure 1 for a critical climb Mach number of 1.4. In this figure the curve for the zero weight condition corresponds to the far-field overpressure levels which would be expected from the airplane volume alone. The inset sketches indicate the growth of effective area with weight for a given altitude and the curves show the corresponding increases in overpressure. The pertinent factor illustrated in figure 1 is that the major attenuating effects of altitude occur in the low-altitude, high-overpressure region. For the 400,000-pound weight condition which is representative of the design climb weight of a supersonic transport airplane, the decrease of overpressure with increased altitude is very slight for overpressure levels below the current standard of 2 psf in climb. Although the overpressure due to lift or weight is fairly constant, it becomes an increasingly larger percentage of the total overpressure as altitude is increased. For example, at the 400,000-pound design weight condition, lift or weight represents approximately 20 percent of the total overpressure at an altitude of 20,000 feet. This lift contribution to total overpressure has grown to approximately 60 percent at an altitude of 60,000 feet.

Since lift or weight increases the time duration of the far-field sonic-boom disturbance as well as the overpressure, it has a multiple effect on the positive pressure impulse. The variation of positive impulse with altitude and weight is shown in figure 2 for the representative transport configuration and conditions of the previous figure. Weight is seen to have a pronounced effect on this pressure-field characteristic, particularly at high altitudes. Due to the multiple influence of weight on pressure impulse, increased operating altitude does not provide an attenuating effect on impulse for the 400,000-pound design weight condition representative of a supersonic transport. Similar trends have been observed in measurements taken during the overflight of a bomber airplane.[1]

Far-Field Effective Area Considerations

Since weight has been shown to have an adverse effect on the magnitude of the sonic-boom disturbance, far-field methods have been used to consider the minimization of overpressure and impulse for a given weight and altitude. This approach involves the optimization of the effective area distribution or component arrangement of the airplane for a given lift condition.

Some far-field effective area considerations are illustrated in figure 3 for a representative climb Mach number of 1.4, design weight of 400,000 pounds, and design altitude of 40,000 feet. Note that although the effective base areas of the three configurations are the same, there are pertinent differences in the area developments from the nose to the base. Configuration A, which is characterized by a canard and aft wing, has a rapid rate of growth of effective area in the region of the nose and wing-body juncture. The maximum area is somewhat greater than the base area. Configuration B, which has been considered in the previous discussion, is characterized by a highly swept arrow wing. This configuration has a rather gradual rate of growth of effective area distribution and a maximum area which is essentially the same as the base area. The lower bound shape is depicted at the right side of the figure as an equivalent body of revolution. This effective area shape which is derived in the literature[3] is the theoretical shape for minimum far-field overpressure and impulse for a given base area and length. Although from drag considerations it appears impossible to attain the blunt lower bound shape with a practical airplane design,[4] the lower bound is a useful reference point for overpressure and impulse comparisons.

The estimated far-field sonic-boom overpressures for the configurations of figure 3 are shown in figure 4 for a representative transport climb condition of $M = 1.4$ and $W = 400{,}000$ lb and for a representative cruise condition of $M = 2.7$ and $W = 350{,}000$ lb. Substantial effects of configuration variables on overpressure characteristics are indicated for both flight conditions. Configuration A, due to the rapid rate of growth of effective area discussed previously, has the highest overpressure for a given altitude and must operate at much higher altitudes to achieve a desired low overpressure level. The overpressure characteristics of configuration B are reasonably close to the lower bound particularly at the cruise Mach number. For all configurations the climb condition appears to be the most critical from overpressure considerations because of the lower altitudes and heavier weights associated with this flight regime. It is interesting to note that even the lower bound shape does not offer much relief from the current supersonic transport overpressure goals of 2.0 psf in climb and 1.5 psf in cruise.

Just as in the case of lift, configuration factors have a multiple influence on positive pressure impulse. This is illustrated in figure 5 for the configurations and representative flight conditions of the previous figure. Rather extreme effects of configuration arrangement or effective area shape on impulse are indicated. While there is no clear indication of the status of impulse as a sonic-boom factor it might be an important consideration in the operation of the supersonic transport.[7]

While a practical airplane configuration has not been developed which can realize the full potential of far-field minimization techniques, the discussion has indicated that these techniques have provided an important assessment of configuration effects on sonic-boom characteristics.

NEAR-FIELD SONIC-BOOM MINIMIZATION

Recent studies have indicated that for large slender airplanes such as the supersonic transport the near-field effects of airplane shape on pressure signature could extend to the ground.[5] The extended near field of a large airplane is illustrated in figure 6. The factor that distinguishes this flow field is the shape of the ground pressure disturbance. Instead of the far-field "N" wave generally assumed to exist for this airplane at normal operating altitudes, the ground pressure disturbance is seen to depend on the shape of the airplane. This could be significant from two considerations. First, the actual ground overpressures would be less than those predicted by far-field theory, and second the pressure signature may be favorably altered by design modifications to the airplane.

Near-Field Effects on Sonic-Boom Overpressure

To consider the possible reduction of sonic-boom overpressure through near-field effects the arrow wing transport configuration B of the previous discussion was analyzed with the general near-field solutions of sonic-boom theory. Further, an analytic modification to the original airplane shape was made to provide a more idealized near-field effective area distribution. The results of these near-field considerations are shown in figure 7 for a representative climb condition of $M = 1.4$ and $W = 400{,}000$ lb. On the left side of the figure the calculated near-field overpressures for the original transport configuration are compared with those obtained from the far-field approximation. Inset sketches of pressure signature for an assumed climb altitude of

40,000 feet indicate that the ground pressure disturbance has not reached the "N" wave shape assumed in the far-field analysis. The more applicable saw-tooth near-field signature has maximum overpressures somewhat lower (about 10 percent) than would be estimated on a far-field basis.

The effect of the proposed modification of the original configuration is shown on the right side of figure 7. The purpose of the modification was to create a smooth effective area in such a manner as to replace the saw-tooth pressure disturbance in the inset sketch with a single bow shock followed by a succession of very weak shocks. The estimated effect of the modification was to reduce the maximum overpressure at the critical climb condition from about 2.2 to 1.3 psf. Note that although the pressure signature in the vicinity of the tail shock has not been altered appreciably by the modification, its pressure jump is less than the modified bow shock rise. Consideration of both the original and modified configurations at a cruise Mach number of 2.7 indicated that far-field conditions had essentially been reached with a maximum overpressure at the current cruise standard of 1.5 psf.

Analytic studies show that for the particular application, the near-field modification would have little or no detrimental influence on other aspects of airplane performance. It should be pointed out, however, that this might not be true for a similar near-field modification applied to some other airplane. It should also be pointed out that there is still some question as to what shape of pressure signature is desirable from the standpoint of public acceptance of sonic boom.

Wind-Tunnel Investigation of Near-Field Modification

With due regard to the unanswered question of what is a desirable signature shape, near-field effects appear to offer some promise for sonic-boom overpressure reductions in the critical climb portion of the supersonic transport flight path. Consequently, a wind-tunnel program was developed to consider the application of these concepts. The balance of the present paper will be devoted to a discussion of some of the results of this wind-tunnel test program.

Small 4-inch models of original and modified versions of the arrow wing transport of figure 7 along with respective equivalent bodies of revolution were used in the investigation. The equivalent bodies of revolution were designed to represent the original and modified airplane effective area distributions at a climb Mach number of 1.4, design weight of 400,000 pounds, and design altitude of 40,000 feet. Some results from the tests of the transport equivalent bodies are shown in figure 8. The nature of the modification to the original airplane effective area distribution is illustrated by sketches at the top of the figure. The original shape is seen to be smoothed in the forward region by the proposed modification. At the bottom of figure 8 theoretical pressure signatures are compared with measurements taken in the flow field 40 inches from the 4-inch models. For both the original and modified shapes the agreement between theory and experiment is good, particularly in the important bow shock region. The modified shape appears to have the desired effect of replacing the original two-shock system with a bow shock followed by a succession of weak shocks. The maximum overpressures within the modified signature are considerably reduced from those generated by the original shape.

Wind-tunnel results obtained in complete model tests of the original and modified arrow wing transport are compared with theoretical estimates in figure 9. These signatures were measured at a Mach number of 1.41, 40 inches below the 4-inch test models. The models were oriented to represent the lifting condition of the airplane at the design weight of 400,000 pounds and design altitude of 40,000 feet. While the correlation of theory with measured signatures is reasonably good for these small complete airplane models, the specified effective area distributions and desired signature shapes were not quite obtained. Very precise construction tolerances are required to duplicate the complex features of a complete airplane in a 4-inch test model such as those considered in the current wind-tunnel investigation. For example, the maximum fuselage diameter of the modified airplane model is approximately 0.2 inch which corresponds to a diameter of 138 inches in the full-scale airplane. Consequently, small differences in the model ordinates from those specified could reflect large differences in the airplane representation.

Consideration of the effect of precise model tolerances on the predicted tunnel pressure signatures is illustrated in figure 10. On the left side of the figure, wind-tunnel results from the actual modified complete model are compared with theoretical estimates for the specified analytic model. On the right side of the figure, the same experimental results are compared with theoretical estimates which correspond to the actual model with the effects of attitude considered in the manner described in the preceding paper.[1] The use of actual model ordinates and attitude effects in the theory leads to a better correlation with test results.

On the basis of the wind-tunnel results presented, configuration oriented changes in the shape and maximum overpressure of the airplane ground pressure signature appear to be possible. If low overpressure is a primary consideration in the supersonic transport operation, near-field effects offer some promise for sonic-boom suppression in the critical climb portion of the flight path.

CONCLUDING REMARKS

In conclusion, some means which can be used to minimize or suppress certain aspects of the sonic-boom disturbance have been explored for representative flight conditions of a supersonic transport. Consideration has been given to the effects of altitude attenuation and configuration variables on the far-field sonic-boom characteristics of transport airplanes. A promising application of near-field concepts to reduce sonic-boom overpressures during the supersonic transport climb path has been illustrated with wind-tunnel-test results.

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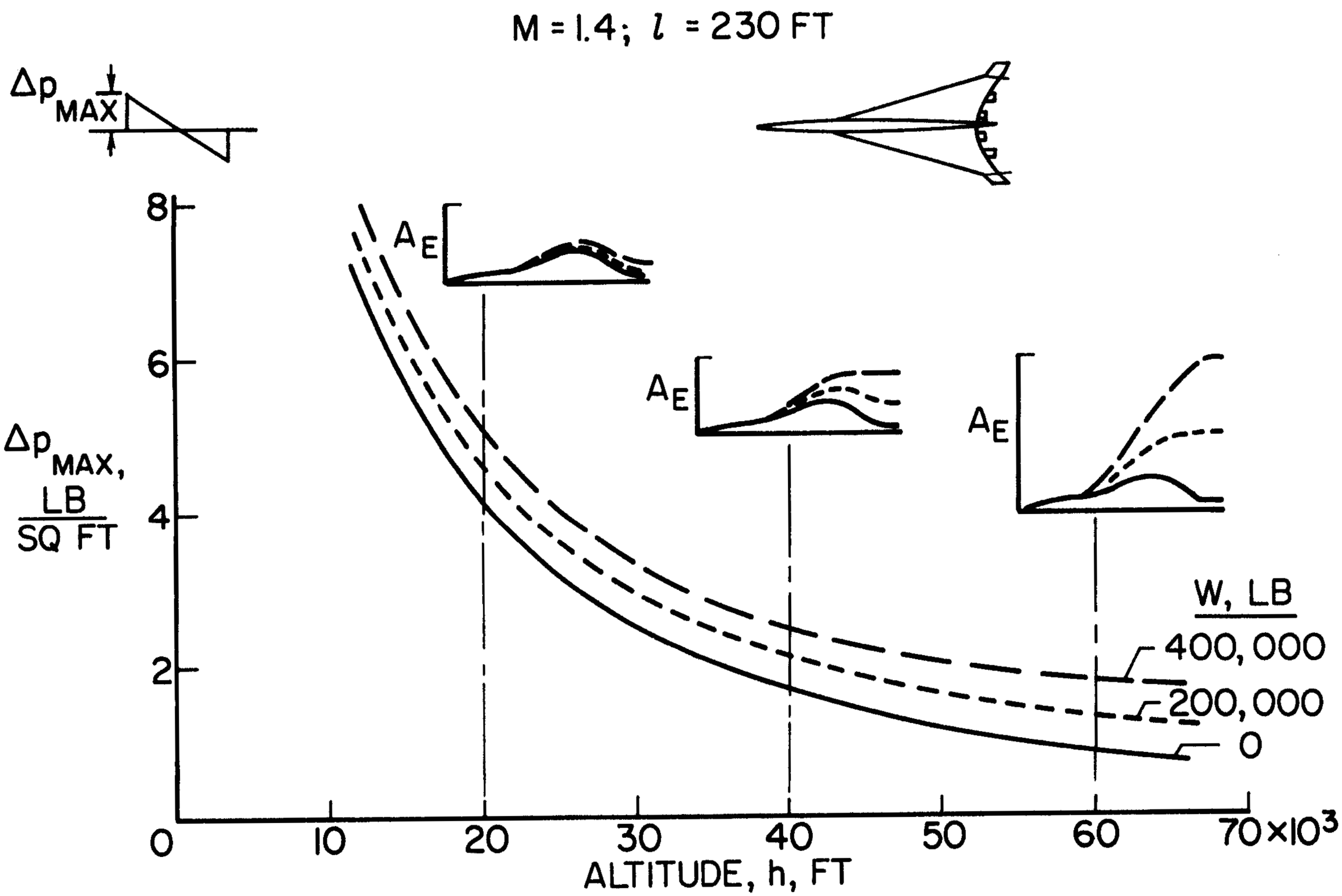

Figure 1.- Effect of weight and altitude on far field overpressures.

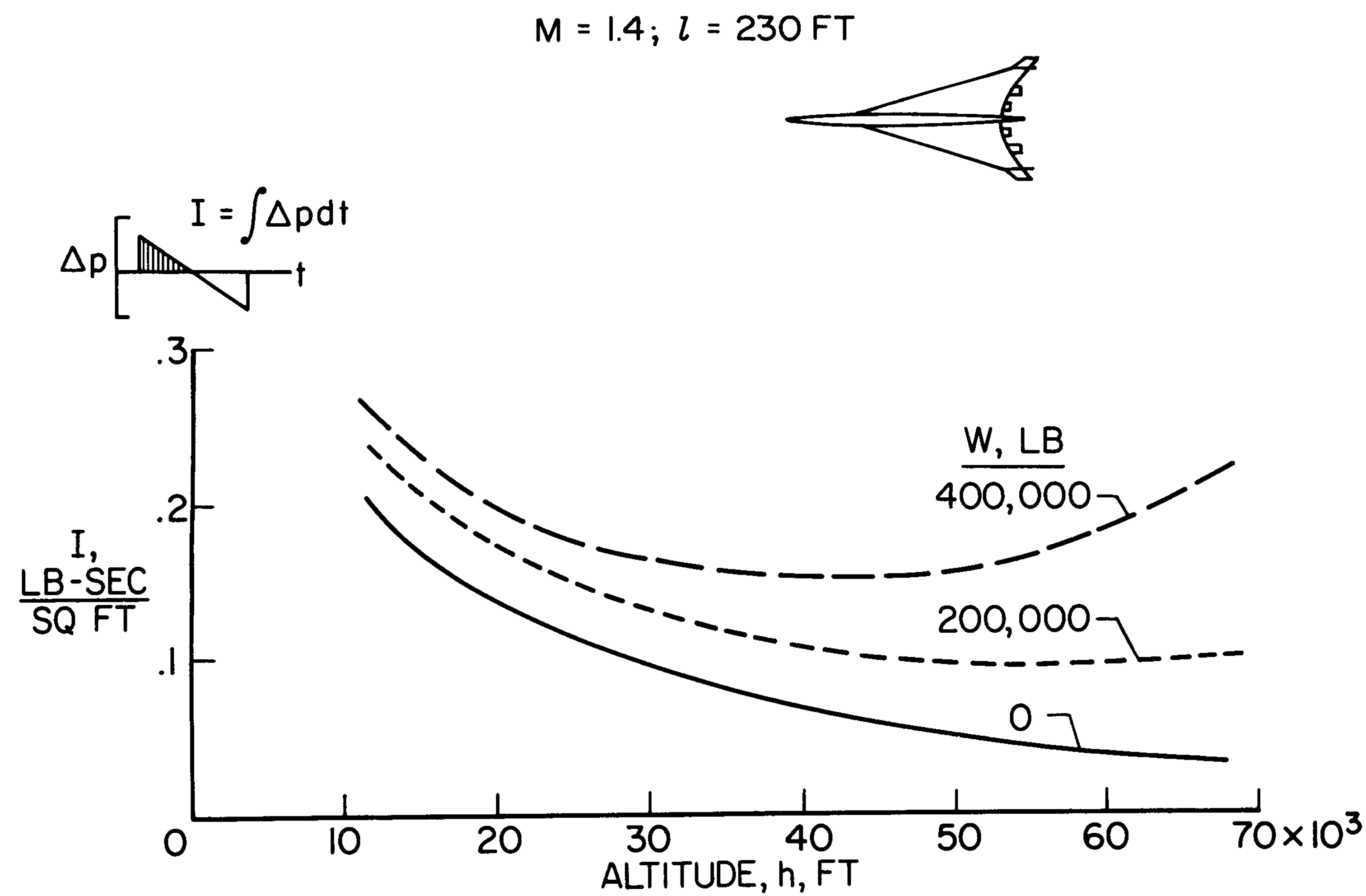

Figure 2.- Effect of weight and altitude on impulse.

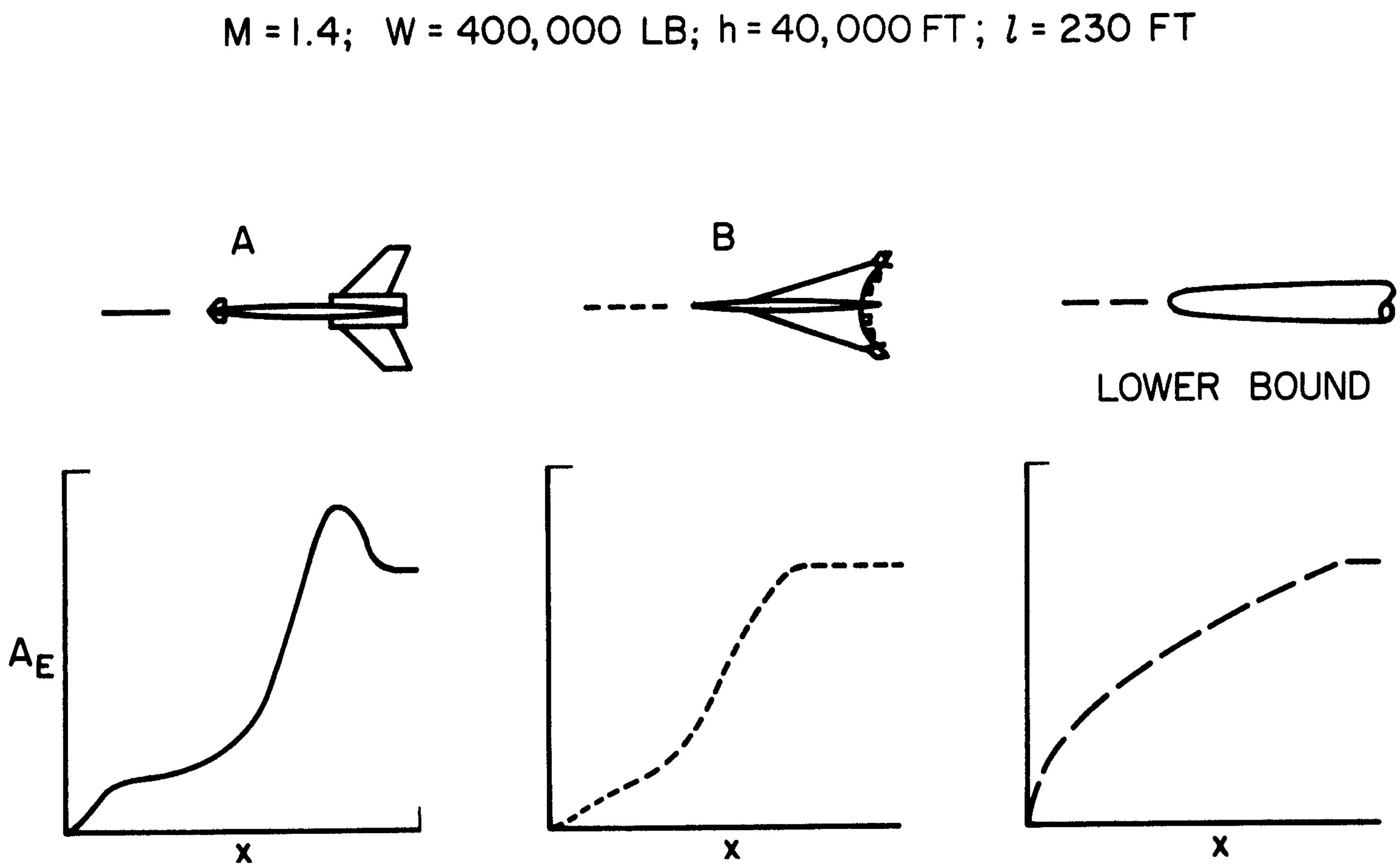

Figure 3.- Far field effective area considerations.

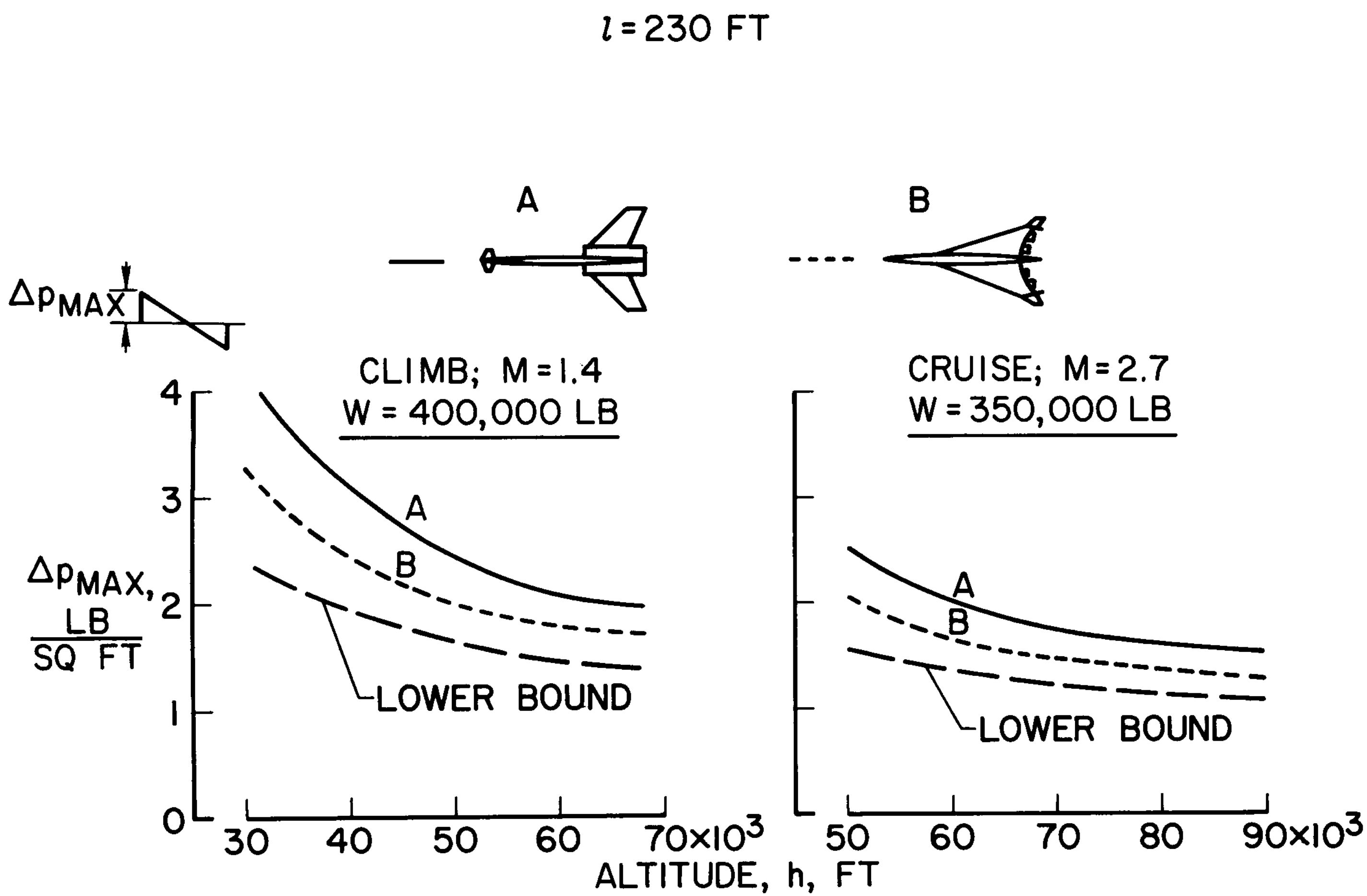

Figure 4.- Effect of configuration arrangement on far field overpressures.

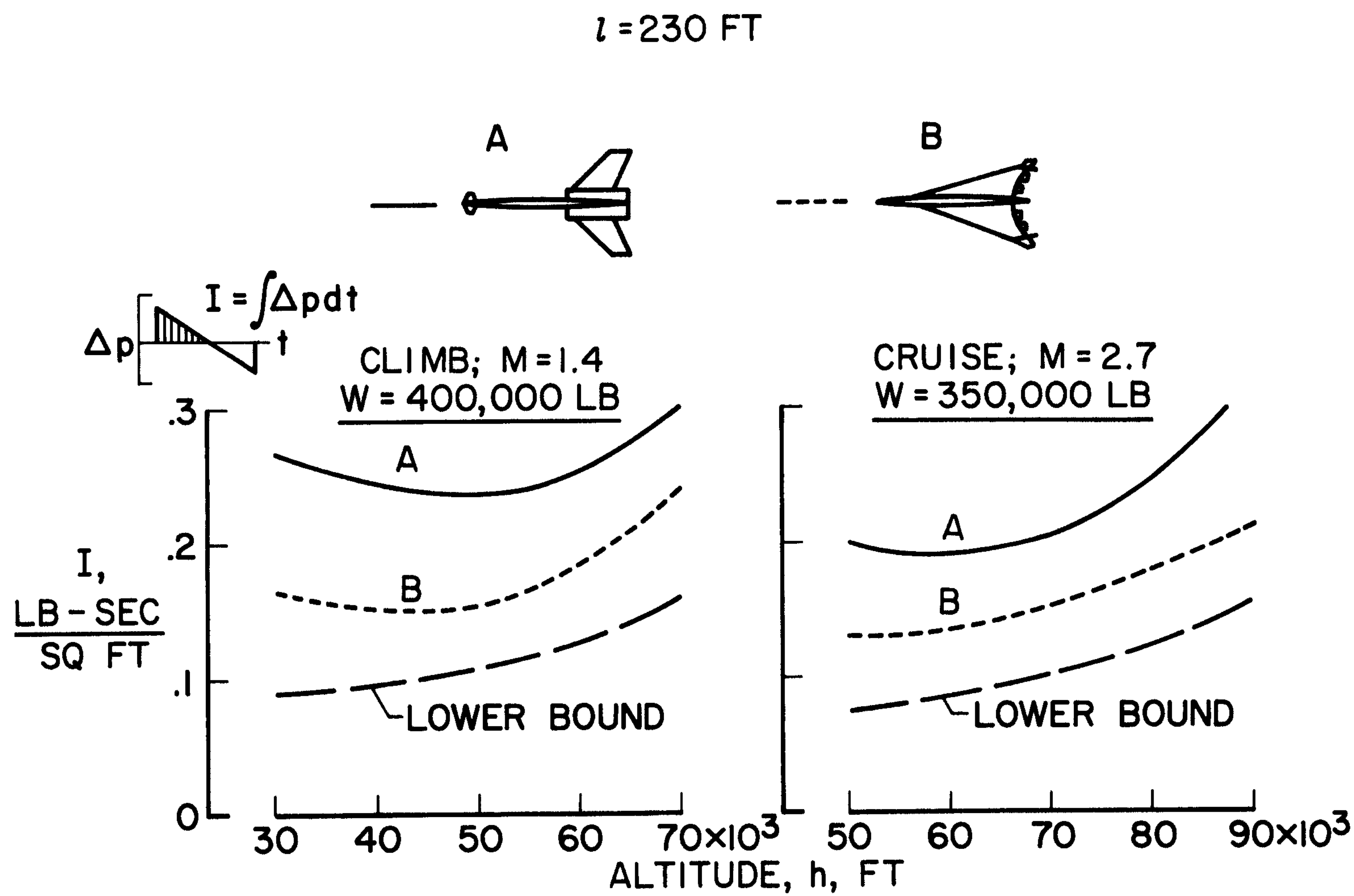

Figure 5.- Effect of configuration arrangement on impulse.

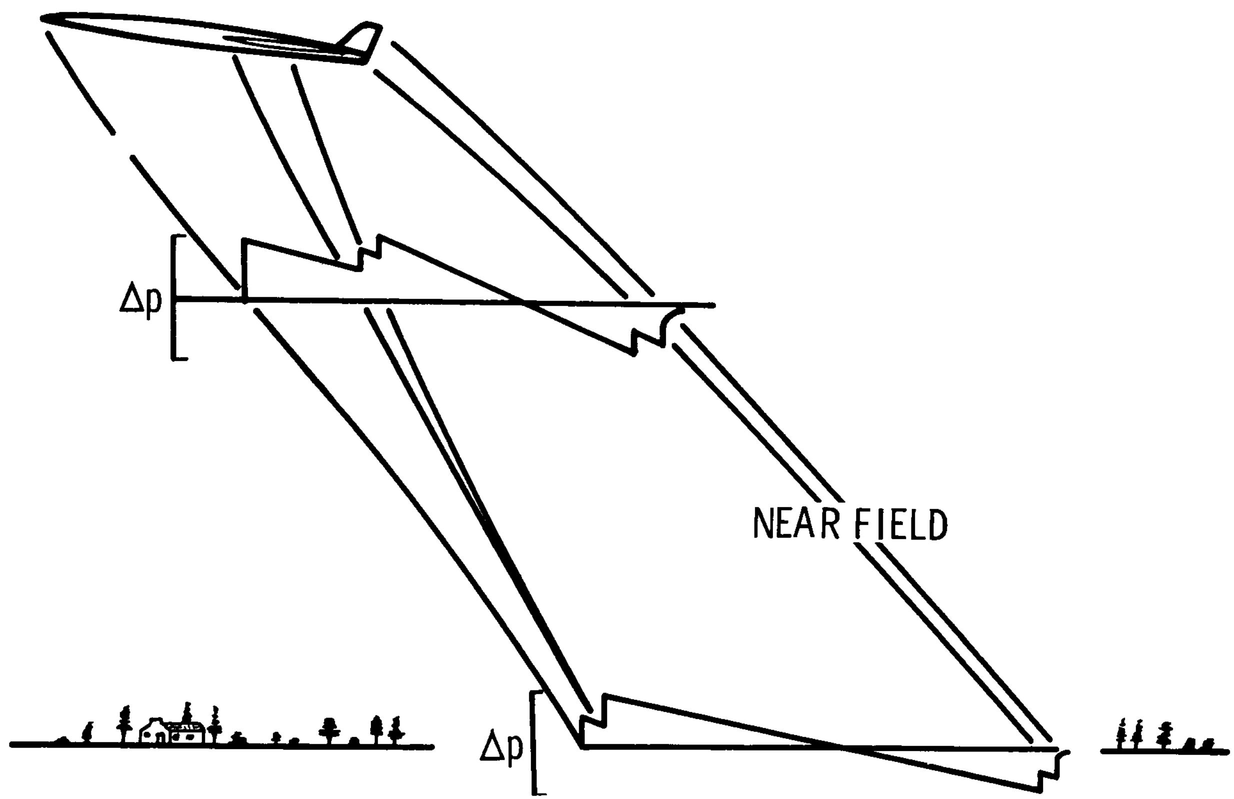

Figure 6.- Extended near field of large airplane.

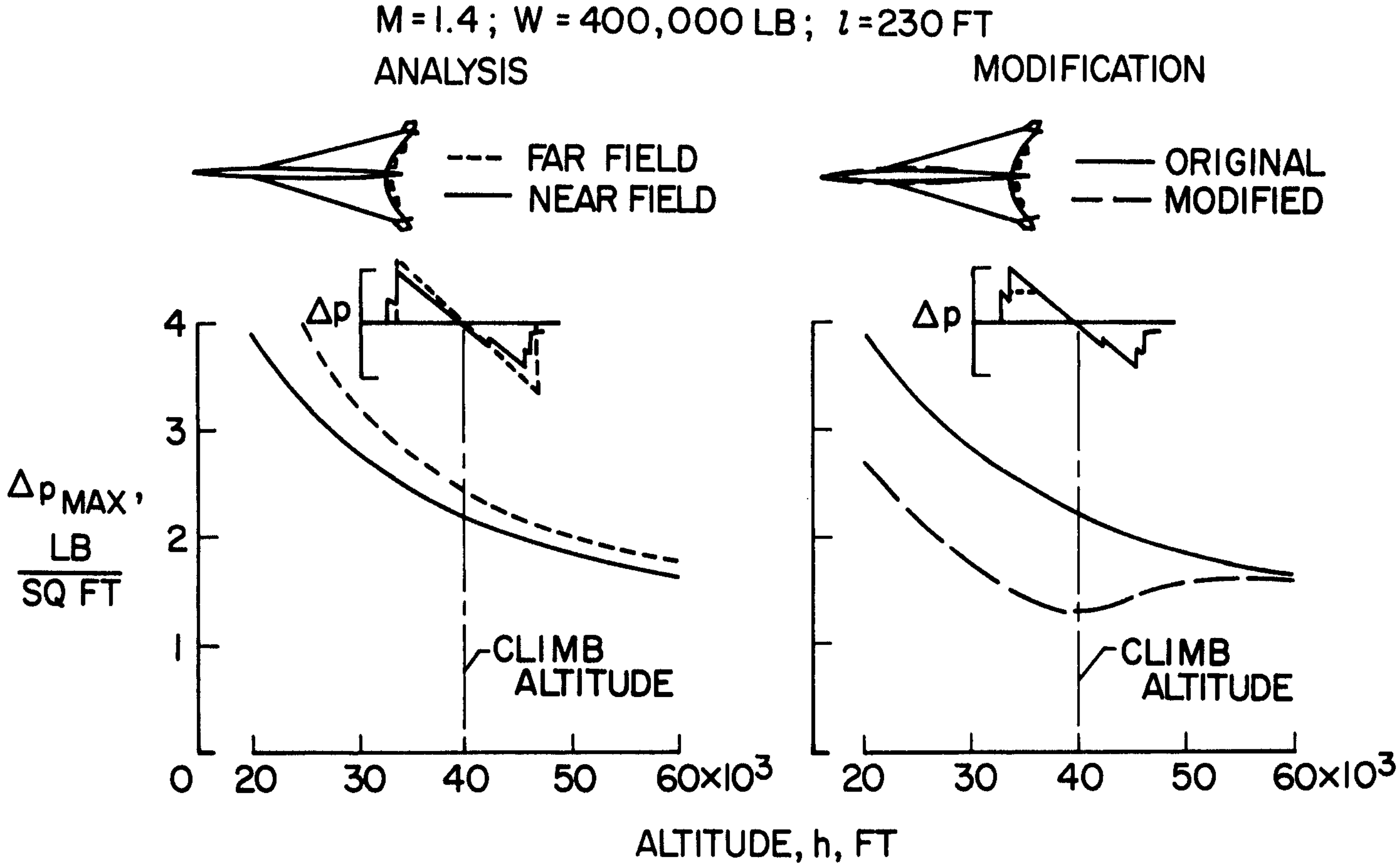

Figure 7.- Near field effects on climb overpressures.

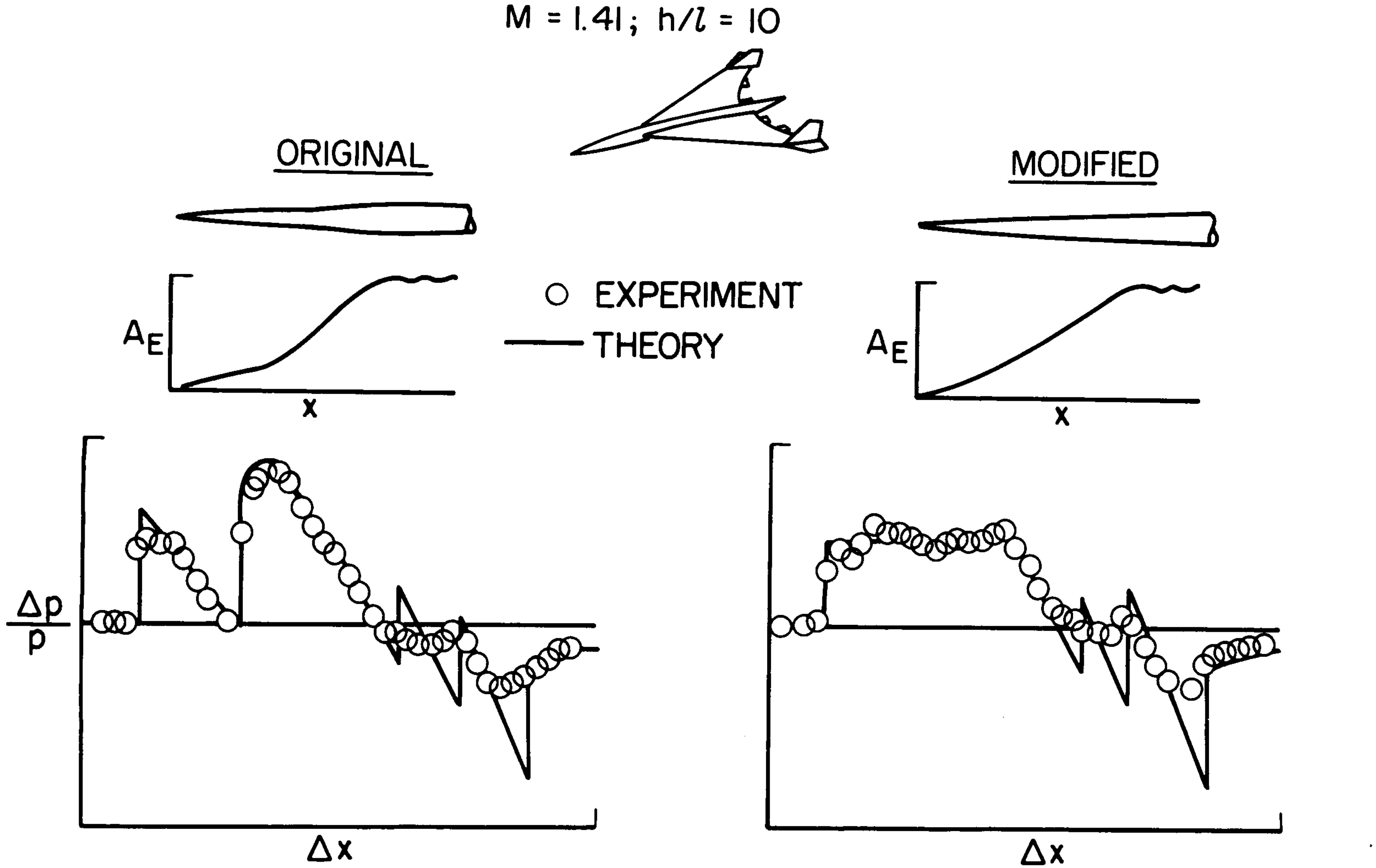

Figure 8.- Results of equivalent body tests of SST modification.

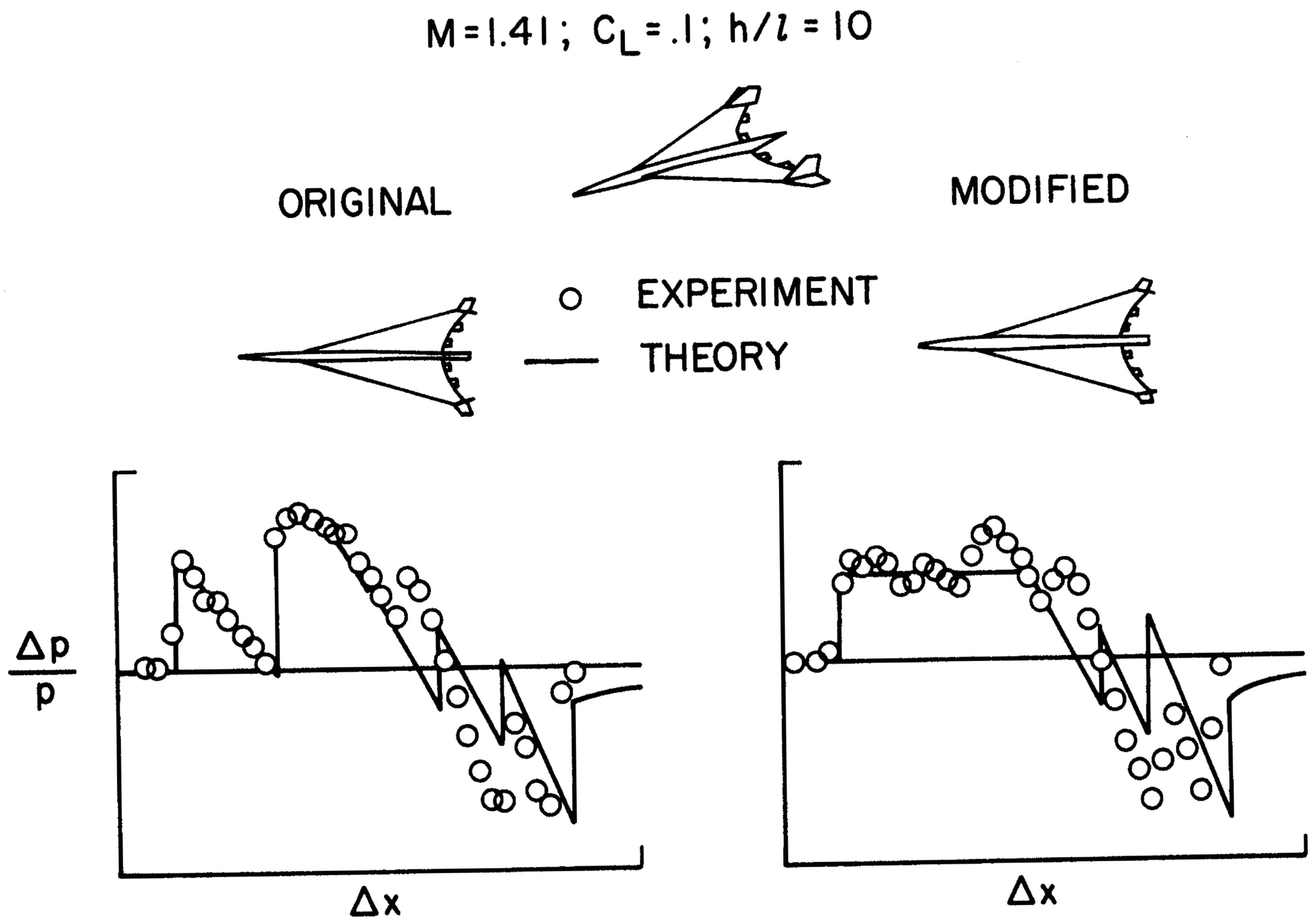

Figure 9.- Results of complete model tests of SST modification.

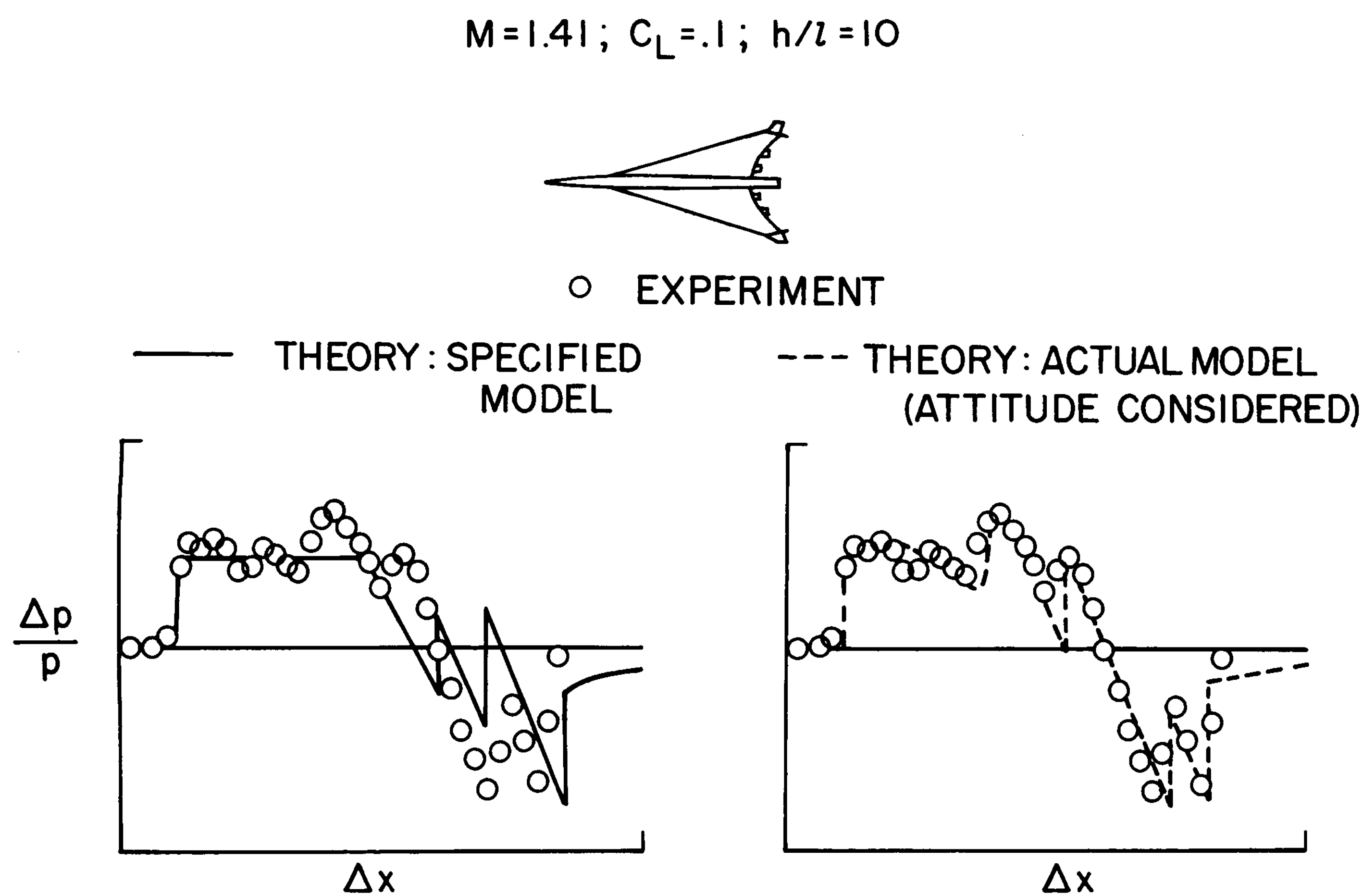

Figure 10.- Analysis of complete model tests of SST modification.

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