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PREDICTION OF AIRCRAFT SONIC BOOM CHARACTERISTICS FROM EXPERIMENTAL NEAR FIELD RESULTS

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SUMMARY

Near field pressure signature data measured in a wind tunnel were used for predicting aircraft sonic boom characteristics. It was found that with the data plus the theoretical concepts of Whitham, an experimental area function $F(y)$ could be determined. Evaluation of the area function for the configuration in turn allows an assessment to be made of the sonic boom pressure signature at any distance ratio greater than that used for the original measurement of the near field data.

On the basis of limited tests of a 12-inch model of the XB-70 airplane, good correlations of wind tunnel to wind tunnel and wind tunnel to flight pressure signature results were obtained. A near field signature measured at a distance ratio of 1.0 and a Mach number of 1.8 was used to predict the overpressure characteristics of the XB-70 configuration. The prediction was accurate at a near field distance ratio of 4.5, and a far field distance ratio of 290.

INTRODUCTION

The determination of the sonic boom characteristics for arbitrary aircraft has in the past followed two different lines. The first, and principal, method employed is based entirely on theory and therefore entails a detailed analysis of the lift and cross-sectional area distributions of the aircraft (ref. 1). The second method involves the use of experimental pressure signature data from wind-tunnel tests of a small-scale model. Here the measured pressure signature is adjusted by the method discussed in reference 2 to give a simple N-wave signature. This adjusted pressure signature has been shown to agree fairly well with ground measurements of far field pressure signatures for the actual flight vehicle, provided the pressure signature measured in the wind tunnel is of the far field type (refs. 2 and 3).

A difficulty often encountered with the theoretical determination of sonic boom characteristics is the inability of linear theories to predict lift distributions accurately. This problem is accentuated when the aircraft being studied has many components that produce large interference effects (e.g., canard, engine compartment, deflected wing tips, etc.).

The experimental procedure for determining sonic boom characteristics outlined in reference 2 gives fairly good results but is limited to far field studies. This means that very small-scale models must be constructed so as to obtain far field type pressure signatures at wind-tunnel altitudes. This is a serious restriction when configurations like the supersonic transport are being studied since these airplanes may be designed to take advantage of near field improvements.

The purpose of the study described herein was to reexamine the experimental test technique in consort with the Whitham near field theory to determine if the difficulties discussed above could be circumvented in any way. Pressure signatures generated by a model of an aircraft configuration and measured in a wind tunnel at very small distance ratios were studied in conjunction with Whitham's theory without the prior knowledge of the lift or volume distribution. The use of small distance ratios makes it possible to test large models in small wind tunnels.

A 12-inch model of the XB-70 airplane was tested in the Ames 9- by 7-Foot Wind Tunnel at a Mach number of 1.8 and at distance ratios of 1.0 and 4.5. The pressure signature obtained at a distance ratio of 1.0 was used to predict pressure signatures at distance ratios of 4.5 and 290. The latter distance ratio corresponded to available flight overpressure data for the XB-70.

SYMBOLS

$F(y)$	effective area distribution function given by equation (3)
h	a function of the Heaviside unit step function
k	$\frac{(\gamma+1)M^4}{\sqrt{2}\,\beta^{3/2}}$
L	reference length for model or aircraft
M	Mach number
p	reference pressure
$\frac{r}{L}$	distance ratio
r	altitude
R	radius or equivalent radius
sl	slope of line used in balancing areas on the F-function curve, $\frac{1}{kr^{1/2}}$
S	effective cross-sectional area

t dummy variable of integration

x longitudinal distance from airplane nose or model nose to point on corrected characteristic

ΔX incremental distance along the abscissa at the pressure signature trace

y distance along longitudinal axis of aircraft measured from nose

β $(M^2 - 1)^{1/2}$

γ ratio of specific heats

Δp sonic boom overpressure

$(\ )'$ first derivative

Subscripts

int interference lift

vol volume

ANALYSIS

A method of obtaining a pressure signature from the F-function based on an area balancing technique was first given by Whitham in reference 4. This technique will be reviewed briefly since the procedure is germane to the discussion that follows.

The asymptotic form of the equations used in developing sonic boom pressure signatures are (refs. 4 and 5).

$$\frac{\Delta p}{p} = \frac{\gamma M^2}{\sqrt{2\beta r}} F(y) \tag{1}$$

$$x = \beta r - k r^{1/2} F(y) + y \tag{2}$$

$$\begin{aligned} F(y) = {} & \frac{1}{2\pi} \int_0^\infty \left(\frac{2}{\beta R_{vol}(t)}\right)^{1/2} h\left(\frac{y-t}{\beta R_{vol}(t)}\right) dS'_{vol}(t) \\ & + \frac{1}{2\pi} \int_0^\infty \left(\frac{2}{\beta R_{lift}(t)}\right)^{1/2} h\left(\frac{y-t}{\beta R_{lift}(t)}\right) dS'_{lift}(t) \\ & + \frac{1}{2\pi} \int_0^\infty \left(\frac{2}{\beta R_{int}(t)}\right)^{1/2} h\left(\frac{y-t}{\beta R_{int}(t)}\right) dS'_{int}(t) \end{aligned} \tag{3}$$

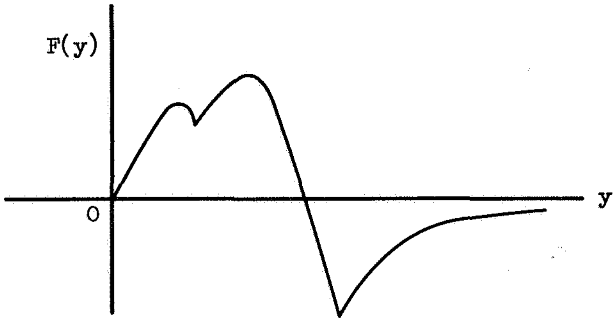

Figure 1.- Example F-function.

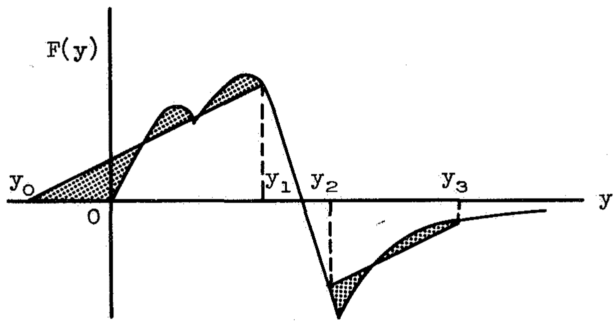

Figure 2.- Area balancing of example F-function.

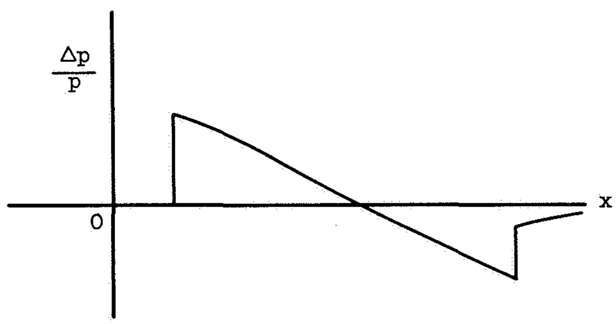

Figure 3.- Pressure signature obtained from area balancing of example F-function.

An example F-function is shown in figure 1. Shocks are obtained from the F-function of figure 1 by balancing areas as illustrated in figure 2. The slope of the line used in the area balancing at an altitude r_1 is given by $sl_1 = 1/kr_1^{1/2}$. The resulting pressure signature is shown in figure 3. The pressure jump and location of the bow shock are given by

$$\left(\frac{\Delta p}{p}\right)_{\substack{\text{bow}\\\text{shock}}} = \frac{\gamma M^2}{\sqrt{2\beta r_1}} F(y_1)$$

$$x_{\substack{\text{bow}\\\text{shock}}} = \beta r_1 - kr_1^{1/2}F(y_1) + y_1$$

while the pressure jump and location of the trailing shock are given by

$$\left(\frac{\Delta p}{p}\right)_{\substack{\text{trailing}\\\text{shock}}} = \frac{\gamma M^2}{\sqrt{2\beta r_1}} \left[F(y_3) - F(y_2)\right]$$

$$x_{\substack{\text{trailing}\\\text{shock}}} = \beta r_1 - kr_1^{1/2}F(y_2) + y_2$$

$$= \beta r_1 - kr_1^{1/2}F(y_3) + y_3$$

The values of $\Delta p/p$ between the bow shock and the rear shock are determined from equation (1) where $y_1 < y < y_2$. Now, if the pressure signature shown in figure 3 had been obtained experimentally (e.g., in a wind tunnel) an F-function which could be used to obtain a pressure signature for the same vehicle at any greater altitude could be calculated by the following equations:

$$F(y) = \frac{\sqrt{2\beta r_1}}{\gamma M^2} \frac{\Delta p}{p}$$

$$y = x - \beta r_1 + kr_1^{1/2}F(y)$$

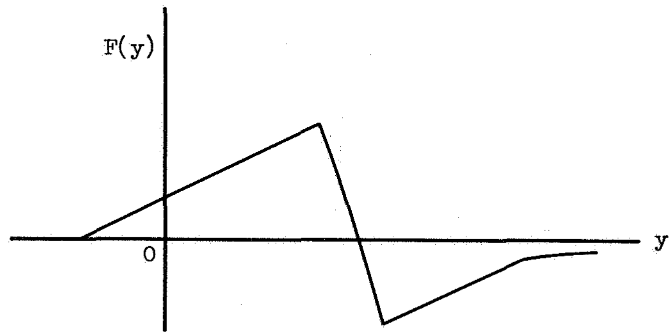

Figure 4.- Experimental F-function.

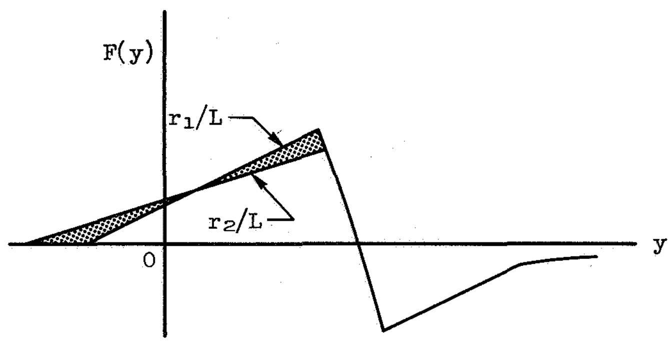

Figure 5.- Experimental F-function with area balancing.

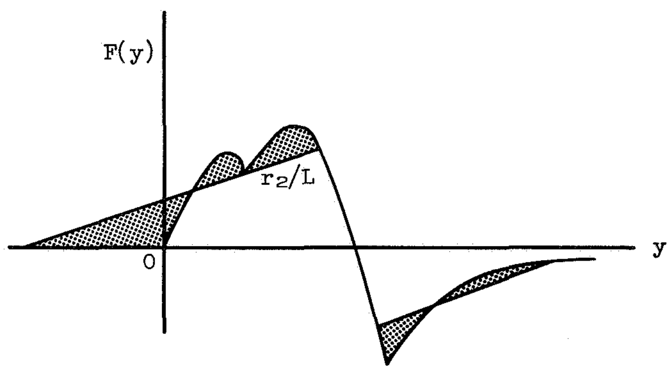

Figure 6.- F-function of figure 1 with area balancing distance ratio r_2/L.

The F-function derived from these relations is shown in figure 4. At first glance there appears to be little similarity between the F-function of figure 4 and the F-function of figure 1. However, it will be shown that the F-function of figure 4 will give exactly the same pressure signature as that of figure 1 if the distance ratio (r/L) of the pressure signature to be calculated is equal to or greater than the distance ratio for which the experimental F-function was determined.

Suppose a pressure signature at distance ratio $r_2/L > r_1/L$ is desired. Then $sl_2 < sl_1$ since $1/kr_2^{1/2} < 1/kr_1^{1/2}$. Hence, the lines used for area balancing when applied to figure 4 would appear as in figure 5. When the same area balancing lines are used in figure 1, areas are balanced as shown in figure 6. Since the F-function of figure 4 has, by definition, the same area as the F-function of figure 1, the areas will balance at the same points on either curve and, hence, yield the same pressure signature at distance ratio r_2/L.

The determination of sonic boom pressure signatures from the experimental F-function is restricted to distance ratios greater than that used for the original measurements since coalesced shocks cannot be separated by the technique described herein.

TEST METHODS AND APPARATUS

Figure 7 is a photograph of the model and related test equipment installed in the Ames 9- by 7-Foot Wind Tunnel. The model was cast from beryllium copper and was 12 inches long. The inlet engine pack consisted of a diverging area duct which permitted internal flow and was designed to start at a Mach number of 2. The model was mounted on a two-component (normal force and pitching moment) strain-gage balance which was manufactured integral

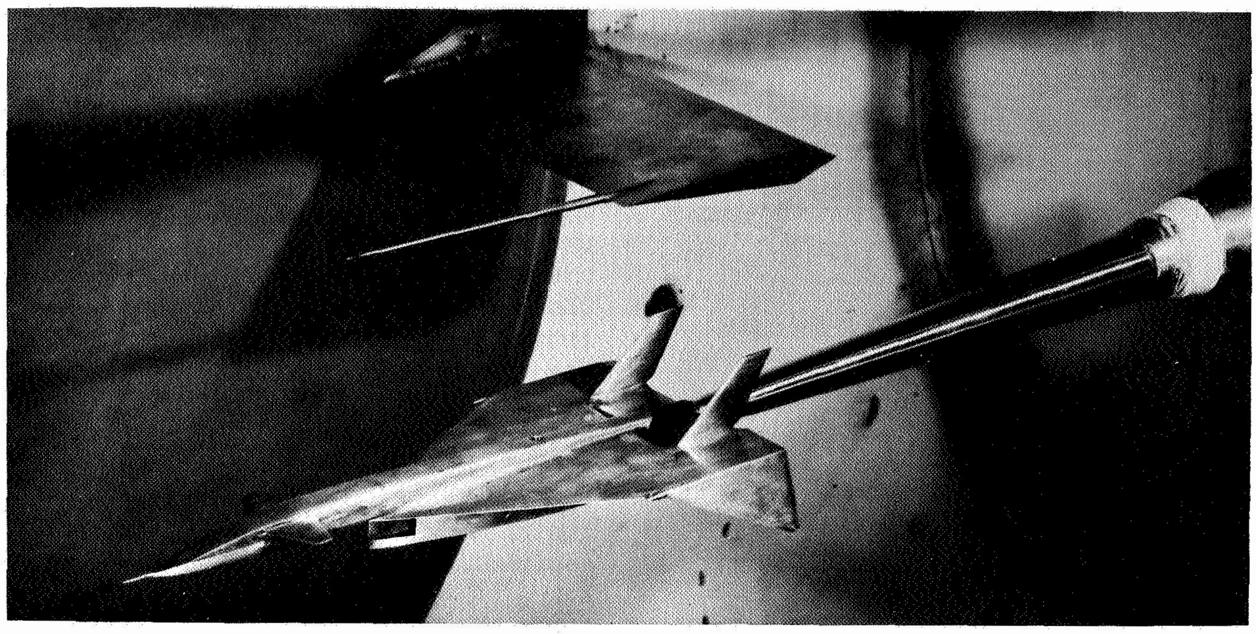

Figure 7.- Model and related test equipment installed in 9- by 7-foot wind tunnel. (Model rotated 90° from running position.)

with the sting. The sting-balance combination was mounted on a linear actuator which had a longitudinal travel of 25 inches.

A conical static probe with a total included angle of 2° measured the pressure field generated by the model. The pressures received by the static probe were transmitted to a capacitance type pressure cell mounted outside the wall of the tunnel.

Pressure signatures were obtained at distance ratios of 1.0 and 4.5 (figure 7 shows the model at a distance ratio of 1.0) for three lift conditions of the model at a Mach number of 1.8. The total pressure for the test was 1 atmosphere.

RESULTS AND DISCUSSION

The pressure signatures obtained for an XB-70 model at a distance ratio (r/L) of 1.0 at a Mach number of 1.8 are shown in figure 8. These near field data were used to derive an F-function for each lift coefficient of the test. The derived F-functions were in turn used to calculate pressure signatures for an r/L of 4.5 and 290 which are given in figures 9 and 10, respectively. Figure 9 also shows the experimental wind-tunnel data obtained for an r/L of 4.5 which can be seen to agree well with the derived curves. The derived pressure signatures of figure 10 for an r/L of 290 were interpolated to obtain the signature for a lift coefficient of 0.096[1] shown in figure 11 along

[1]Value for the airplane at the time the sonic boom was generated.

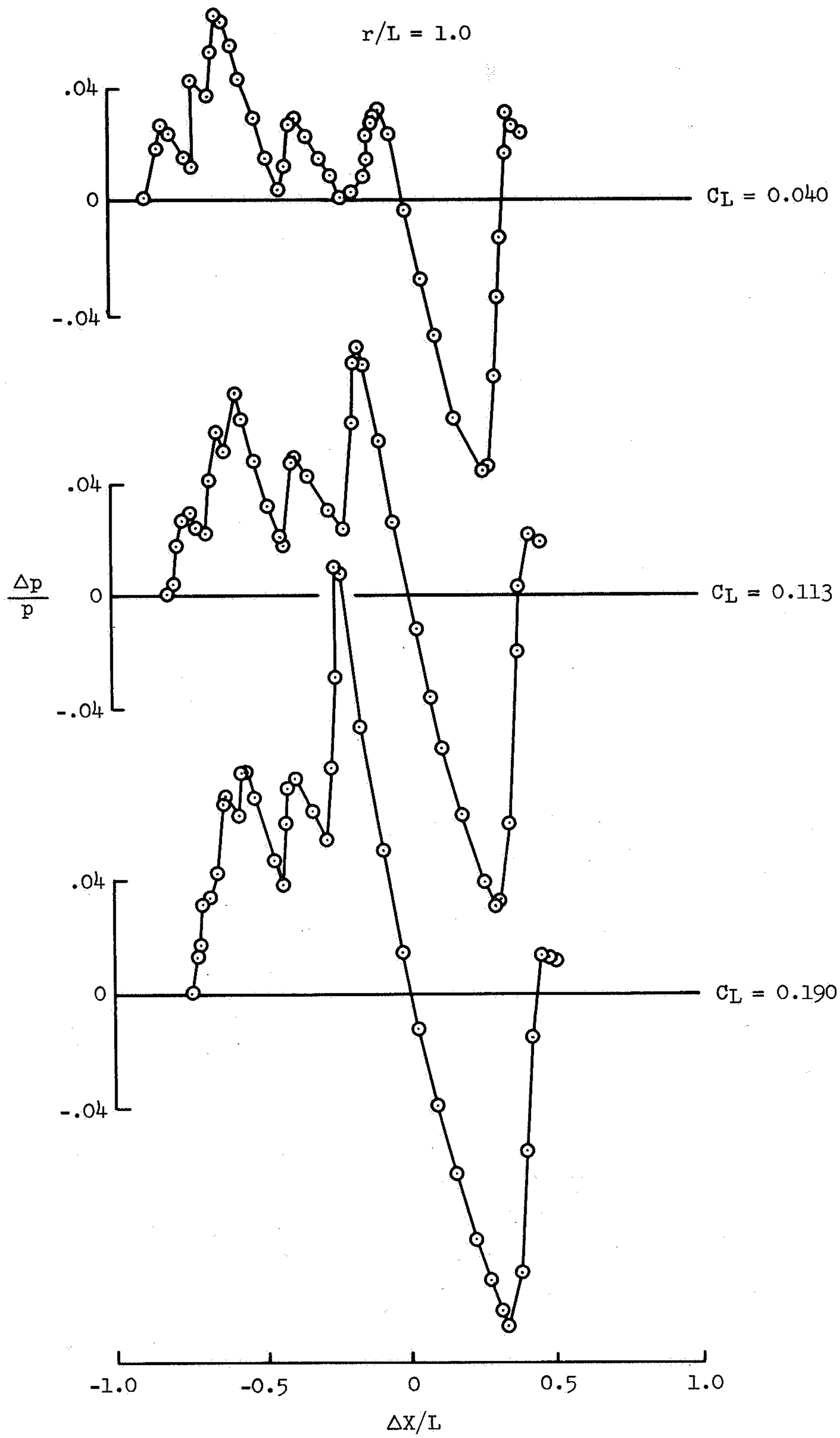

Figure 8.- Pressure signatures measured in wind tunnel at r/L = 1.0.

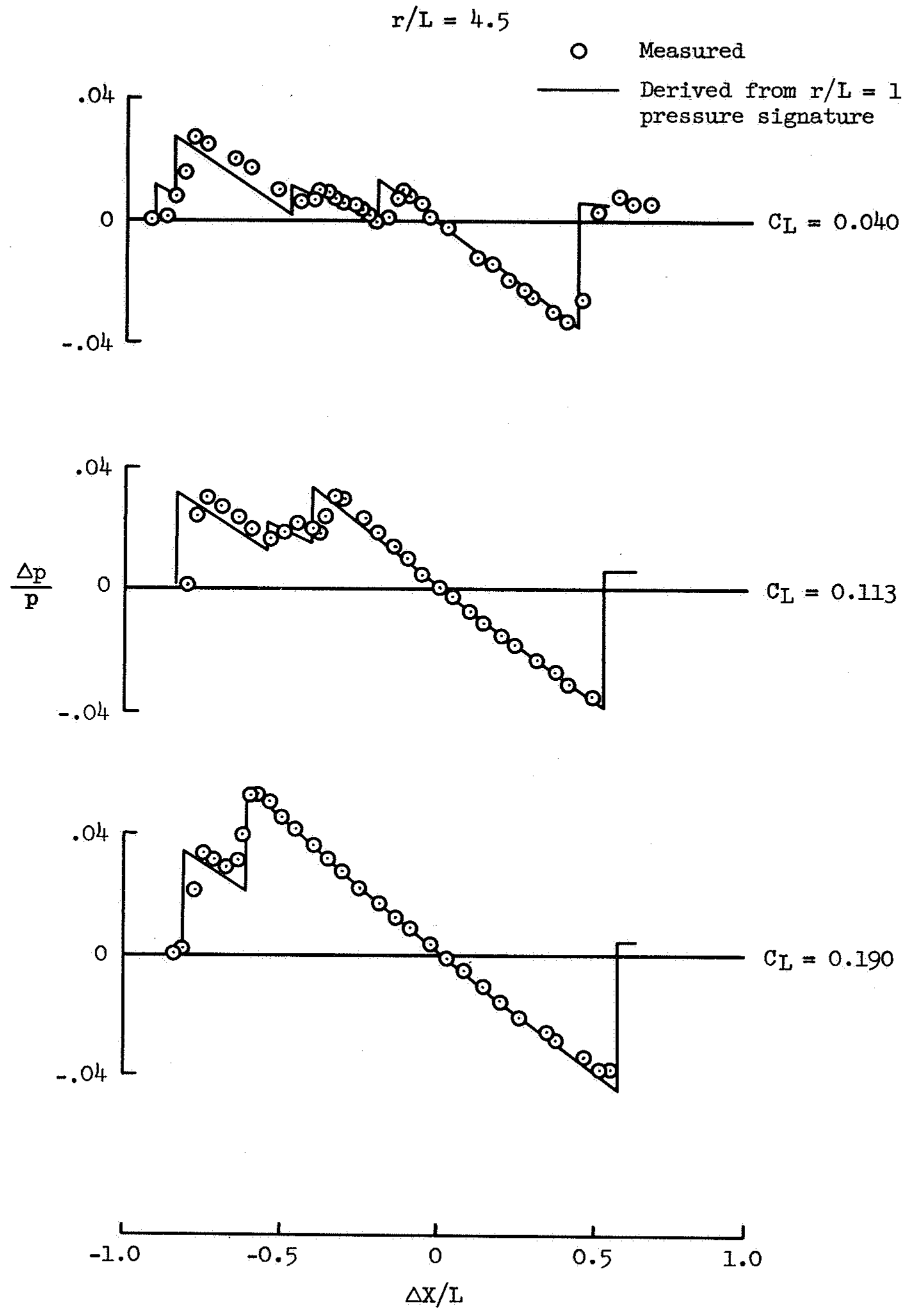

Figure 9.- Comparison of pressure signatures measured at $r/L = 4.5$ with pressure signatures derived from pressure signatures at $r/L = 1.0$.

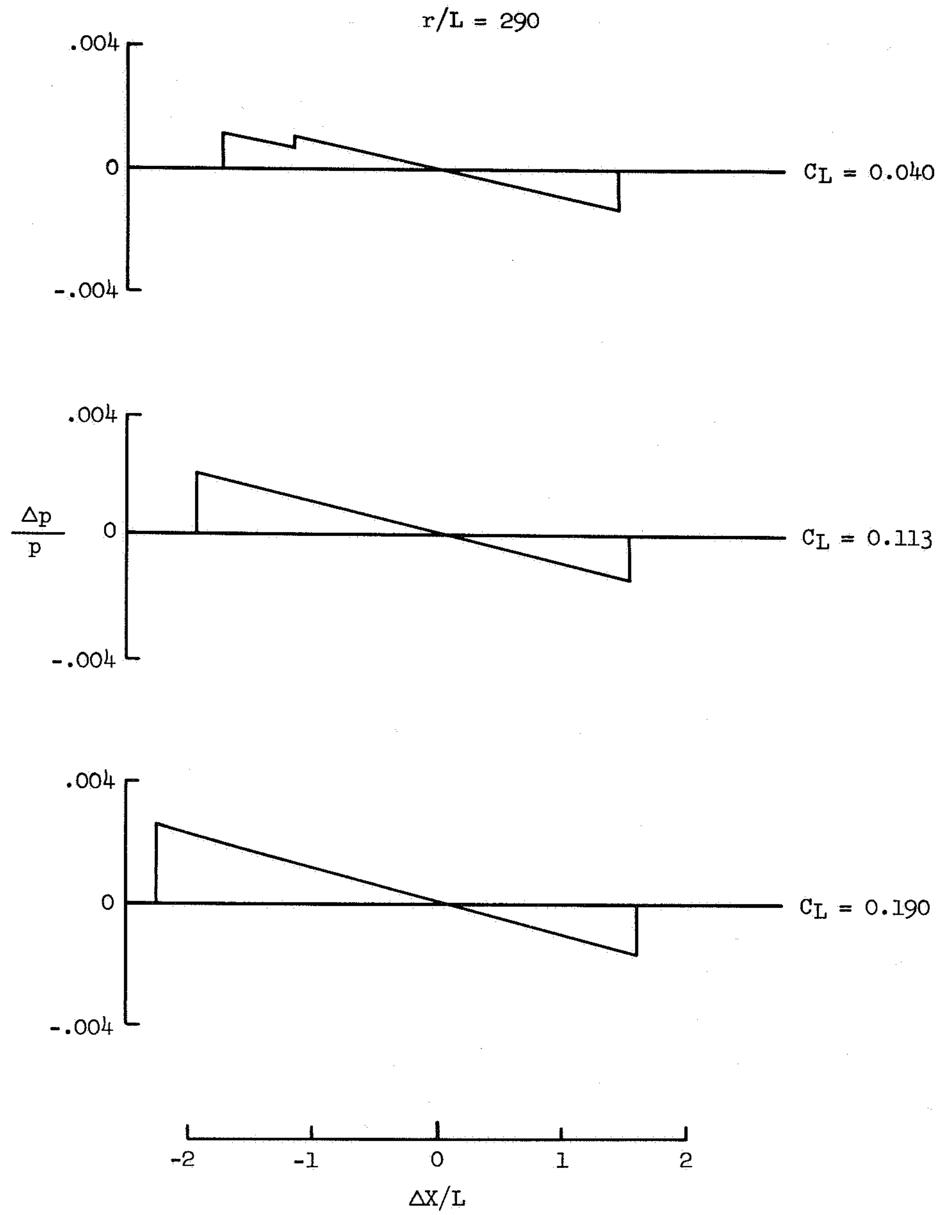

Figure 10.- Pressure signatures derived from wind tunnel pressure signatures taken at $r/L = 1.0$.

r/L = 290

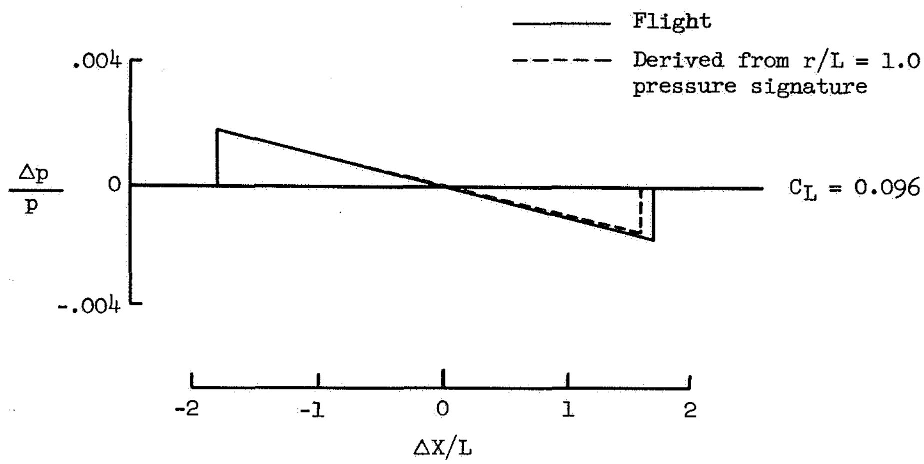

Figure 11.- Comparison of flight pressure signature with pressure signature derived from wind-tunnel pressure signatures measured at r/L = 1.0.

with overpressure data obtained for the XB-70 airplane at Edwards Air Force Base. The flight curve was determined from an average of three separate pressure signatures for the airplane. These measured results were the only data available at a Mach number of 1.8 for which the ground track of the aircraft was sufficiently close to the ground instruments.

As can be seen, the agreement between the pressure signature derived from wind-tunnel data taken at an r/L of 1.0 and the flight pressure signature is good except for the small discrepancy in the location of the rear shock. This discrepancy is attributed mainly to two factors. First, no attempt was made to simulate the flow of hot exhaust gases for the wind-tunnel model. Second, the sting support used with the wind-tunnel model was too short to allow for an accurate determination of the decay of the pressure signatures downstream of the rear shock in the wind tunnel (see fig. 8). In order to balance areas for the determination of the rear shock strength and location on the experimental F-function at an r/L of 290, it was necessary to extrapolate the wind-tunnel pressure signatures of figure 8 downstream several model lengths. A pressure decay proportional to the reciprocal of y^2 was assumed for purposes of the extrapolation. If model loads and stream turbulence permit, the sting support should equal several model lengths so that the shape of decay of the pressure signature downstream of the rear shock can be determined more accurately. With a little research it should also be possible to determine an appropriate shape for a fairing between the model base and the sting support which would more accurately simulate the flow of gases from the exhaust nozzles.

When the experimental technique is applied, some care must be exercised in making certain that the effects of vibrations of model and probe, probe boundary-layer effects, differences between model and airplane boundary-layer conditions, and differences between model and airplane geometry are either properly accounted for or are negligible. These effects were found to be negligible for the results reported herein.

CONCLUSIONS

A study has been conducted to determine the extent to which measured near field pressure signature data can be used for predicting the general overpressure characteristics of a given configuration. The following conclusions have been drawn from this investigation:

(a) Wind-tunnel near field pressure signatures for a complete aircraft configuration measured at a distance ratio as small as 1.0 were found to be quite adequate for predicting the overpressure characteristics of the configuration at two alternate distance ratios, including one in the wind tunnel and one in flight.

(b) The use of this testing technique generally permits the study of larger, more accurate models and smaller distance ratios which result in increased pressure levels and, therefore, better definition of the pressure signature.

(c) Accurate sonic boom predictions can be made without accurate lift distribution and interference estimates.

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National Aeronautics and Space Administration
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