NACELLE AND FOREBODY CONSIDERATIONS IN DESIGN FOR REDUCED SONIC BOOM*

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SUMMARY

Several aspects of designing for reduced sonic boom were investigated to assess the adequacy of the conventional modified linear theory. For a simple test case of a nacelle with a small forecowl angle (2 degrees) mounted below a flat plate, the linear theory compared favorably for a case with simulated nacelle lift and for a CFD analysis. In a second study, several methods of analyzing the area distribution due to volume were examined. And finally, in a preliminary study, the effect of forebody shape on the rise time of the bow shock was investigated, indicating a significant increase (several msec) can be obtained by proper forebody shaping.

INTRODUCTION

Modified linear supersonic theory has proven to be a very powerful and useful tool for the analysis and design of slender supersonic aircraft between Mach 1.2 to about Mach 3.0. The soundness of the theory is indicated by its ability to give useful results with slight modification well beyond the expected range of validity, for example, blunt bodies at Mach numbers up to 6.0.

For the design of low-sonic-boom aircraft, the modified linear theory (MLT) has been used with reasonable success. However, questions have surfaced about the accuracy of MLT for defining the very precise pressures required for a low-sonic-boom aircraft. A related concern is the proper implementation of MLT, since there is some latitude in the geometry modeling within MLT. In this study, two aspects of designing for reduced sonic boom were selected (nacelles and fuselage forebody) for comparing to CFD results ("STUFF," a PNS code in the Euler model).

A third study reported here is the possibility that fuselage forebody shaping can influence the shock wave rise time at the ground, providing reduced sonic boom loudness with little penalty to the airplane.

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NACELLE LIFT INTERFERENCE EFFECTS

The strong local pressure field produced by the nacelles provides a beneficial lifting effect for nacelles located beneath the wing and near the wing trailing edge. For low sonic boom design, however, it is difficult to incorporate this strong pressure field into the desired overall smooth pressure distribution; this may require severe fuselage area-ruling, significant nacelle stagger, or modified nacelle forebody shapes. A more fundamental question, however, is whether the standard Modified Linear Theory (MLT) method provides an accurate calculation of the pressures, in particular the reflected nacelle pressure from the wing lower surface.

A simple test case was devised for verifying the MLT lift interference effect. The geometry for the test case is shown in Figure 1. A 20-foot long nacelle with a forecowl angle of 2 degrees is mounted below a flat plate. The sonic boom calculated in the usual manner for volume and lift is shown in Figure 2, using the methods of References 1 and 2.

The lift effect can be simulated with a mirror-image nacelle by considering volume effects only without a wing reflecting surface (see the bottom half of Figure 1). This was compared to the sonic boom F-function calculated in the usual manner for volume and lift, with the nacelle installed below a flat-plate wing surface. The two methods should agree, except for the effect of the Mach cuts on the volume F-function for the mirror-image nacelle, which shifts the F-function values aft slightly, as can be seen in Figure 3. This result verifies that the MLT is capturing the major features of the flow field beneath the nacelle for this simple nacelle geometry.

This analysis was carried a step further by using a CFD calculation method called "STUFF" (a PNS code in the Euler mode). Figure 4 compares the MLT and STUFF results at two distances away (10 and 20 feet) directly below the nacelle. Close to the nacelle, STUFF indicates that there is some blockage or shielding by the nacelle itself (the MLT on the other hand assumes a "transparent" nacelle). Further away, however, there is better agreement, although in the CFD STUFF pressure distribution the shocks are smeared due to the numerical effects. Figure 5 shows the pressure signatures propagated to the ground using the Thomas method (Reference 3). Both of the STUFF pressure signatures underestimate the bow shock strength compared to MLT.

The results of Reference 4 suggest that corrections need to be applied to the MLT method for a forecowl angle of 6 degrees. The results of this study suggest, however, little or no correction is needed for the small forecowl angle of 2 degrees.

Several different methods have been used in the basic modified linear theory (MLT) for calculating the area distribution due to volume. A major difference is the method that places the configuration at angle-of-attack, which produces significantly greater equivalent areas. A secondary difference is in the treatment of camber, twist, and dihedral.

The method used at Boeing does not include camber or angle-of-attack effects in wave drag or volume calculations. The reasoning for this approach is as follows. Strictly speaking, the linear theory assumes all disturbances are in one horizontal plane since there are no influence coefficients for out-of-plane effects. This basic assumption of the linear theory suggests that camber and angle-of-attack effects should not be included in wave drag (volume) calculations. The camber and angle-of-attack effects are accounted for in the drag-due-to-lift calculation; to include them in volume effects would be double bookkeeping. The 1080-911 configuration was designed with this "no-camber" method as described above.

However, there is some evidence that the above reasoning and the "no-camber" method are not correct. CFD results of the 1080-911 predict quite different sonic boom waveforms than the "no-camber" method (References 5, 6 and 7). Figure 6 compares MLT "no-camber" results with a CFD code, STUFF, showing a bow shock of about 1.4 psf instead of the MLT 1.0 psf shock. Figure 7 compares the forebody pressures for several versions of MLT (camber and angle-of-attack) and CFD at 160 inches below the 1080-911 configuration.

More in-depth study is required to firmly establish the proper method for calculating wave drag and volume effects for sonic boom analysis and design.

FOREBODY SHAPE EFFECTS ON BOW SHOCK RISE TIME

It is well-known that shock wave overpressure has a very powerful effect on shock wave rise time. At lower overpressures, the effects of molecular relaxation of oxygen and nitrogen in the lower atmosphere produce a significant shock thickening (or increased rise time) and reduced loudness. In designing for reduced sonic boom, we have focused on reducing the shock wave intensities to somewhat less than 1.0 psf, which provides reduced loudness through the increased rise time, as well as the reduced shock intensity.

In reducing the shock strengths much below 1.0 psf, however, the configuration design becomes more difficult, with deficiencies in takeoff gross weight, drag, balance, and high lift capability. In this study an attempt was made to examine the waveform characteristics just behind the shockwaves to see if there were some way to increase the rise time through configuration design.

Figure 8 shows a series of very simple sonic boom waveforms that were used in this study. Each waveform has a bow shock of about 0.5 lb/ft^2, but the waveforms have different slopes of pressure just behind the bow shock. The effect of duration was also considered, and was one way to obtain variations in the slope of pressure just behind the shock. The six signatures were propagated from 44000 ft. altitude to the ground using the method of Raspet and Bass (Reference 8). This method is a numerical technique that alternates between calculations of the wave steepening in the time domain and atmospheric absorption in the frequency domain. A standard atmosphere was used with 10% relative humidity, except 50% relative humidity below 1000 ft. altitude.

The pressure slope just behind the shock has a significant effect on the rise time, as shown in Figure 9. The N-waves have the longest rise times, of about 10 msec, while the "ramp" waveform has the shortest of 5 msec. The increasing or constant pressure just behind the shock (cases 2, 5 and 6) reduces the rise time by feeding energy from low frequency to high frequency (the shock steepening effect). Duration has no effect, except as it influences dp/dx behind the shock. Case 2 has a very short constant-pressure region behind the shock and amazingly has the same rise time of case 5, which has a much longer constant-pressure region.

These results have implications for configuration design. The designer can control the pressure level of the shock as well as the pressure slope behind the shock. By designing for a slight expansion just behind the shock, an increase of about 2 msec in rise time can be obtained. The forebody would have to be slightly smaller in diameter to achieve the desired effect. While this may mean an added constraint on the configuration design, the benefits in terms of reduced loudness may be attractive.

Several other important conclusions are as follows:

1. The statistical rise time data from flight test programs have been used to estimate rise times of shaped booms. However, these results indicate that "flat-top," "ramp," or "hybrid" waveforms would have <u>shorter</u> rise times than N-waves of the same amplitude.

2. A numerical method, such as the Raspet and Bass technique, must be used to calculate the rise time of complex waveforms (or alternatively the similar method of Reference 9).

3. The "ramp" waveform (also called the minimum-shock waveform) has the shortest rise time. In addition, it is sensitive to atmospheric variations and therefore is a poor candidate waveform for low-boom design.

4. The effects of turbulence on sonic boom propagation have been ignored and could modify these results.

5. A slightly decreasing pressure just behind the shock can provide a significant increase in rise time. For the waveforms studied the rise time varied from 5 msec to 10 msec for 0.5 psf shock strength.

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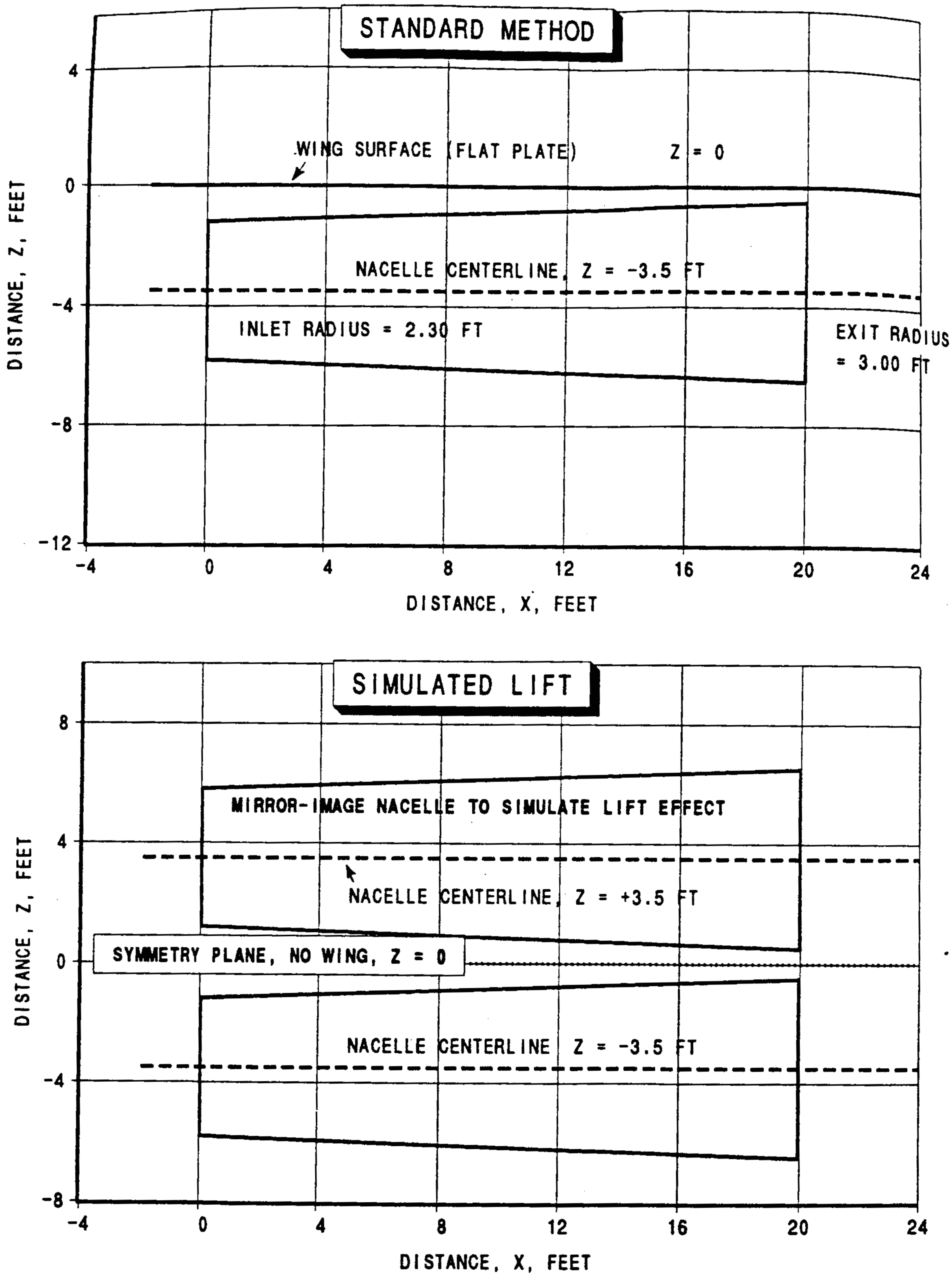


Figure 1. Geometry for simple test case -- single nacelle mounted below a flat plate and simulated lift with a mirror-image nacelle.

F-FUNCTION, (FEET)**0.5

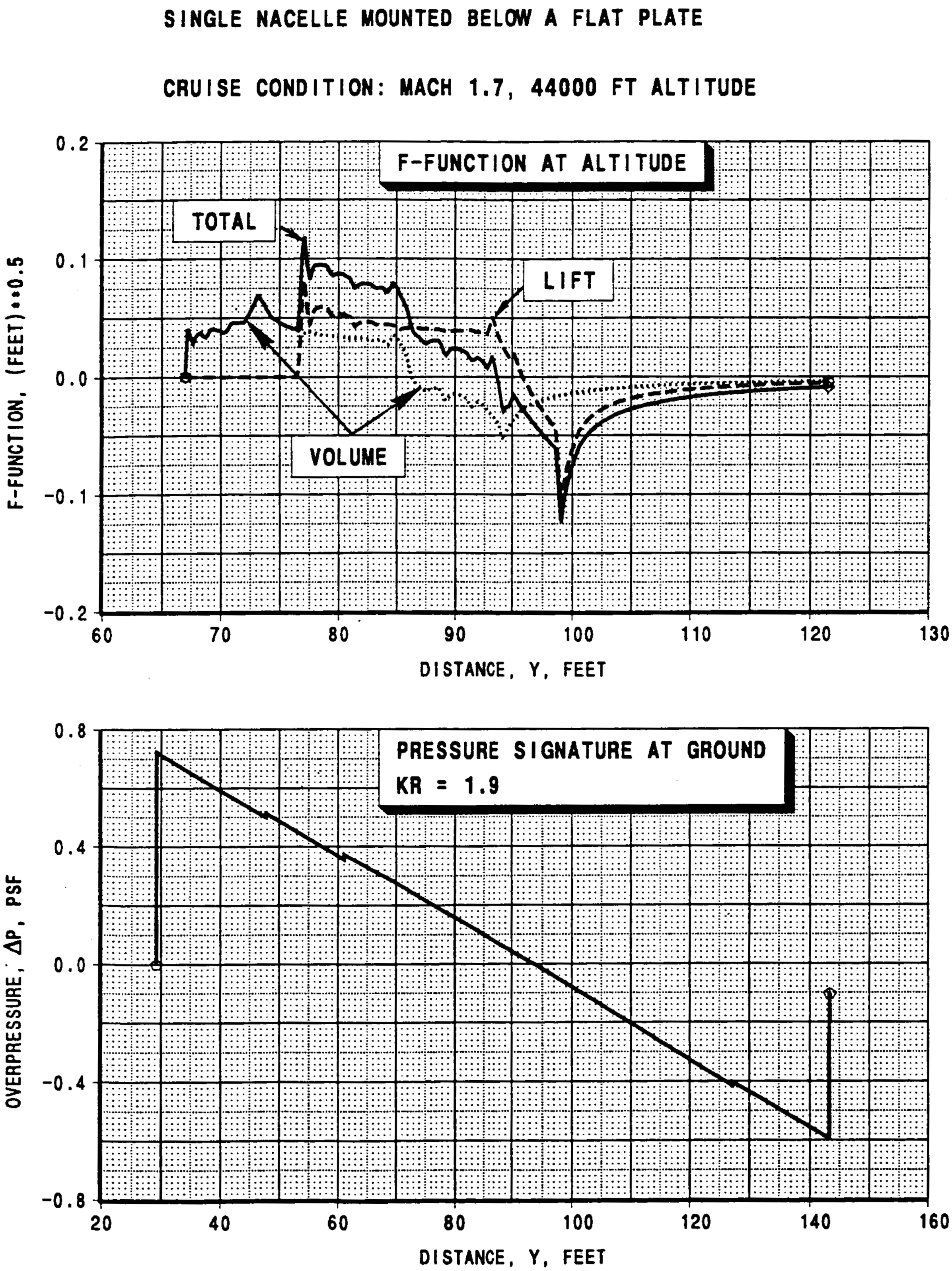


Figure 2. Sonic boom F-function and waveform at ground (standard sonic boom method calculation).

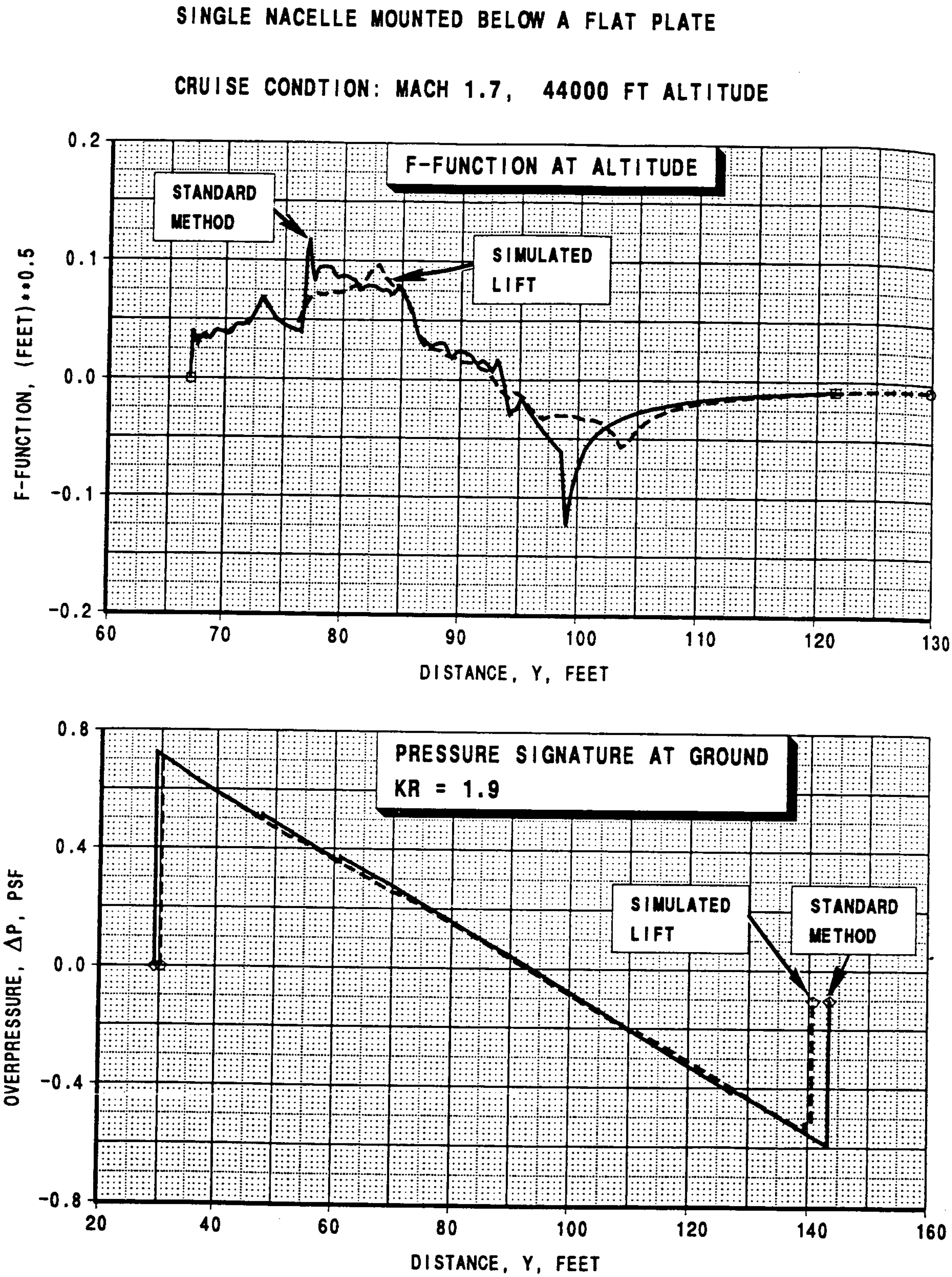


Figure 3. Sonic boom F-function and waveform at ground (standard method compared to simulated lift case).

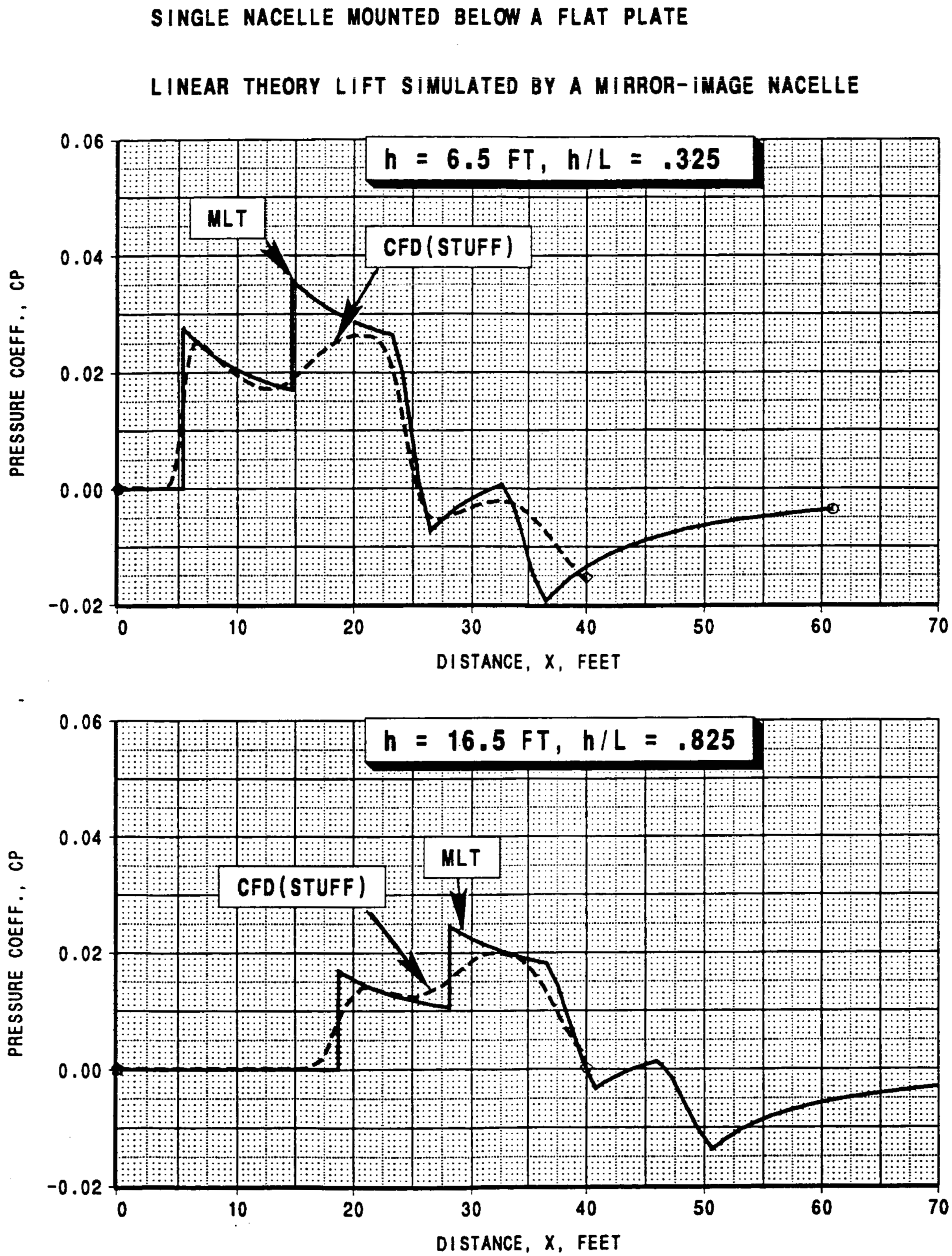


Figure 4. Near-field CFD pressures compared to Modifed Linear Theory (MLT) pressures.

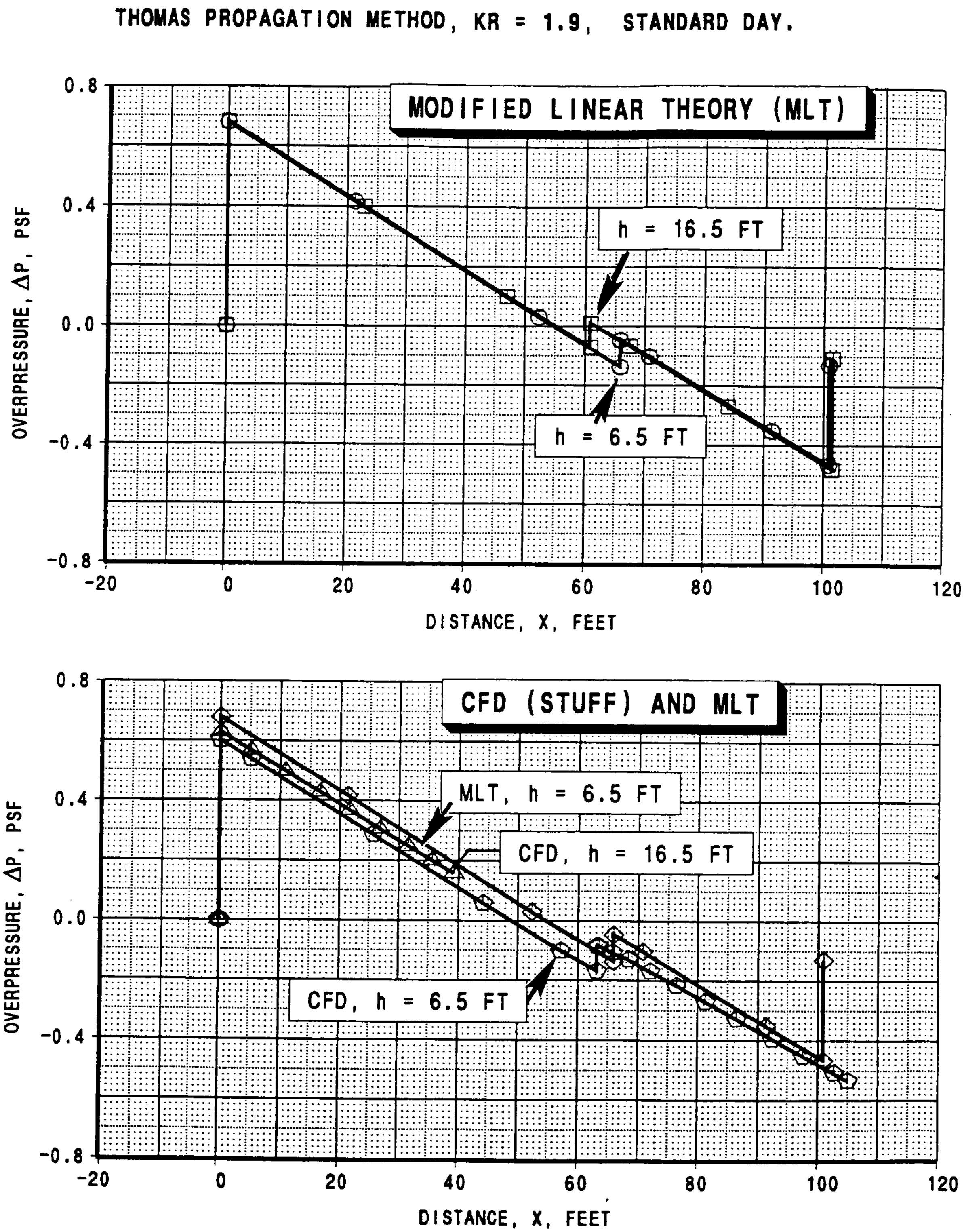
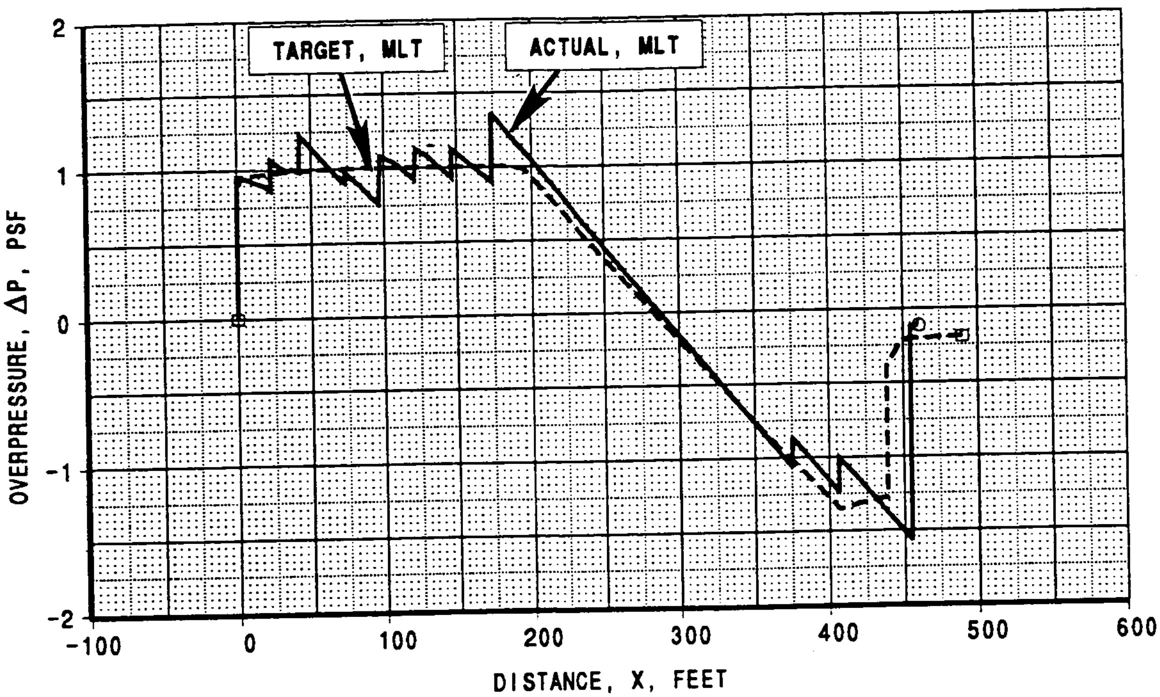


Figure 5. Pressure signatures propagated to the ground (Thomas Method).

MLT WITH ZERO ALPHA AND NO CAMBER
AT GROUND SURFACE, KR = 1.9
CRUISE CONDITION: MACH 1.7, 44000 FT ALTITUDE



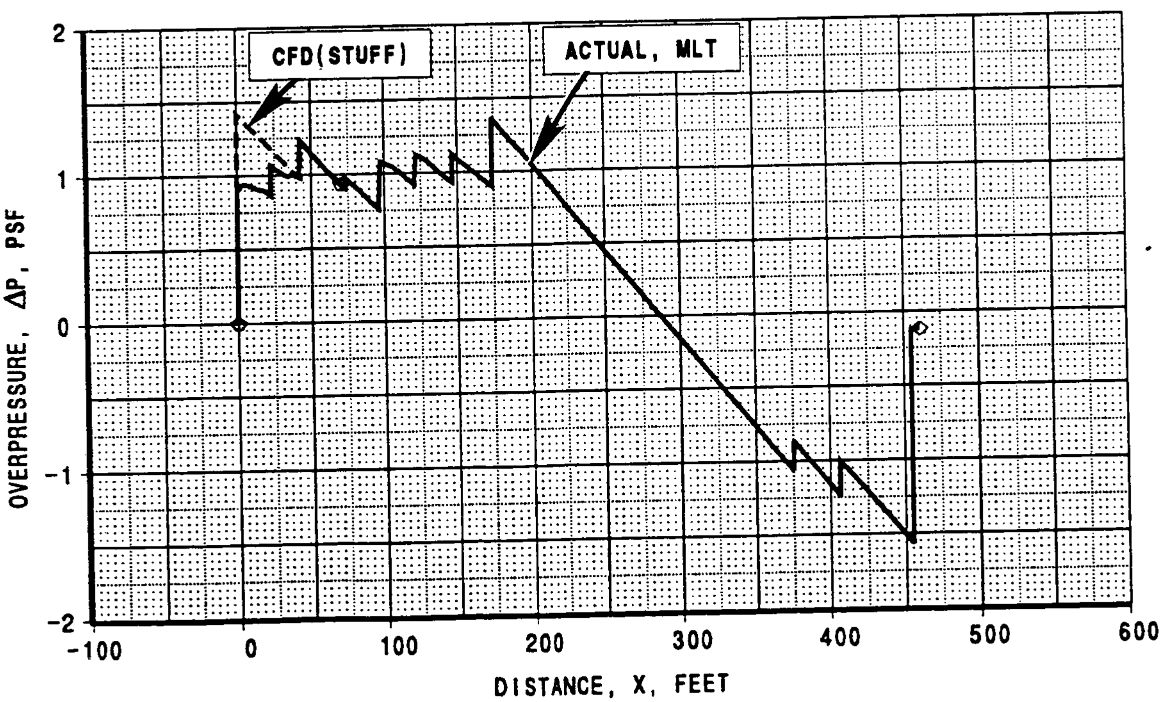
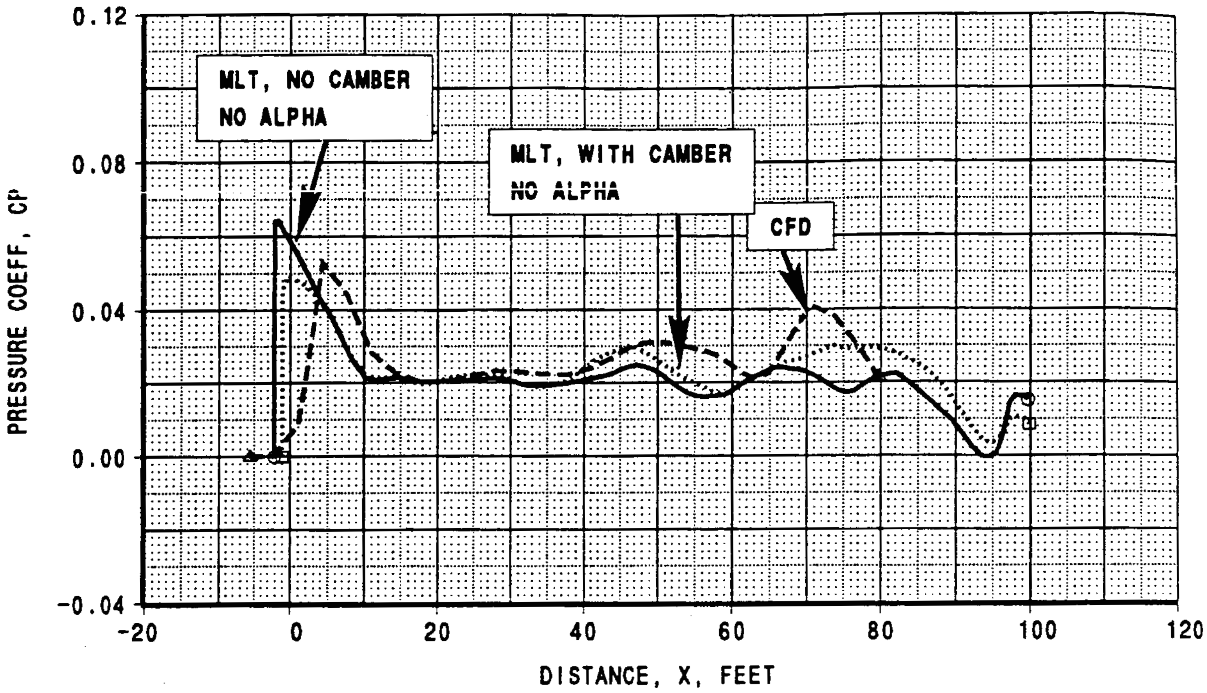


Figure 6. Target and actual pressure signatures at ground surface for 1080-911.

PRESSURE DISTRIBUTIONS 160 INCHES DIRECTLY BELOW

CRUISE CONDTION: MACH 1.7, 44000 FT ALTITUDE



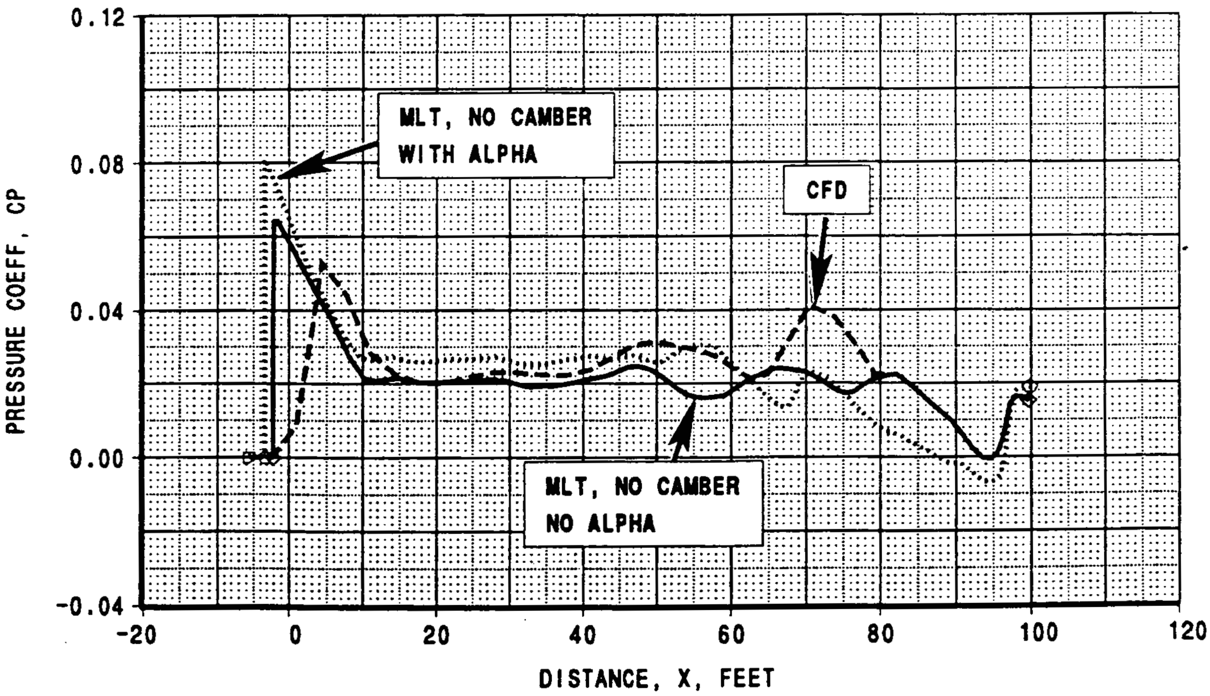
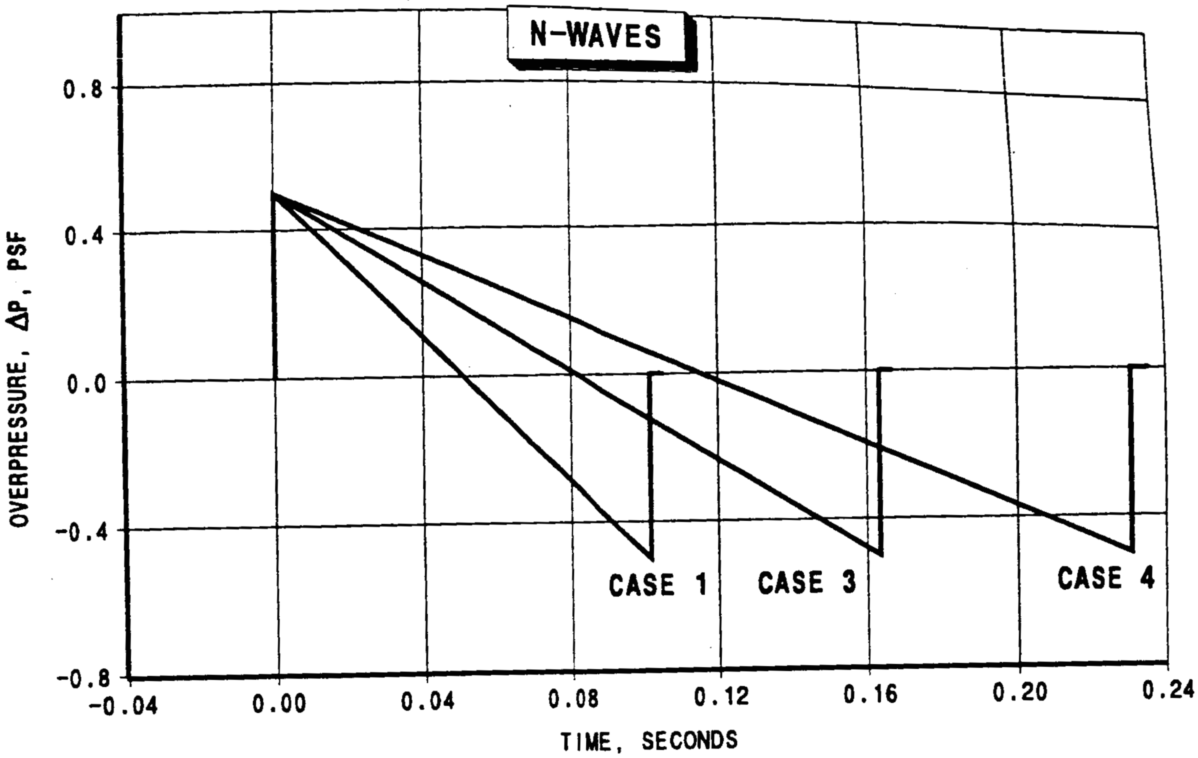


Figure 7. Forebody pressure distributions for 1080-911 at 160 inches directly below.



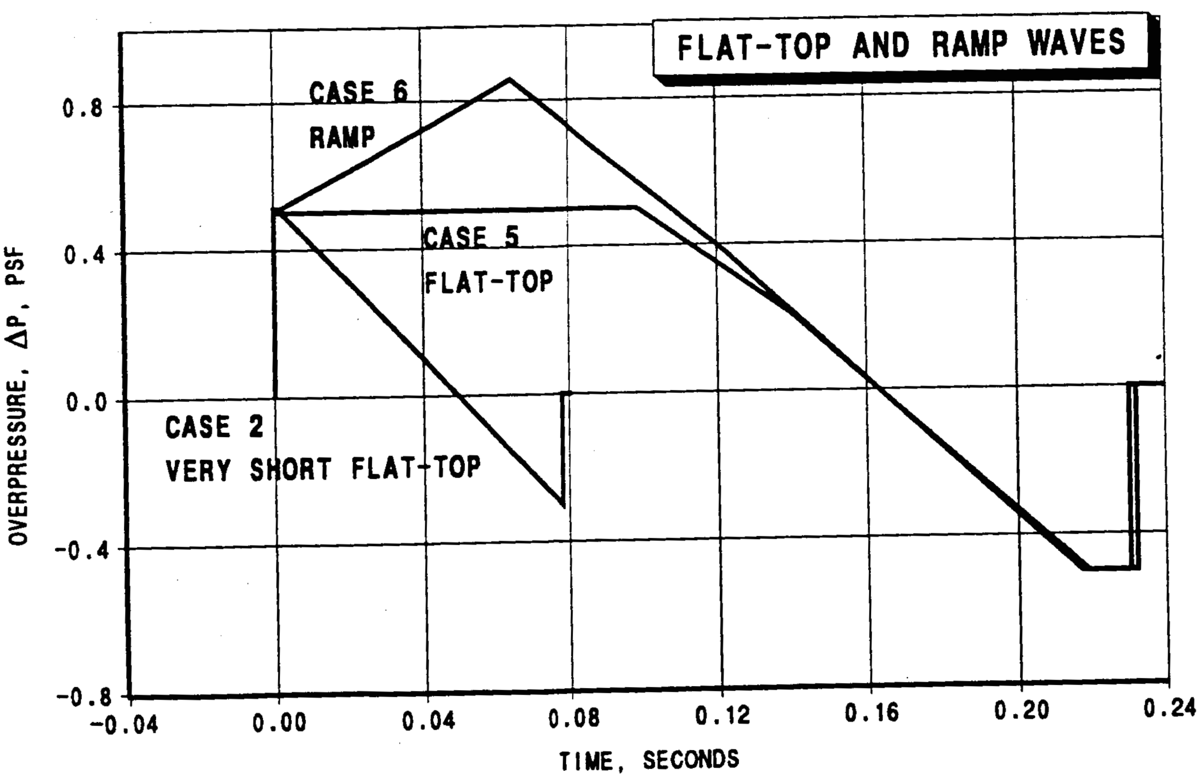


Figure 8. Waveforms at ground surface for rise time study ($K_R = 1.0$).

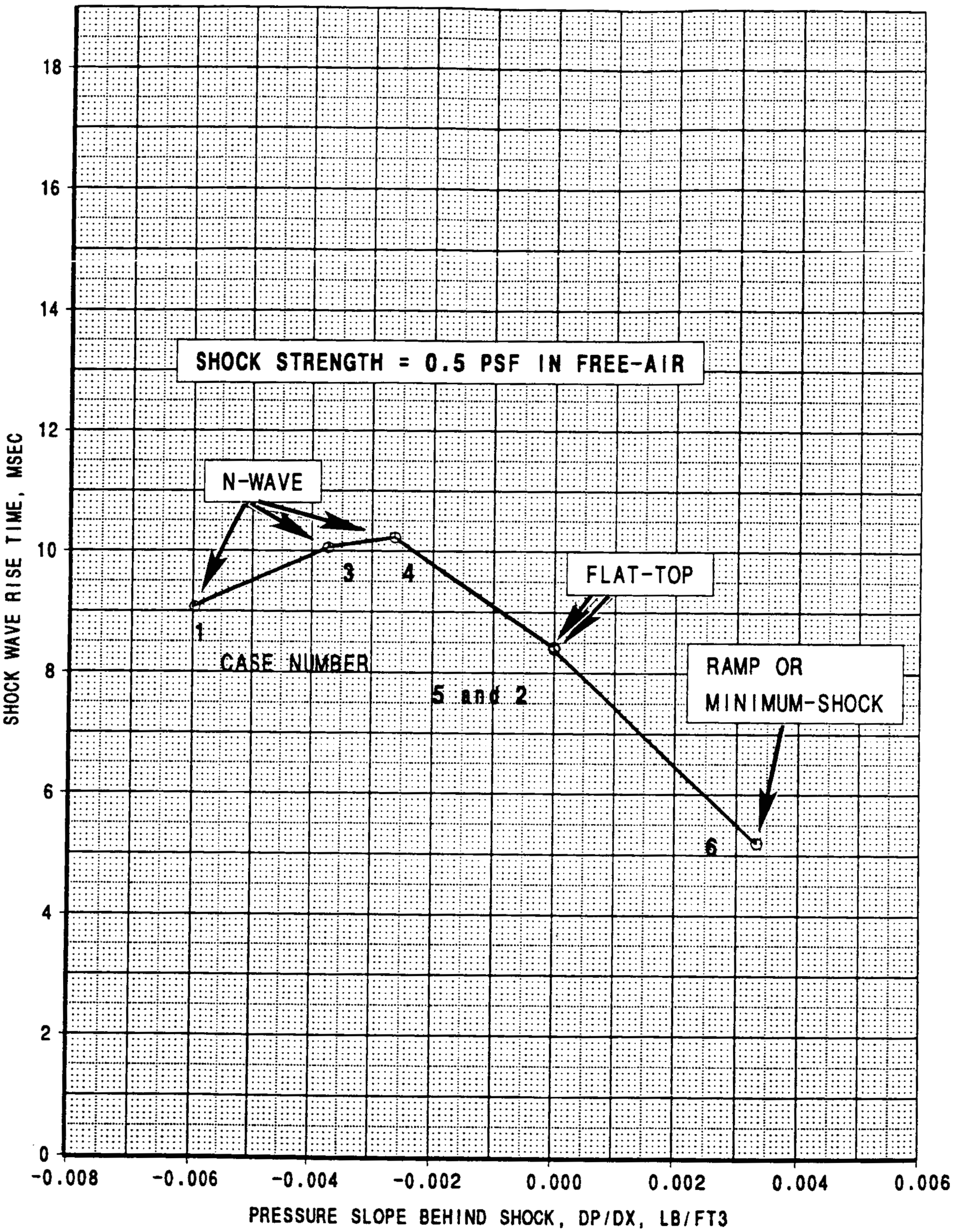


Figure 9. Effect of pressure slope behind the shock on rise time.