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# Background Pressure Profiles for Sonic Boom Vehicle Testing in the NASA Glenn 8- by 6-Foot Supersonic Wind Tunnel

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## Abstract

In an effort to identify test facilities that offer sonic boom measurement capabilities, an exploratory test program was initiated using wind tunnels at NASA research centers. The subject of this report is the sonic boom pressure rail data collected in the Glenn Research Center 8- by 6-Foot Supersonic Wind Tunnel. The purpose is to summarize the lessons learned based on the test activity, specifically relating to collecting sonic boom data which has a large amount of spatial pressure variation. The wind tunnel background pressure profiles are presented as well as data which demonstrated how both wind tunnel Mach number and model support-strut position affected the wind tunnel background pressure profile. Techniques were developed to mitigate these effects and are presented.

## Nomenclature

| | |
|---|---|
| $h$ | Distance below vehicle, in. |
| $l$ | Vehicle length, in. |
| $M_\infty$ | Free-stream Mach number |
| $P$ | Measured static pressure, psia |
| $P_\infty$ | Test section static pressure, psia |
| $\Delta P$ | $P - P_\infty$. |
| $\Delta P/P$ | $(P - P_\infty)/ P_\infty$. |
| $T_\infty$ | Test section total temperature, R. |
| $t$ | Time, sec. |
| $x_{ts}$ | tunnel station, in. |
| $x_a$ | Travel distance for axial linear actuator, in. |

## I. Introduction

Supersonic travel is not allowed over populated areas due to the disturbance caused by the sonic boom. At the vehicle nose there is a rise in pressure, followed by a steady decrease in pressure, followed by a rise to atmospheric pressure. When propagated to the ground, this pressure profile takes the shape of an N-wave. The two large pressure changes create a “double boom” effect. The impact of the sonic boom is so large that the Federal Aviation Administration has issued a noise policy for supersonic aircraft stating: “Since March 1973, supersonic flight over land by civil aircraft has been prohibited by regulation in the United States. The Concorde (Ref. 1) was the only civil supersonic airplane that offered service to the United States, and it is no longer in service” (Ref. 2). The same policy also states that “noise operating rules would propose that any future supersonic airplane produce no greater noise impact on a community than a subsonic airplane.” Subsonic noise limits are prescribed in Code of Federal Regulations 14-Part 36 stage 4 (Ref. 3).

An experimental validation program was sponsored by NASA in which Boeing designed a supersonic aircraft configuration. The configuration was to generate a low sonic boom signature intended to enable flight over populated areas (Ref. 4). To assess facilities that offered sonic boom measurement capability, an exploratory test program was initiated using wind tunnels at NASA research centers.

The first exploratory test was conducted in April 2012 at the NASA Ames Research Center (ARC) 9- by 7-Foot Supersonic Wind Tunnel, where Mach numbers range from 1.55 to 2.55. The second test was conducted in June 2012 at the ARC 11-Foot Transonic Wind Tunnel, where Mach numbers range from 0.2 to 1.45. The third exploratory test was performed in September 2012 at the Glenn Research Center (GRC) 8- by 6-Foot Supersonic Wind Tunnel (Ref. 5) (8×6 SWT), where Mach numbers range from 0.36 to 2.0.

The subject of this report is the sonic boom pressure measurement rail (referred to as the pressure rail) data collected in the 8×6 SWT. The purpose is to summarize the lessons learned based on the test activity, specifically relating to collecting sonic boom pressure profiles in the 8×6 SWT which has a large amount of spatial pressure variation. The wind tunnel background pressure profiles are presented. Results demonstrate how both wind tunnel Mach number and model support strut position affect the measured pressure profiles. Techniques were developed to mitigate these effects and are presented.

## II. Experimental Setup

### A. Test Setup

The 8×6 SWT transonic test section was configured with the 14-ft test section, setup for Schlieren imaging, and the 5.8 percent porosity setting, shown in Figure 1. Porous blanks, where the bleed holes were filled with plugs, were installed in the upstream windows. The Schlieren windows were rotated to the lower 45° position. Halfway through the test there were concerns regarding the porous blanks influencing data quality on the pressure rail. The Schlieren windows were re-located to the upstream position and the porous blanks downstream. Test section configuration after this switch was the 14-ft test section and 5.8 percent modified porosity setting. The Schlieren windows were rotated so that they were positioned upstream and on the tunnel centerline. The window position did not affect the results.

Three models were tested at supersonic speeds ranging from Mach 1.2 to Mach 1.8. A pressure rail was installed in ceiling plates along the centerline of the test section to capture model pressure signature data. The model was installed on the sting in an upside down orientation, so the pressure signature, or boom signature, from the bottom of the model was measured by the pressure rail. A force balance was installed between the model and the strut, and was used to measure both forces and moments on the model.

During the test, each model’s spatial position was varied horizontally (x-axis, in line with the sting) up to 24 in. by a linear actuator and vertically (z-axis) up to 64 in. by raising and lowering the supersonic strut. Pressure measurements from the translations were averaged to generate the vehicle pressure profiles. The supersonic strut position was controlled remotely, and was raised or lowered while the tunnel was operating.

### B. Models

The Boom model was a 0.65 percent scale replica of the Boeing N+2 Quiet Experimental Vehicle Concept (Ref. 4) (QEVC) and is displayed in Figure 2. It was 14.994 in. long, 0.858 in. thick and had a 6.732 in. wingspan. This low-boom wing/body configuration was manufactured in five pieces: nose assembly, wing/body, upper-swept strut and attachment, cone-section, and balance shield. All leading and trailing edges on the boom model were 0.004 in. thick.

The Performance model was a 1.79 percent scale replica of the Boeing N+2 QEVC. It was 41.158 in. long, 2.343 in. thick and had an 18.524 in. wingspan. It had a removable nose assembly, outboard wing, nacelle, aft deck, vertical tail, horizontal airfoil, and canard. All leading and trailing edges on the performance model were also 0.004 in. thick.

The axisymmetric model, number 2, (AS2) was used to obtain calibration data (Fig. 3). The AS2 calibration model was the same scale and had approximately the same initial overpressure as the 1.79 percent scale research model. Data were obtained from the AS2 calibration model at the same test conditions indicated for the research model testing. Angle of attack for the AS2 calibration model was set to zero.

### C. Instrumentation

The 14-in. pressure rail was 90 in. long, 14 in. tall, and 1 in. thick at its base. The rail tapered down to 0.050 in. thickness at the tip. Instrumentation included 420 pressure taps distributed 0.1575 in. apart over a 66 in. length, Figure 4. The leading edge of the pressure rail was positioned at Tunnel Station 158.2.

### D. Spatial Averaging Measurement Method

Spatial averaging (Ref. 6) was conducted by averaging data at several positions in the fore and aft direction for an “X-sweep”, or in the vertical direction for a “Z-sweep”. The model was moved in incremental distances of approximately 4 rail pressure ports, for a total of 13 model positions (Ref. 4).

Test conditions were nominally between Mach 1.2 and Mach 1.8, where Mach number was initially held to ±0.01, and later improved to ±0.001. In the 8×6 SWT, Mach number is controlled by three variables: (1) flex wall nozzle throat position, (2) compressor speed, and (3) balance chamber exhaust valve position. The exhaust valve in the balance chamber controls the flow of air exiting the porous walls, which has an effect on the static pressure in the test section.

Measurements of vehicle pressure profile (ΔP/P) were collected as defined by the following equation:

$$\Delta P/P = ((P_{\mathrm{rail}} - P_{\infty}) / P_{\infty})_{\mathrm{model}} - ((P_{\mathrm{rail}} - P_{\infty}) / P_{\infty})_{\mathrm{reference\ run}}$$

Reference runs were originally performed at h = 68 in., and later changed to an in-line reference at h = 56 in. (Fig. 5).

## III. Experimental Results

The initial sonic boom pressure profiles collected in the 8×6 SWT did not match predictions, as demonstrated with data collected from the AS2 calibration model. The AS2 model pressure profile should be characterized by a nose shock followed by a “flat-top” region. The signature collected displayed the nose shock, but the “flat-top” feature was missing. Additionally, profile values were lower than zero leading up to the nose shock, which was an undesireable characteristic. The profile is shown in Figure 6, where the 13 individual measurements are plotted, along with the spatial average. Profiles are shown for Mach 1.8, but were consistent for all Mach numbers examined in this experiment.

Resolution of this problem was accomplished through an examination of four factors: (1) the reference run, (2) variation of rail pressures with Mach number, (3) variation of the reference run profile with Mach number, and (4) the effect of strut position on the reference run. After each factor was understood and controlled, a significant improvement to the AS2 model sonic boom pressure profile was demonstrated.

## A. Reference Run

The uncorrected pressure profile (ΔP/P) was measured by the pressure rail. To represent the pressure variation in an empty wind tunnel, the wind tunnel model was moved to a position 12-in. off the floor (h = 68 in.). In this position the Mach waves from the model did not intersect the pressure rail. The tunnel background pressure profile was characterized by a number of shock and expansion waves, starting at $x_{ts} = 175$ to $x_{ts} = 210$ in. along the pressure rail. The pressure profile between the peaks exhibited steep pressure gradients. The region from $x_{ts} = 210$ to $x_{ts} = 278$ exhibited shock and expansion waves of smaller magnitude, as shown in Figure 7. At values greater than $x_{ts} = 280$, the profile returned to a series of strong shock and expansion waves, some caused by the model support system.

During testing, this reference pressure pattern was subtracted from the measurement to determine vehicle pressure profile, or sonic boom signature. As this reference profile shifted in position or magnitude, it had a dramatic effect on the vehicle measurement. The effect depended on location. In an area of steep pressure gradient, small changes in the reference run had a large effect on the measurement. Conversely, the effect was smaller in areas of low pressure gradients, as will be shown in Section III.C.

## B. Variation of Individual Rail Pressures

Individual measurement ports on the pressure rail were examined for the data that was collected from September 4 to 10, 2012. During this time, the tunnel Mach number was controlled to ±0.01. An example is provided where the value of ΔP/P at the first pressure rail measurement port was examined. The first port exhibited a linear correlation with Mach number, indicating that variation in Mach number caused the value of ΔP/P to change by 0.01, see Figure 8. This 0.01 variation for the individual pressure rail port was greater than the peak-to-peak value of the AS2 signature to be measured.

The wind tunnel Mach number exhibited variations from Mach 1.786 to Mach 1.792, a difference of 0.006. If variation in wind tunnel Mach number could be controlled to ±0.001, then the variation in ΔP/P would also be reduced.

## C. Variation of the Reference Run Pressures

The effect of Mach number on all of the pressure rail pressures was examined. For this data, the wind tunnel Mach number was controlled to ±0.001, and was held at constant values of Mach 1.776, 1.777, 1.778, and 1.779. Pressure rail pressures were normalized to the Mach 1.776 condition. For some locations on the pressure rail, the ΔP/P pressure variation was 0.007, as seen in Figure 9. This data demonstrates how regions of high pressure gradient affected the reference run as Mach number was increased. The variations in background pressure profile had the potential to cause significant offset in the measured sonic boom pressure profile.

## D. Effect of Strut Position

The supersonic strut in the 8×6 SWT was not symmetric, as there was only blockage below the support sting and not above. During tunnel operation, the remote strut movement allowed reference runs at two model heights, h = 68 in. (near the floor) and h = 56 in. Variations in the reference values of ΔP/P, some greater than 0.018, were noted when the reference run height was changed. It was found that as the model was moved to different heights, the resulting change in test section blockage produced variations in

Mach number. To collect adequate pressure profiles, a reference run was performed at h = 56 in., and then the sonic boom data were collected at the same height. This was achieved by moving the model to the aft portion of the pressure rail (x = 0, linear actuator fully retracted) for a reference run, and then to the forward portion of the pressure rail for the measurement. Data sets from x = 12 to 24 in. were averaged to obtain the final vehicle pressure profile. Figure 10 shows the difference in the reference run pressure profile due to model height.

Near the end of the test, the Mach variations due to strut movement were controlled to within tolerance by the tunnel control system, but took a large amount of test time. Minimizing strut movement reduced the amount of time needed for the tunnel to maintain the desired conditions during data collection.

### E. AS2 Model Signatures

The AS2 calibration model signature was collected and the reference run was conducted at the same Mach number as the measurement, with a tolerance of ±0.001. The reference run was conducted at h = 56 in., which was the same height used in the measurement. In this case, the AS2 model pressure profile was captured properly; with a value of zero leading up to the nose shock, and a “flat-top” region after the nose shock (Fig. 11). These results for the AS2 model were the same as those reported by Magee (Ref. 3), who also reported the near field pressure profiles for the Boeing QEVC vehicle concept as collected in the 8×6 SWT. Even with these improvements, boom model profiles sometimes exhibited a small zero offset. To mitigate the zero offset, improvements to the process need to be investigated. These improvements include the effect of strut position on wind tunnel Mach number, and options for tighter control of Mach number.

## IV. Conclusions

A test was conducted in the NASA Glenn Research Center 8- by 6-Foot Supersonic Wind Tunnel to assess the capability to make sonic boom measurements on a vehicle design with a low sonic boom signature. The test was conducted in September 2012. Three models were tested at supersonic speeds from Mach 1.2 to Mach 1.8, where pressure measurements were collected with a pressure rail mounted in the tunnel ceiling. This report summarizes the lessons learned to collect quality sonic boom pressure profiles; specifically relating to the background pressure profile that contains a large amount of spatial variation. Results were demonstrated for Mach 1.8 and were applicable to all Mach numbers.

Spatial variation of the background pressure profile in the wind tunnel was caused by a series of shock and expansion waves which were generated and reflected throughout the wind tunnel. These waves were likely created by the wind tunnel nozzle, throat, and/or imperfections in the tunnel walls. However, the origins of these shock and expansion waves were not well understood. These waves needed to be controlled when collecting sonic boom data on models with low sonic boom signatures. It was shown that the shock and expansion waves caused a background pressure profile with a large amount of spatial variation and steep pressure gradients.

As the tunnel Mach number changed, the shock and expansion waves generated and reflected through the tunnel changed position, related to the Mach angle. As these waves changed position, the background pressure profile moved upstream or downstream in very small increments. This movement was demonstrated by the correlation of the individual rail measurements with changes in Mach number. During the measurement of sonic boom signatures, the shock and expansion waves must not move. If the shocks are not stationary, background pressures that were subtracted from the measurement, move dramatically up and down steep gradients. The movement of the background pressure profile made for incorrect measured vehicle pressure profiles.

For this test, the wind tunnel Mach number had to be maintained to ±0.001 and the model support strut had to remain in one position. Mach number was controlled by three variables: (1) flex wall nozzle throat position, (2) compressor speed, and (3) balance chamber exhaust valve position. The 8×6 SWT has several unique features that created variability of the Mach number in the test section. These features included the asymmetric strut, the flow through the porous walls, and the balance chamber pressure. When these key variables were controlled, successful measurement of sonic boom pressure profiles was achieved.

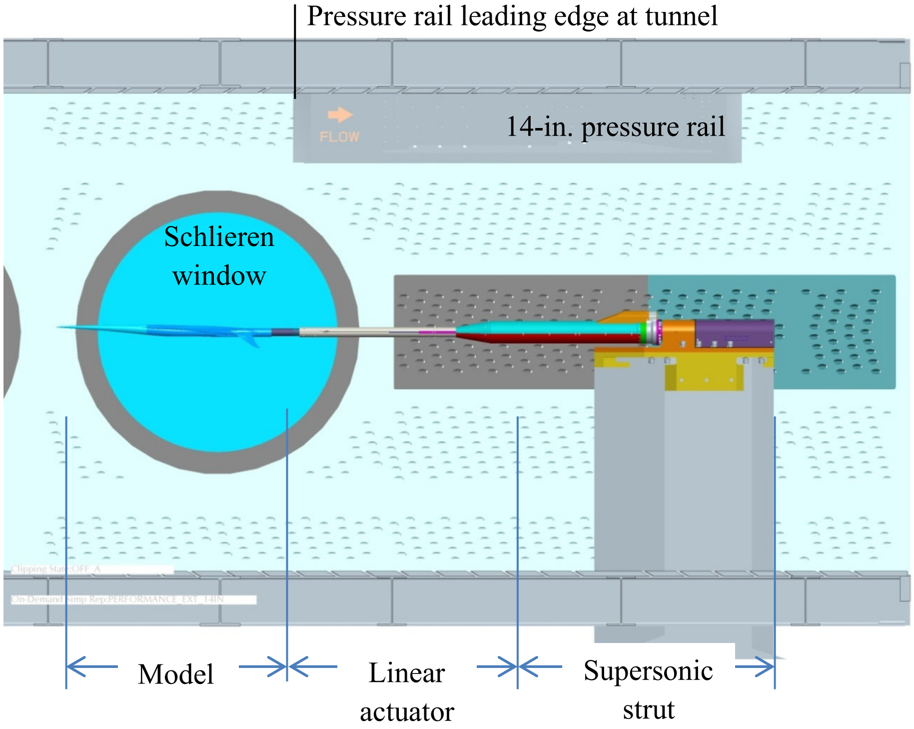

Figure 1.—Wind tunnel layout for the sonic boom model in the 8×6 SWT.

Figure 2.—Boeing N+2 validation model and 14-in. sonic boom pressure rail installed in the 8×6 SWT.

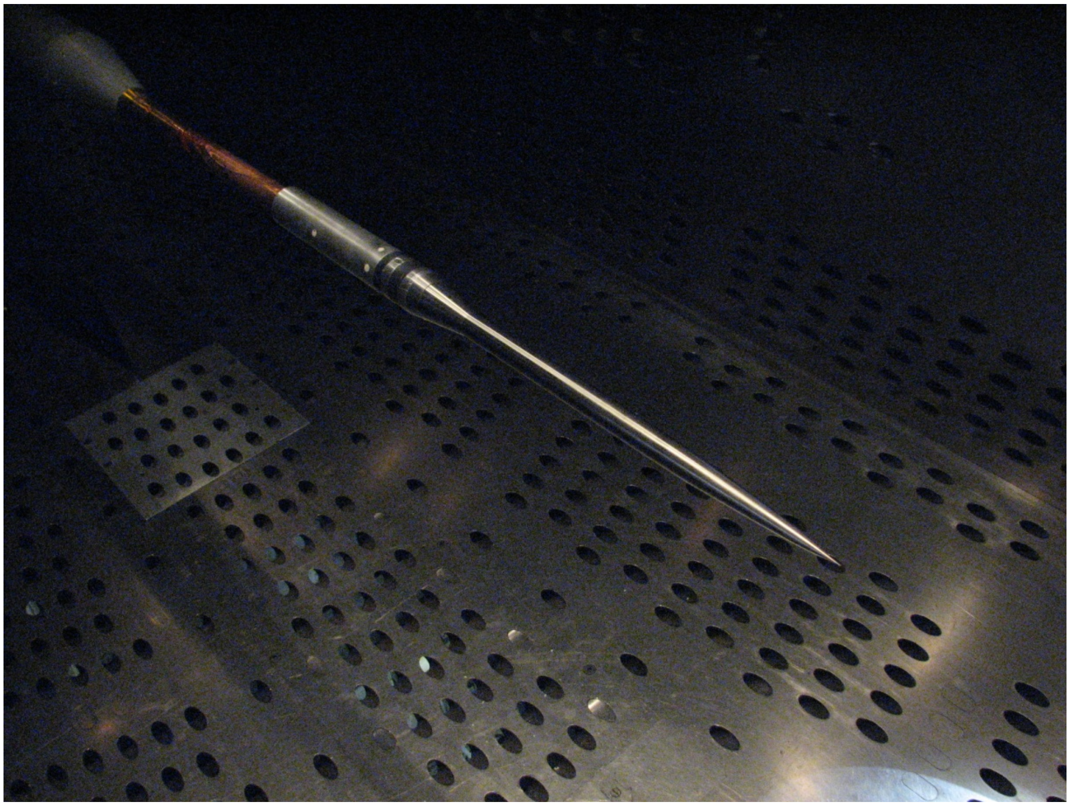

Figure 3.—AS2 calibration model.

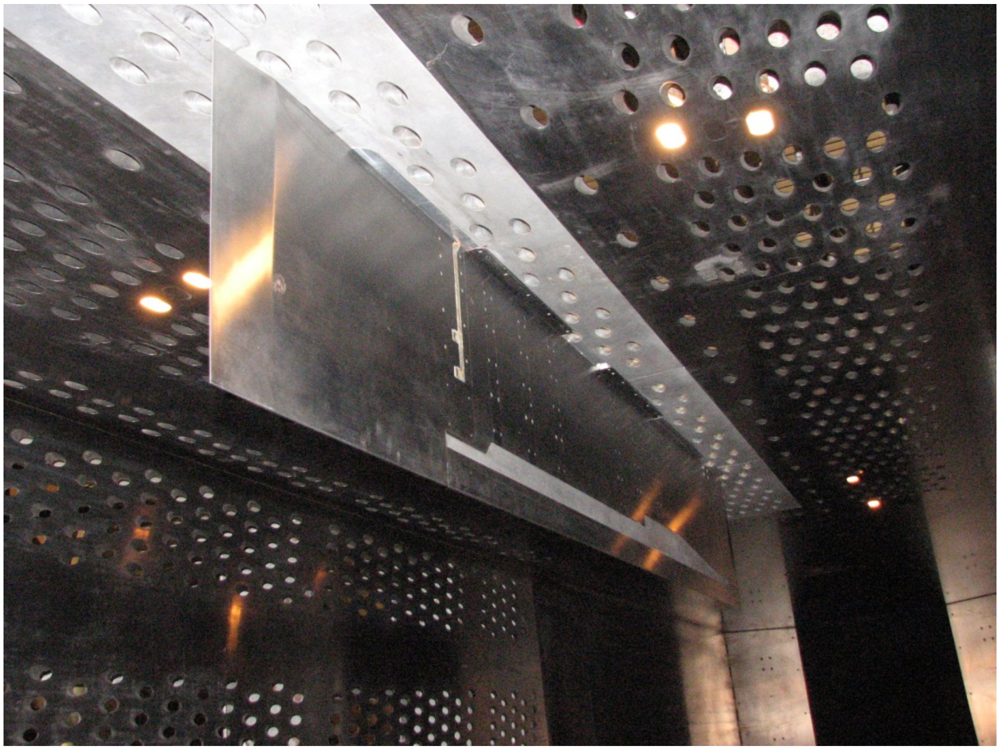

Figure 4.—14-in. pressure rail.

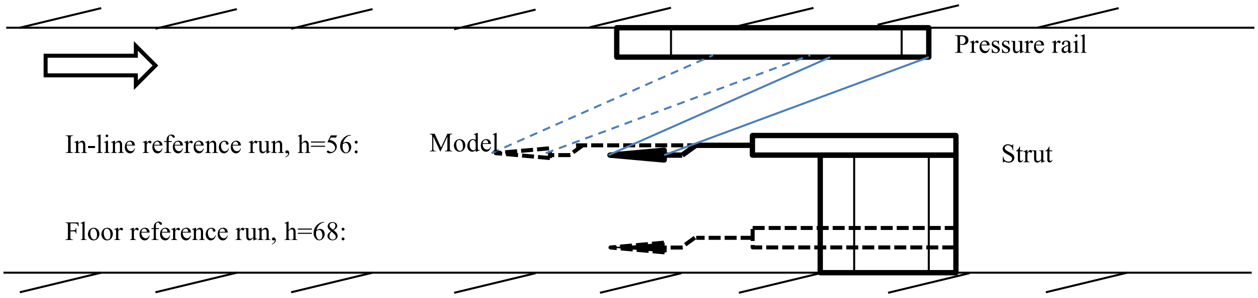

Figure 5.—Reference run positions.

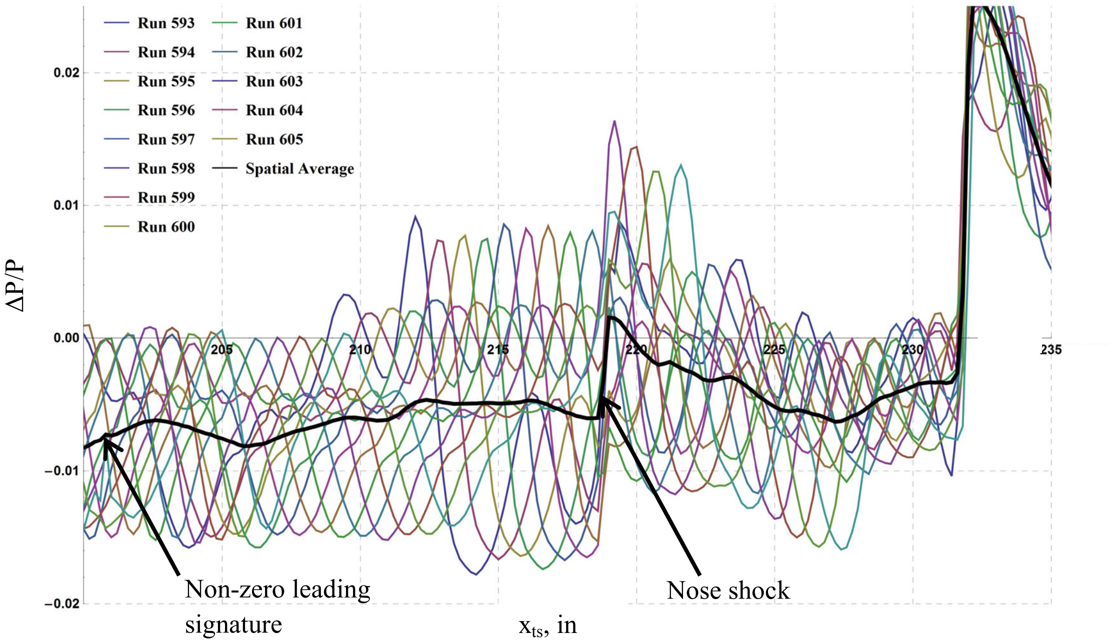

Figure 6.—Mach 1.8, AS2 model signature at h = 56 in., reference run h = 68 in.

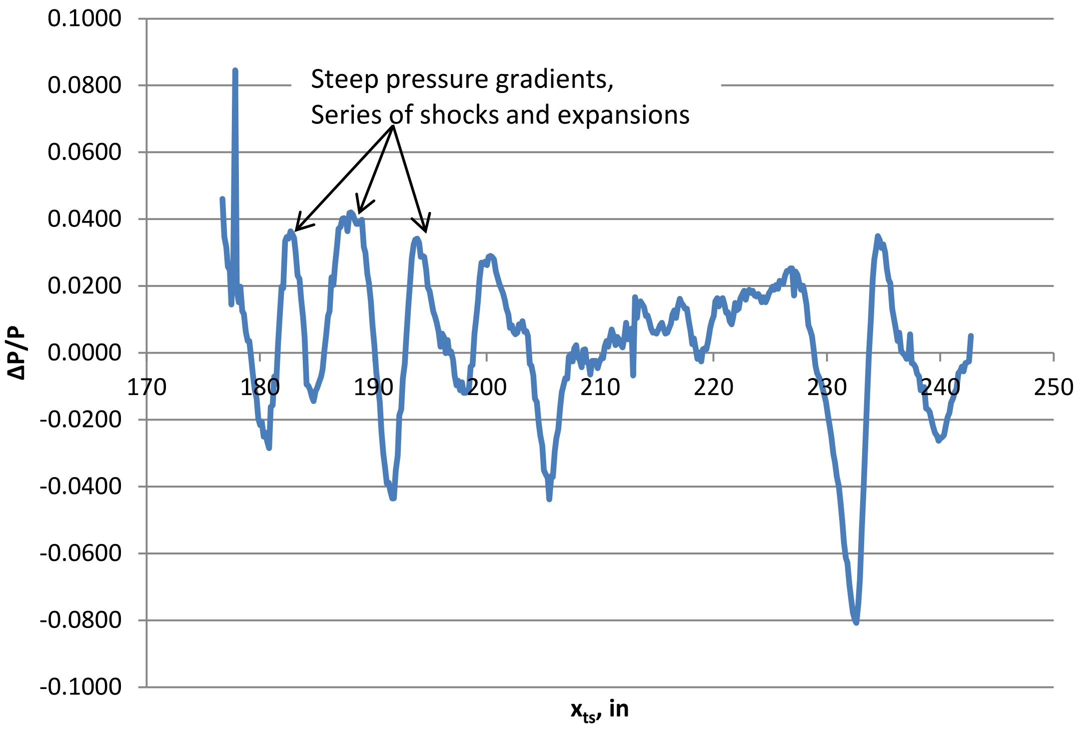

Figure 7.—Tunnel reference run ΔP/P, Mach 1.8.

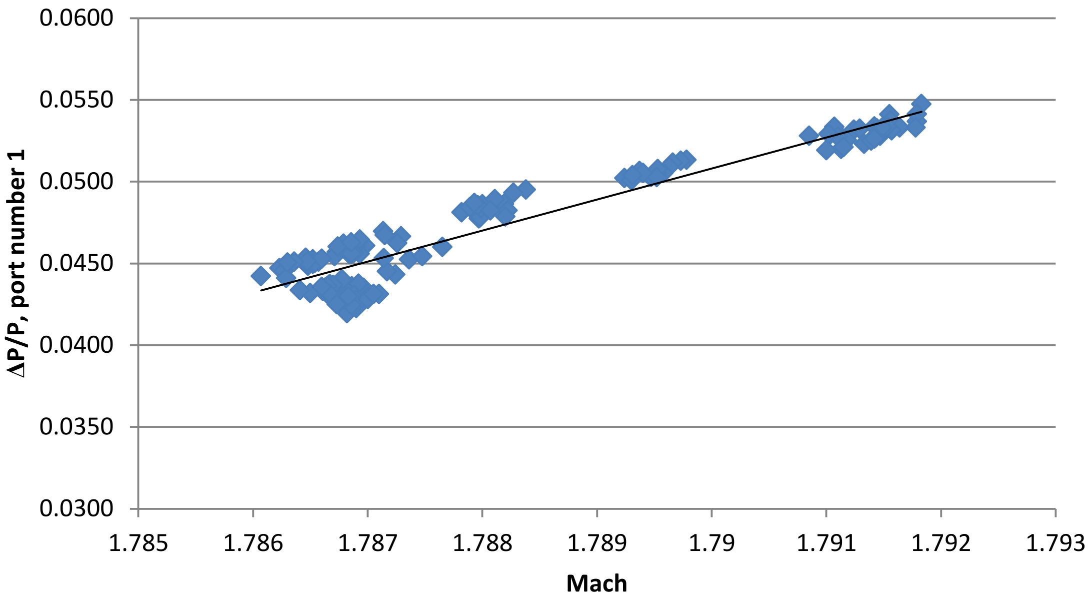

Figure 8.—Rail pressure variation with Mach number, nominal Mach 1.8.

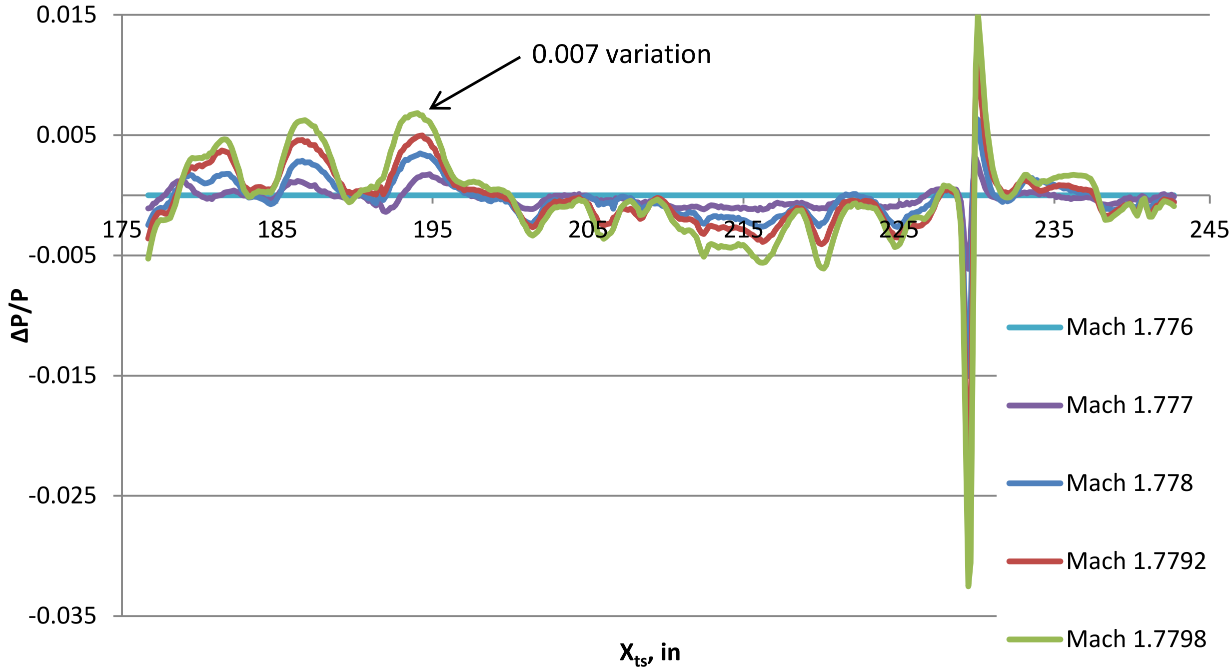

Figure 9.—Change in pressure profiles for reference run with Mach number, nominal Mach 1.8.

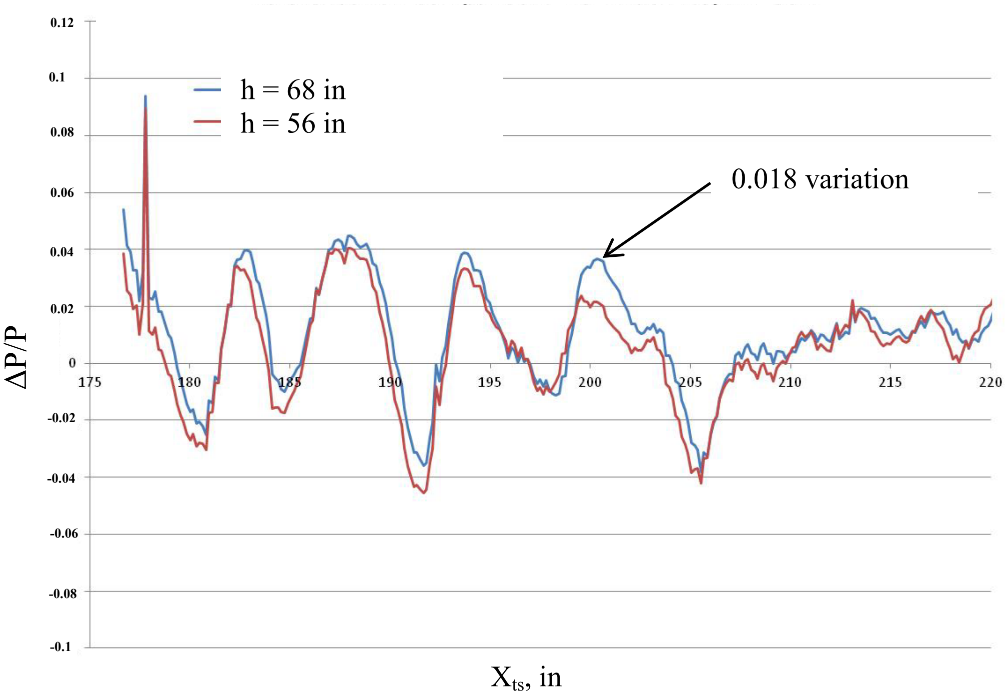

Figure 10.—Effect of strut position on reference run signature, h = 68 in. compared to h = 56 in. height.

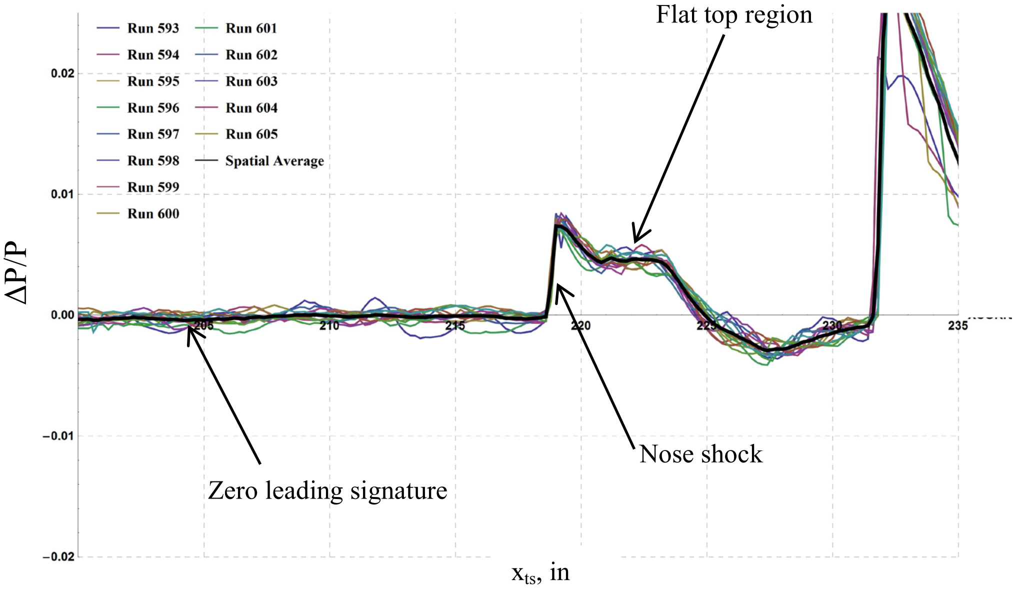

Figure 11.—Mach 1.8, AS2 model signature at h = 56 in., reference run h = 56 in.

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**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**

In an effort to identify test facilities that offer sonic boom measurement capabilities, an exploratory test program was initiated using wind tunnels at NASA research centers. The subject of this report is the sonic boom pressure rail data collected in the Glenn Research Center 8- by 6-Foot Supersonic Wind Tunnel. The purpose is to summarize the lessons learned based on the test activity, specifically relating to collecting sonic boom data which has a large amount of spatial pressure variation. The wind tunnel background pressure profiles are presented as well as data which demonstrated how both wind tunnel Mach number and model support-strut position affected the wind tunnel background pressure profile. Techniques were developed to mitigate these effects and are presented.

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