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Method for Standardizing Sonic-Boom Model Pressure Signatures Measured at Several Wind-Tunnel Facilities

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Summary

Low-boom model pressure signatures are often measured at two or more wind-tunnel facilities. Preliminary measurements are made at small separation distances in a wind tunnel close at hand, and a second set of pressure signatures is measured at larger separation distances in a wind-tunnel facility with a larger test section. Although both sets of pressure signature measurements are made at the same Mach number and Reynolds number per foot, differences in total temperature and pressure and varying reference probe locations on wind-tunnel section walls can provide different reference static pressures. Comparisons with theory, however, require all the measured pressure signatures to have a reference static pressure that is consistent with wind-tunnel operating parameters. In this report, a method for standardizing the wind-tunnel-measured pressure signatures obtained in different wind tunnel facilities is presented and discussed to draw attention to differences between real flow measured data and idealized flow measured data.

Introduction

Pressure signatures from low-boom models often need to be measured at two or more wind-tunnel facilities. Preliminary measurements are made at small separation distances in a wind tunnel with a small-to-medium size test section to obtain data for a preliminary check of anticipated low-boom performance. Wind-tunnel tests in a facility with a small-to-medium sized wind tunnel test section are relatively economical, and usually require less expensive and less complicated test apparatus. If this preliminary data is judged to be satisfactory, then a follow-on set of pressure signatures, measured at larger separation distances in a second wind-tunnel facility with a larger wind-tunnel test section, can be justified. This procedure makes it possible to determine the change and the rate of change in signature shape over a wide range of separation distances.

In references 1 and 2, a series of pressure signatures, measured in a study conducted at two wind-tunnel facilities with two research wind-tunnel models, were analyzed and discussed. Although both sets of pressure signature measurements were made at the same Mach number and Reynolds number per foot, differences in total temperatures, total pressures, and test section locations resulted in somewhat different reference static pressures. Since the pressure signatures from the two facilities were to be compared with each other and with theory, both sets of pressure signatures had to have reference static pressures consistent with wind-tunnel operating parameters.

In this report, a method for correcting and standardizing wind-tunnel-measured pressure signatures obtained in different wind tunnel facilities is presented and discussed. This method was briefly introduced in an abbreviated form in reference 2. There, however, the emphasis was on the design of low-boom models (carried over from reference 1), the measurement of pressure signatures at two wind-tunnel facilities, and the interpretation of pressure signature changes with increasing separation distances, references 1 and 2. In this report, the mathematical basis and formulation of the method is presented and discussed more completely.

Nomenclature

$F(y)$	value of the Whitham F-function at effective distance y, $ft^{1/2}$
h	vertical separation distance between the model nose and flight-track probe, in
I	non-dimensional pressure signature impulse, $I = \int_0^{\tau_o} \frac{\Delta p}{p} d\tau$
l_e	effective length of model, in
M	cruise Mach number
p	ambient pressure, psf
p_P	static pressure measured at survey probe in model flow field, psf
p_S	static pressure measured at survey probe, psf
$p_{S,O}$	static pressure measured at survey probe ahead of the model's flow field, psf
p_{TS}	static pressure in the center of the test-section outside the model flow field, psf
p_W	reference static pressure measured by wall probe, psf
Δp	incremental free-stream overpressure, psf
RN	Reynolds number
T_{TOTAL}	wind tunnel total temperature, degrees F.
x	longitudinal distance, in
x_o	longitudinal distance where the impulse is a maximum, in
y	spanwise distance normal to x, in, or effective distance in F(y), ft
τ	dimensionless dummy variable, x / l_e, in the equation of the impulse, I
τ_o	dimensionless ratio, x_o / l_e, along the pressure signature where the impulse, I, is a maximum

Wind-Tunnel Measurement of Pressure Signatures

The ideal supersonic wind tunnel has a uniform test section Mach number and static pressure flow from front to back, top to bottom, and side to side. This ideal wind tunnel would also have air moving with negligible turbulence and no flow angularities. All supersonic wind tunnels are less than perfect in some of these desirable attributes, which means that care and judgement must be exercised to measure pressure-signatures in the most-ideal-flow parts of the test section at the wind-tunnel facility used.

The first research sonic-boom models were small wing-fuselage bodies or bodies of revolution, so the reference and survey probes were mounted close to each other. The short pressure signature was completely measured before the model's flow field started to impinge on the reference probe's orifices. Under these conditions, the static pressure field around the model and two probes in the wind-tunnel test section was very nearly uniform.

As models were made larger to have more accurate component detail, the distance between the survey probe(s) and the reference probe grew. At these larger distances, the survey probe(s) might be in a relatively uniform static pressure field, but the reference probe could be in a slightly different static pressure regime. This possibility is illustrated in figure 1 which is a typical arrangement of a model, a survey probe, and a reference probe.

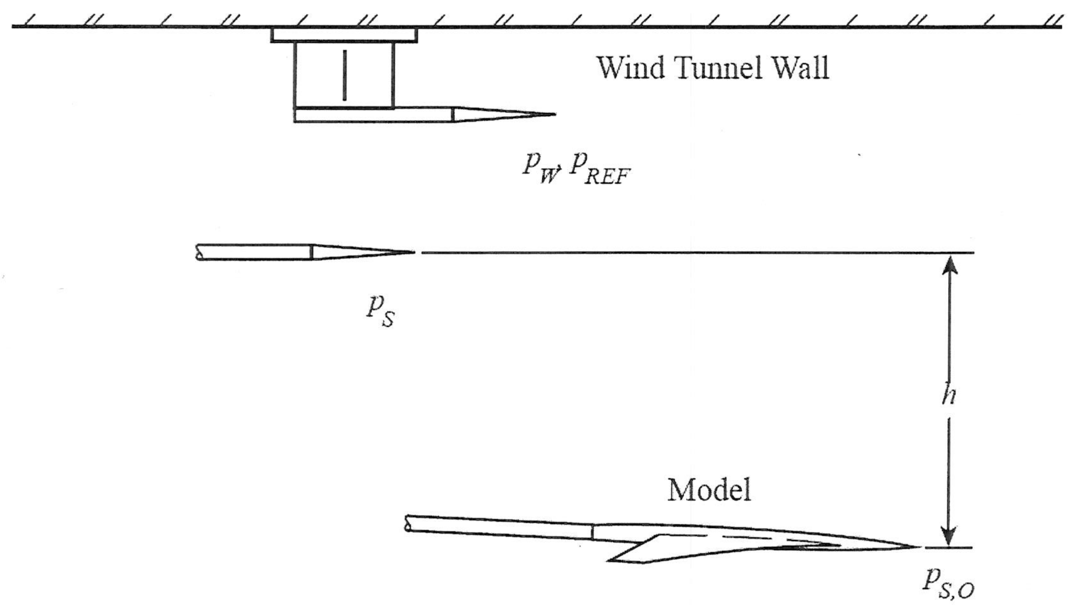

Figure 1. Typical model, survey probe, reference probe in wind-tunnel test section.

A typical pressure signature, measured in the wind-tunnel test section with the apparatus shown in figure 1, would resemble the one shown in figure 2.

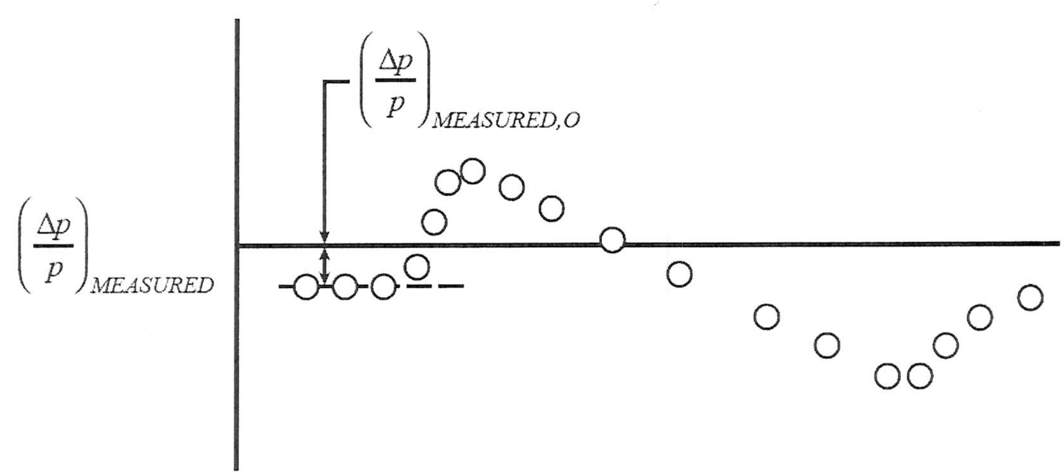

Figure 2. Typical initial-data measured pressure signature.

In the ideal, constant Mach number, constant-static pressure wind-tunnel test section, each disturbance point in the model flow field pressure signature would be defined and measured by:

$$\left(\frac{\Delta p}{p}\right)_{TRUE} = \frac{p_P - p_S}{p_S} \tag{1}$$

Obviously, this ideal cannot be met because the reference probe and the survey probe cannot occupy the same location simultaneously. Instead, the points in the pressure signature are obtained from the survey probe and the reference probe mounted on the wind-tunnel wall:

$$\left(\frac{\Delta p}{p}\right)_{MEASURED} = \frac{p_P - p_W}{p_W} \tag{2}$$

Equation (1) and (2) can be combined to obtain:

$$\left(\frac{\Delta p}{p}\right)_{TRUE} = \left(\frac{p_W}{p_S}\right)\left[\left(\frac{\Delta p}{p}\right)_{MEASURED} - \left(\frac{\Delta p}{p}\right)_{MEASURED,\,O}\right] \tag{3}$$

where $\left(\frac{\Delta p}{p}\right)_{MEASURED,\,O}$ is the overpressure measured outside or ahead of the model flow field.

If the total volume of the test section were at a uniform static pressure,

$$\left(\frac{\Delta p}{p}\right)_{TRUE} = \left(\frac{\Delta p}{p}\right)_{MEASURED}$$

because

$$p_W = p_{S,0} = p_S \quad \text{and} \quad \left(\frac{\Delta p}{p}\right)_{MEASURED,\,O} = 0.0$$

When Whitham theory, reference 3, was used to predict disturbances, $\Delta p / p$, generated by simple models in a wind tunnel test section, the required equation was:

$$\frac{\Delta p}{p} = \frac{\gamma M^2}{\sqrt{2\beta h}} F(y) \tag{4}$$

In equation (4), $\Delta p / p$ is a function of the Mach number and F(y), where F(y) is calculated from the model's "Mach sliced" volume distribution and lift distribution. For models 6 to 12 inches in length, however, the size of 4 ft x 4 ft wind tunnel test section in the LaRC Unitary Plan Wind Tunnel imposes near field flow conditions. So, higher-order sources such as Computer Fluid Dynamic (CFD) codes, must be used to obtain the theoretical pressure signature predictions for experiment / theory comparisons. Whichever prediction method is used, Whitham theory or CFD codes, a reference static pressure that corresponds to the test section Mach number environment must be used to obtain wind-tunnel-measured values of $\Delta p / p$.

Two wind-tunnel facilities were employed to obtain the data in references 1 and 2. Static pressures in these two wind-tunnel facility test sections are listed in TABLE 1. In both facilities, wind-tunnel model pressure signatures were measured at Mach number of 2 and at a Reynolds number (RN) = 2×10^6 per foot. An analysis of the test data showed there were small but significant static pressure differences in the air flowing in the wind-tunnel test sections and over the models used to measure pressure signatures at these two facilities. The static pressures listed in TABLE 1 were obtained by averaging the measured static pressures and rounding to the nearest tenth.

TABLE 1. Facility Reference and Test Section Static Pressures.

M = 2, and RN = 2 x 10^6 per foot

Langley Research Center (LaRC) Unitary Plan Wind Tunnel Facility

h, inches	9.0	13.5	18.0	22.5	27.0
p_W, psf	169.7	169.6	169.5	169.5	169.5
p_{TS}, psf	161.2	161.1	159.7	159.7	160.0

John Glenn Research Center (GRC) 10 ft x 10 ft Supersonic Wind Tunnel Facility

h, inches	22.5	45.0	67.5	88.9
p_W, psf	152.0	152.2	152.2	152.2
p_{TS}, psf	148.2	149.3	149.5	149.3

The free-stream static pressure in the test section of the LaRC Unitary Plan Wind Tunnel Facility at M = 2, T_{TOTAL} = 125 deg. F., and a RN = 2 x 10^6 per foot is about 160.2 psf. However, the static pressure in the GRC 10 ft x 10 ft Supersonic Wind Tunnel Facility would be somewhat lower because the T_{TOTAL} was lower at about 92 deg.F. Differences between p_W and p_{TS} in each test section were due to the particular reference probe location on the wind-tunnel side wall, and to the different total temperatures and total pressures at which the two wind tunnels operated. During the pressure signature measurements, these static pressures were usually achieved and maintained with a high degree of accuracy.

Implementation

The flight-track survey probe was mounted directly under and behind the model in a plane along the center of the wind-tunnel test section. In this location, it was assumed that both were in the same static pressure field, i.e. $p_{TS} = p_S$. After the pressure signatures were measured, corrections to the nose-shock $\Delta p / p$ were made by using equation (3). Data points in nose shock pressure rise were adjusted for measurement "rounding" with the technique defined in reference 4 so comparisons with theory could be made. Impulse calculations were corrected in a similar manner, but the nose shock overpressure data points did not need to be adjusted. With this technique, all the measured overpressures reflected the presumed uniform-pressure flow between model and the survey probe. This data could now be compared with the data obtained at any other wind-tunnel facility, once the data measured at that facility was similarly corrected. Similar equations would corrected the overpressures measured by the other survey probe(s) in the test section. The parameter $p_{S,O}$ at each of the survey probes would be obtained from:

$$p_{S,\,O} = p_W\left[1.0 + \left(\frac{\Delta p}{p}\right)_{MEASURED,\,O}\right] \qquad (5)$$

The overpressure ratio at the survey probes would be obtained from equations (3) and (5).

During the measurement of pressure signatures in supersonic wind tunnels, a variety of model location data and measured flow field data are recorded. Some of these data are:

(1) the x-distance of the model nose from the reference station,
(2) the model angle of attack,
(3) the x-distance of the orifices of the survey probe(s) from the reference station,
(4) the flow-field differential pressure ratio, $\Delta p \,/\, p$, measured at each survey probe,
(5) the static pressure at the wall reference probe, p_W ,
(6) the test section Mach number, M,
(7) the value of Reynolds number per ft ,
(8) the test section dynamic pressure,
(9) the wind-tunnel operating total temperature, etc.

This list of output data contains all the information required to standardize the test data from a couple to several wind tunnel facilities so an accurate and a reliable data matrix is available for comparison with theoretical predictions.

Example

In the previous sections, it was shown that most wind-tunnel-measured pressure signatures from sonic-boom models have upstream overpressures that are not ideally zero in value, i.e.

$$\left(\frac{\Delta p}{p}\right)_{MEASURED,\,O} = \left(\frac{\Delta p}{p}\right)_{MEASURED} = \frac{(p_P - p_W)}{p_W} \neq 0$$

due to the survey probe(s) and the wall reference probe being in slightly different static pressure fields. A typical measured pressure signature generated by a low-boom, wind-tunnel model is shown in figure 3.

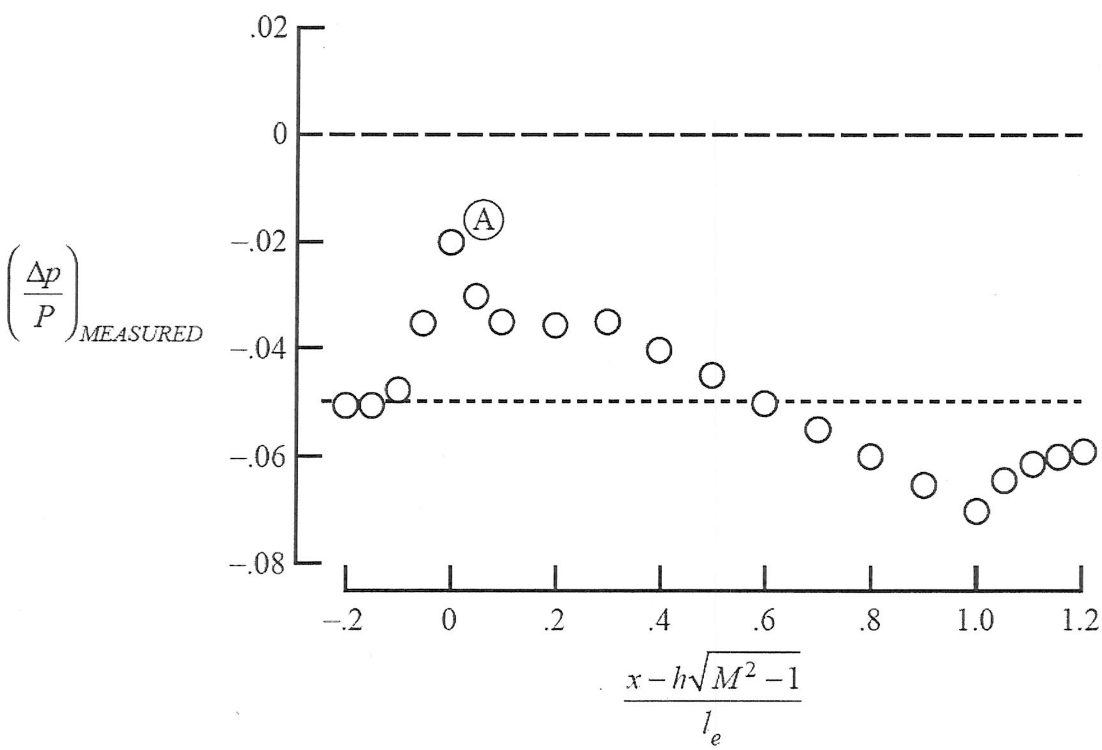

Figure 3. Typical measured low-boom model pressure signature. M = 2, RN = 2x10^6/ft

Usually, the "upstream offset" seen at the start of the pressure signature is subtracted from the measured pressure signature to obtain a corrected pressure signature. As was shown in the previous sections, this is only part of the correction required. In figure 3, the overpressure ratio, $\Delta p / p$, ahead of the nose shock pressure rise is:

$$\left(\frac{\Delta p}{p}\right)_{MEASURED,\,O} = -0.050,$$

and at point A, it is:

$$\left(\frac{\Delta p}{p}\right)_{MEASURED} = \frac{p_P - p_W}{p_W} = -0.020$$

Assuming (erroneously) that the static pressure differences across the two probes are negligible, the resulting partially corrected overpressure ratio at point A would be:

$$\left(\frac{\Delta p}{p}\right) = \left(\frac{\Delta p}{p}\right)_{MEASURED} - \left(\frac{\Delta p}{p}\right)_{MEASURED,\,O} = 0.030 \qquad (6)$$

A complete printout of the wind-tunnel model orientation and the test section flow-field properties included the wall static pressure, p_W . Its averaged value during this test run was:

$$p_W = 169.7 \text{ psf}$$

at a separation distance $h = 9.0$ inches. From equation (5), the calculated static pressure at the survey probe was:

$$p_S = 169.7 * (1.0 - 0.050) = 161.2 \text{ psf}$$

which was close to the Table I value of about 161.2 psf, but significantly different from the measured level of: $p_W = 169.7$ psf. Using equation (3) to obtain the full correction,

$$\left(\frac{\Delta p}{p}\right)_{TRUE} = \left(\frac{p_W}{p_S}\right)\left[\left(\frac{\Delta p}{p}\right)_{MEASURED} - \left(\frac{\Delta p}{p}\right)_{MEASURED,\,O}\right] \qquad (3)$$

provided a fully-corrected overpressure ratio of:

$$\left(\frac{\Delta p}{p}\right)_A = (169.7 / 161.2) * (-0.020 + 0.050) = 0.0316 \qquad (7)$$

instead of the partially corrected value given by equation (6):

$$\left(\frac{\Delta p}{p}\right) = \left(\frac{\Delta p}{p}\right)_{MEASURED} - \left(\frac{\Delta p}{p}\right)_{MEASURED,\,O} = 0.030 \qquad (6)$$

because the difference between the local wall static pressure and the appropriate Mach number static pressure has been taken into account. In practice, the treatment used to obtain a corrected pressure signature data value at point 'A' would be given to all the data points to obtain a fully corrected pressure signature. A comparison of a partially corrected and a fully corrected pressure signature, using the data shown in figure 3 corrected with equation (3), is shown in figure 4.

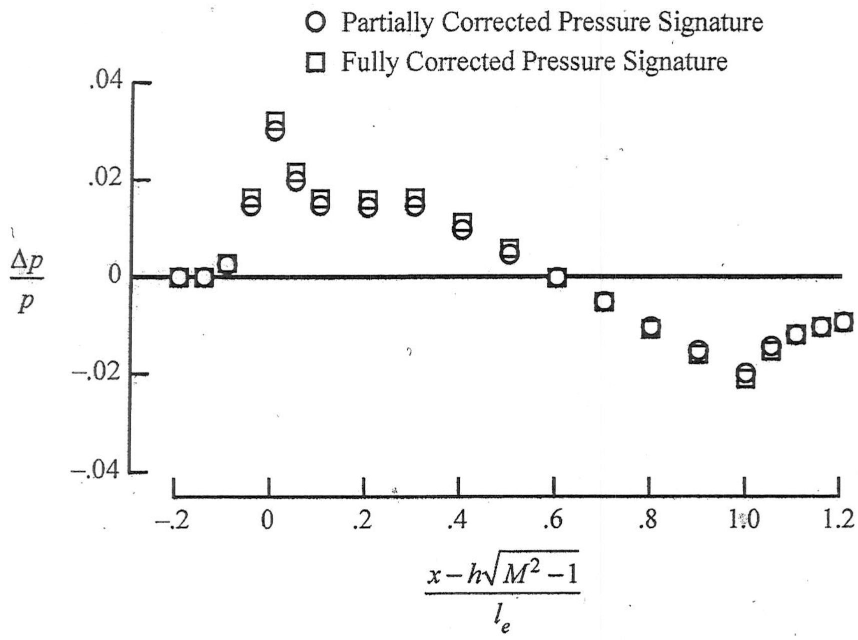

Figure 4. Comparison of a partially and a fully corrected pressure signature.

Since the correction in magnitude is only about 5.3 percent, the two pressure signatures lay very close together. The major differences are the change in magnitudes and the increase in the slope of the expansion overpressures leading to the aft recompression, a slope readily compared with a predicted slope. If the wall and Mach number dependent static pressures were further apart in magnitude, the correction factor would be larger, and the pressure signature differences would be more apparent.

Test section static pressures usually change by less than 1 percent during the measurement of the pressure signature. So, an averaged value of p_W can be employed to correct the pressure signature data. If they were to vary by more than 1 percent during the test run, the corrections given in equation (3) would need to be applied at each data point as it was taken. These corrections appeared to be small. Usually they are within the normal experimental scatter of less than the 0.5 percent quoted in the differential gauge specifications. If ignored, however, they could affect results. The available data points used to obtain theoretical nose shock predictions from corrected measured pressure-rise data, using the method in reference 4, usually decrease in number with increasing separation distance. This makes useful idealized nose shock strengths more difficult to obtain. However, if the measured data points were left uncorrected, the comparisons of theoretical and measurement-derived nose shock strengths could certainly be further compromised.

In contrast with the nose shock determination, the impulse, *I* (the integral of the overpressure ratio over the positive-pressure section of the measured or calculated pressure signature), depends on all, not just the first few, measured pressure signature data points in the positive overpressure integration range. So, errors of 5 percent, due to a lack of corrections, could change the conclusions drawn from comparisons of measured and predicted impulse as well as those drawn from theoretical and modified measured nose shock comparisons. These pressure signature corrections were noted, calculated, and used in references 1 and 2 to obtain measured pressure signature data so that a minimum pressure signature interpolation distance could be determined.

Concluding Remarks

The determination of pressure-signature shape change over a wide range of separation distances will usually require the measurement of sonic-boom model pressure signatures at several wind-tunnel facilities. Each of these wind-tunnel facilities will have its own set of unique operating conditions. Even though the Mach number and Reynolds per foot is the same at each facility, their different operating total temperatures and total pressures will result in slightly different static pressures in the test section. These differences in static pressure are by themselves inconsequential, but can lead to measured $\Delta p / p$ data that will not properly correlate with theory or with other wind-tunnel data when other test section effects are included.

Other small inaccuracies, introduced during the construction of the wind tunnel nozzle and test section, are seen in slightly non-uniform and/or non-constant static pressures in wall or ceiling regions of the wind-tunnel test section. So, the reference pressure probe could be located on a wind-tunnel wall in a section where the static pressure was somewhat different from its magnitude along the geometric center of the wind tunnel where the model and/or survey probe(s) are located.

These differences in operational conditions and in test-section geometry effects introduced the need to standardize the overpressure ratio of the pressure signature data so it would be compatible with the other data sets, and with the theoretical method(s) employed in experiment/theory comparisons. The standardization method described in this report can make this goal achievable with a minimum of extra effort, so reliable interpretations of pressure signature measurement results can be obtained. Thus, this method is based on and emphasizes the differences between the data measured in real wind-tunnel flow and data obtained in an ideal wind-tunnel test section.

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14. ABSTRACT
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