Sonic-Boom Wind-Tunnel Testing Techniques at High Mach Numbers

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Sonic boom testing techniques and some of the problems encountered in obtaining wind-tunnel measured sonic-boom signatures at high supersonic Mach numbers have been discussed. The presence of tunnel flow non-uniformities, effects of vibration, and boundary layer on the measuring probe are examples of some problems which were encountered in testing at lower Mach numbers and were found to be enhanced at the higher Mach numbers. The high Mach number testing procedure was also confronted with new problems such as interference from model mounting apparatus. Methods for avoiding these problems or minimizing these effects have been presented. Samples of measured sonic-boom pressure signatures obtained at Mach numbers up to 4.63 through the use of improved techniques are shown, together with a comparison of theoretical sonic-boom signatures.

Nomenclature

A = effective cross-sectional area
C_L = lift coefficient
h = perpendicular distance from model to measuring probe
l = model reference length
M = Mach number
p = reference pressure (freestream static)
Δp = incremental pressure due to flowfield of model
Δx = distance from bow shock to point on pressure signature measured parallel to freestream direction
α = angle of attack

Introduction

FOR more than a decade wind-tunnel tests have been conducted at the NASA Langley Research Center to determine the sonic-boom characteristics of various research models as well as scaled models of existing airplanes. Early tests made use of simplified research models in order to study the basic physics of the problem.[1–3] Later tests were performed to establish sonic-boom characteristics of specific airplane configurations.[4–6] Special apparatus and test techniques are required because of the small size of the models and the requirements for the sensitivity in the measurement of relatively small sonic-boom overpressures. Until recently, the major portion of the wind-tunnel research was limited to the Mach number range between about 1.2 and 2.0. Now, however, interest in hypersonic aircraft configurations has created a need for information about sonic-boom characteristics at high Mach numbers and, at present, very little experimental data are available. As a result, exploratory sonic-boom tests have been conducted in the higher Mach number range between about 2.3 to 4.63. The present paper will discuss some of the testing techniques employed and problems encountered in measuring sonic-boom overpressures in this speed range.

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Discussion

General Test Procedure

A series of sonic-boom tests have recently been conducted in the high Mach number test section of the Unitary Plan wind tunnel which has a Mach number range of 2.3 to 4.62. The test techniques followed much the same pattern as those developed over the years in tests at the Langley 4-ft by 4-ft supersonic pressure tunnel. The basic concept of the testing technique is quite simple and has been described in detail in Ref. 7. In brief, the desire model configuration is sting supported in the tunnel and measurements of the model-induced pressures are made using a slender static probe. Figure 1 shows an arrangement of the wind-tunnel apparatus which was used for the high Mach number tests. The model is sting supported by a remotely controlled actuator that permits longitudinal positioning of the model. Angles of attack may be positioned by a remotely controlled angle-of-attack mechanism. The measuring probe and reference probe assembly, which is used to measure the sonic-boom pressure, is mounted on the tunnel main sting which provides for both lateral and longitudinal motion. The measuring orifice and the reference orifice are spaced in the vertical plane to avoid mutual interference and are spaced longitudinally to permit measurement of a complete signature before the forward motion of the model and its flowfield influences the reference orifice. The differential pressure between the two probes is measured by a sensitive pressure gage which may have a full gage output as small as ± 0.05 psi. A safety bypass valve which is connected in parallel with the pressure gage is

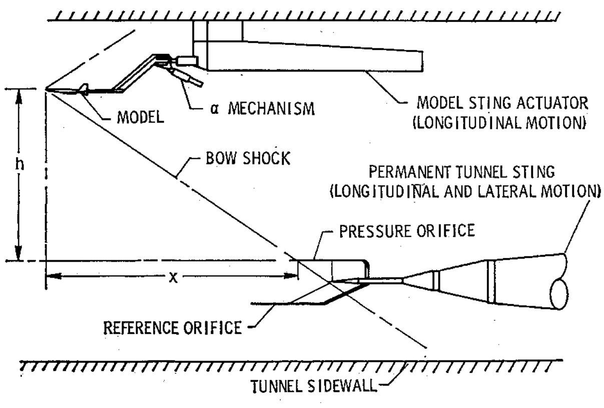

Fig. 1 Wind-tunnel apparatus.

opened during tunnel startup and shutdown to prevent overloading and possible damage to the gage. During a tunnel run, a complete sonic-boom signature is built up point by point as the model is moved to successive positions and the resulting pressure field is passed across the measuring pressure probe. For each model position, a sufficient time is allowed for the pressure gage reading to settle; this normally takes about 30 sec. A complete pressure signature may thus require about 15 to 30 min of testing time, depending on the number of data points measured.

Extraneous Tunnel Variations

As pointed out in Ref. 1, a number of difficulties are encountered in the test procedure which include accurate construction of the extremely small models, pressure variation at the measuring orifices, model and probe vibration, and tunnel flow angularities. Pressure variations were found to exist in the presumably uniform and steady tunnel flow in the absence of a test model due to small tunnel-wall deformities that were encountered as the probe was moved from position to position. These variations in pressure are eliminated or at least greatly reduced by positioning the measuring probe at a fixed tunnel location and by moving the model itself from position to position. Also variation of pressure was found to occur due to oscillations of the tunnel pressure control system. It has been found that this source of error can be eliminated by positioning the reference probe and the measuring pressure probe relatively close together. These same problems are encountered in the high Mach number test range together with several additional ones. One of the first problems realized was the fact that flow angularities encountered in the Unitary tunnel were larger than the flow angles in the 4-ft by 4-ft supersonic tunnel. Figure 2 shows a plot of the tunnel flow angularities as measured with a conical probe in the region of the tunnel sidewall where the model would be located. It can be seen that the tunnel flow angle varies from about 0.15° to 0.30°. Consequently, flow angles of this magnitude must be accounted for in order to obtain accurate estimates of the lift generated by the model whose flowfield is being measured. In the past, measured flow corrections were applied to the model angle of attack and lift was estimated from experimental or theoretical model lift characteristics. Recently, a miniature one-component strain-gage balance has been used to measure model lift, thus eliminating the need for flow angle corrections.

Interference Considerations

Another difficulty encountered in the high Mach number range was concerned with interference from the model mounting strut and the angle-of-attack mechanism. It was found that equipment which allowed for the measurement of interference-free sonic-boom signatures at the lower Mach number range would produce interference pressures that tended to blanket out a large portion of the model signature at high Mach numbers. Figure 3 shows a sketch of a model and the mounting strut which serves to illustrate the problem. To separate the model signature from the pressure field produced by the α-mechanism, an offset strut was employed. The sketch shows how the shocks from the model and the mounting strut tend to merge together. A typical sonic-boom signature is shown in the lower part of the figure. For the example shown, a full-length pressure signature would be obtained with no interference from the mounting strut. To obtain this separation distance, the strut cross-sectional area in the region of the sting-strut mount was reduced as much as possible to prevent a strong strut-produced shock wave from merging with the pressure field generated by the model. It was found that in designing the sting-strut mounting combination, theoretical calculations using the sonic-boom computer program[8] for the model strut combination were very helpful in determining an interference-free model setup. Another small detail that may be of interest is the fact that the longitudinal positions of the model and probe should be precalculated for the desired test range of Mach numbers and separation distance. Otherwise, it may be possible to start a tunnel run with the model in the wrong position and waste expensive tunnel time measuring a pressure signature from some of the mounting equipment before the error is detected.

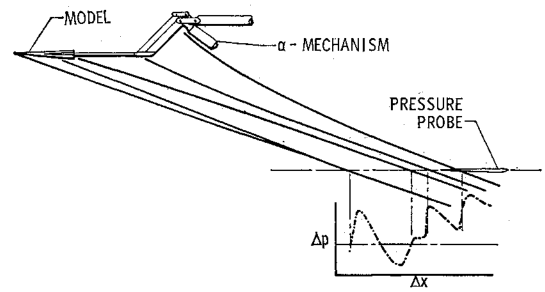

Fig. 3 Model mounting interference.

Measuring Probes

The drawing of Figure 4 shows a sketch of the pressure probes which were used in measuring the sonic-boom signatures. The static probe (shown at the top of the figure) is the basic probe design which has been used for a number of years and has proved to be quite satisfactory. The probe is a slender cone (2° half-angle) with four 0.035-in.-diam static pressure orifices leading to a common chamber. The four orifices were circumferentially spaced 90° apart around the probe and were arranged to be aligned with the Mach angle for

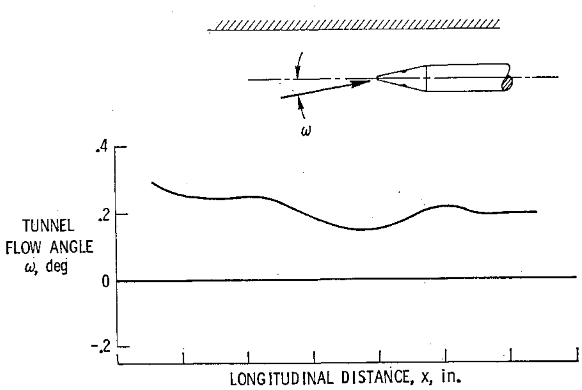

Fig. 2 Typical wind-tunnel flow angle variation.

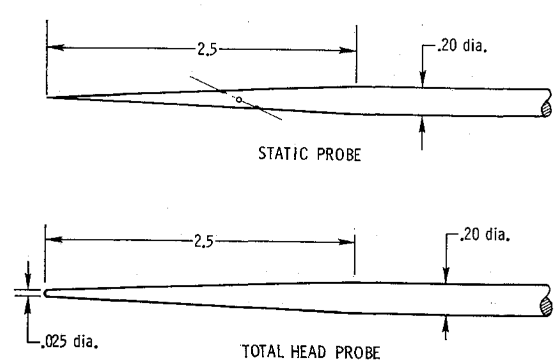

Fig. 4 Details of pressure probes.

Mach 2.92 so as to permit a better definition of the shock front for a range of Mach numbers near 3.0. In the lower part of Fig. 4, a sketch is shown of a total-head probe which was used to measure a number of signatures. For this probe, a single total-head orifice was located at the tip of the probe which had a diameter of 0.025 in.

For test over a wide Mach number range, it was thought that the total-head probe might offer some advantages over the static probe. One would be to eliminate the problem of aligning the orifices with the Mach cone for a wide Mach number range which, hopefully, would result in the measuring of more sharply defined peak overpressures. Also, the total-head probe would not encounter the boundary-layer interference effects that might occur for a static probe design. Figure 5 shows the results of the test runs using both types of probes. It is seen that the signatures measured with both probes have the characteristic rounding of the peak pressures with only a slight change noted in the signature shape. Thus it appears that the rounding of the peaks is predominantly the result of model and probe vibration rather than the effects of the orifice's alinement with Mach cone or boundary layer. However, it should be pointed out that these measurements with the two probe designs are only a first step and that additional work needs to be done to more fully develop accurate sensing devices for hypersonic speeds.

Model Lift Determination

As was previously noted, a miniature one-component strain-gage balance has been used quite successfully for measuring model lift. The one-component strain-gage balance was designed and developed specifically for sonic-boom tests with small models. In addition to measuring model lift, the balance also provides a much faster method for making the angle-of-attack setting during a test. Previously, model angle of attack was optically set by focusing a spectrometer on a prism mounted in the surface of the model. The over-all length of the sting-balance combination is 8 in. and the balance unit, which is internally mounted, has a small rectangular cross section measuring 0.090 in. 0.096 in. The balance is slip-fitted into the model cavity and is held in place with a small screw. The balance was designed to measure maximum lift loads of about 0.75 lb and the sting-balance and model combination is calibrated mounted in the tunnel using a small weight pan and 0.1 lb weights. This provides the balance sensitivity constant, and at the same time clearance around the sting at the model base is checked to insure that no fouling between the model and sting will be encountered for the loadings anticipated. The photograph of Fig. 6 shows two recently tested research models which incorporated the balance to measure lift. Both configurations are simple lifting wing models used for studying lift-induced sonic-boom characteristics in the high Mach number range. The models had an over-all length of 3.0 in. with sufficient volume to house the small balance. These models were relatively large in comparison to other models that have been tested. Tests with models as small as 1 in. in over-all length have been successfully made employing a balance to measure lift.

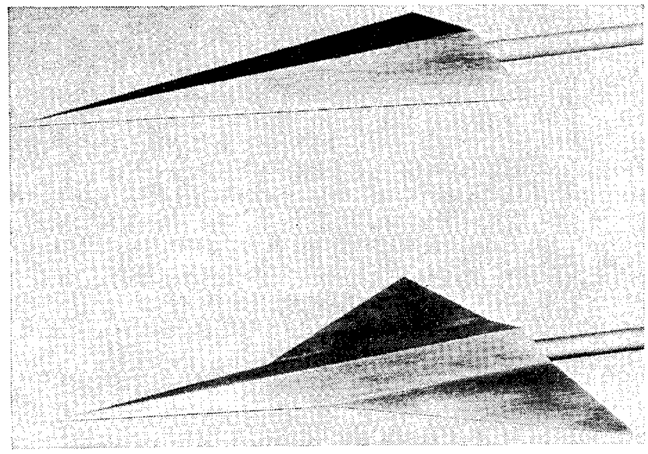

Fig. 6 Two test models with the minature balance.

Typical Lift Measurements

Figure 7 shows a sample of the balance lift measurements plotted against angle of attack for the simple double-delta wing model at $M = 4.63$. Comparison of the experimental lift with the calculated values shows that the measured values are about 15 % higher. However, differences between theory and experiment at this Mach number might be expected, because it is generally felt that linearized theory above about Mach number 3 is beyond its usable range and thus cannot be safely relied upon. Figure 7 also shows two corresponding sonic-boom signatures for the same model at a lift coefficient of zero and 0.09. A comparison of the change in sonic-boom overpressure levels shows that an increase in maximum peak overpressure of about 55 %. This large change in overpressure due to lift tends to illustrate the importance of accurately measuring lift in obtaining sonic-boom signatures for lifting conditions.

Experimental Results and Comparison with Theory

Over a period of years, sonic-boom test programs in the low Mach number range have provided data for a number of basic research models and for specific airplane configurations. The

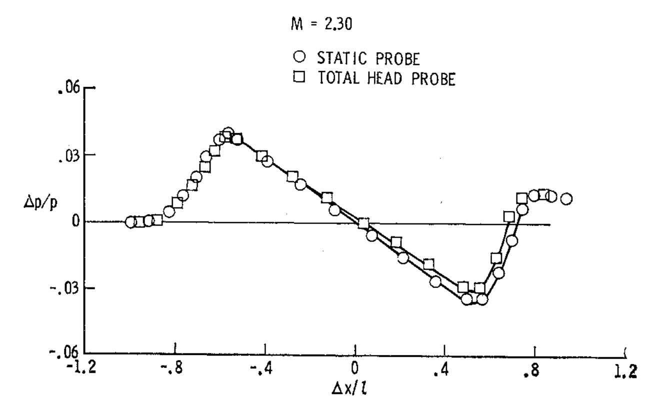

Fig. 5 Comparison of probe data.

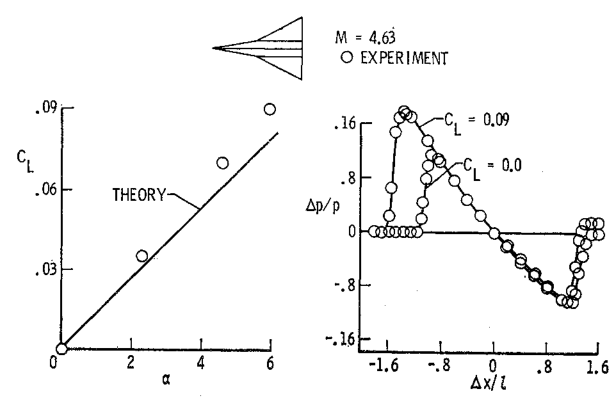

Fig. 7 Model lift and sonic-boom pressure signatures.

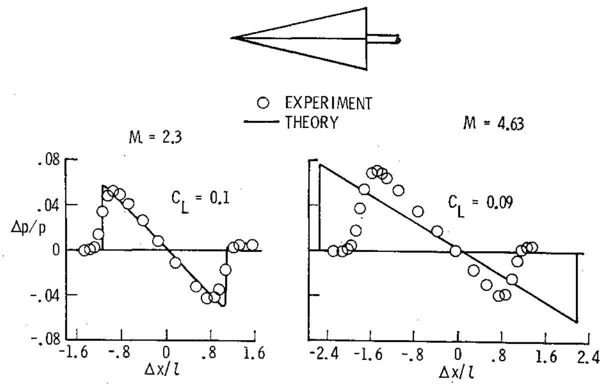

Fig. 8 Theory and model data comparison.

experimental results from these wind-tunnel test programs have provided valuable data which have aided in the development of theoretical sonic-boom prediction techniques that have proved to be very reliable for this Mach number range. Figure 8 shows a comparison of the current sonic-boom theory (for low Mach number) with the experimental data for the slender delta wing model. The theoretical signatures were calculated using a number of machine computing programs which have been operational at Langley for some time and are described in Refs. 8–10. It can be seen that fairly good agreement between the experiment and theory is shown at Mach numbers of 2.3; however, as the Mach number is increased to 4.63, the theory tends to depart considerably from the experimental values. For the latter signature, not only is there a large difference in the slope of the pressure decline in the positive pressure region, but there is also an appreciable discrepancy in the areas under the positive portion of the signature. It is apparent that the theory does not adequately predict the signature shape for high lift condition. This may be attributed to the fact that the equivalent body fineness ratio of the model is reduced at lifting conditions and the signatures shown here are for a relatively close-in position. Under these conditions, it is possible that the model-induced pressures may be too large to meet the small disturbance assumption of linearized theory. At larger distances from the model, some improvement in correlation might be expected as the over-all pressure field disturbances become weaker and as the large distance approximations of the theory become more applicable. However, these results illustrate the fact that further research needs to be done in this speed range and that the wind-tunnel studies will be a valuable tool in the development of more reliable sonic-boom prediction techniques.

Conclusions

Testing techniques employed and problems encountered in obtaining wind-tunnel measured sonic-boom signatures at high supersonic Mach numbers have been discussed. The presence of tunnel flow nonuniformities and effects of vibration and boundary layer on the measuring probe are examples of some problems which were encountered in testing at lower Mach numbers and were found to be enhanced at the higher Mach numbers. The high Mach number testing procedure was also confronted with new problems such as interference from model mounting apparatus. Methods for avoiding these problems or minimizing their effect have been presented. In order to study lift-induced sonic-boom characteristics, a miniature strain-gage balance was developed specifically for this purpose and has proved to be invaluable not only for measuring the model lift force but also for easily and accurately setting model angle of attack. A comparison of typical experimental and theoretical sonic-boom signatures for a Mach number of 4.63 was presented to illustrate shortcomings of current-sonic-boom prediction techniques at high supersonic speeds. The results presented in this paper illustrate the need for further research in developing both experimental and theoretical methods for studying sonic-boom phenomena at high Mach numbers.

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