Technical Memorandum No. 33-179

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Calibration of a Compact Survey Probe for Pitot Pressure, Mach Number, and Flow Angularity Measurements

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ABSTRACT

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A pressure survey probe, designed to evaluate the flow field between a body in hypersonic flow and its shock wave, has been fabricated and experimentally calibrated. The probe geometry consisted of a 60-deg total angle cone with a maximum diameter of 0.234 in. A concentric pitot pressure port and four symmetrical cone static pressure ports were calibrated in terms of pitot pressure, Mach number, and flow angularity in the vertical plane. The calibration included Mach numbers of 1.33 to 3.26, Reynolds numbers of 3×10^4 to 3×10^5 per inch, and flow angles to 10 deg. This probe and calibration departed from the conventional wind tunnel cone static probe in two ways: the cone static pressure ports were quite close to the cone nose which was blunted by the pitot pressure port, and the calibration extended to both sides of the theoretical sharp-cone bow-shock detachment Mach number of 1.48. In view of its compact size and these compromises, the calibration data indicate that this relatively rugged probe will yield unambiguous results of moderate accuracy.

Author

I. INTRODUCTION

The technique of using cone static pressure measurements to evaluate flow conditions in a wind tunnel has been well established. References 1 through 3, and the references given in Ref. 1 and 2, constitute examples. In general, such cone pressure probes are intended as fundamental calibration devices for use in relatively uniform flow regions of moderate dimensions. Because of this, they are carefully designed, usually at the expense of geometric size, to make the theoretical analysis (Ref. 4) valid.

A slender body in supersonic or hypersonic flow produces a non-uniform flow region between the body and its shock wave. When the slender body includes a stabilizing flare, the possibility of flare-induced separation on the body further complicates the analysis of this flow region. Only a limited amount of experimental data, such as Ref. 5, are available to evaluate theoretical analyses of this flow.

Since wind tunnel models are size-limited by interference considerations, the non-uniform flow region between the body and its shock wave will be small. Any probe designed to investigate this flow region must therefore be quite compact. Hot wire anemometry techniques provide a possible solution to the problem; this approach was rejected due to the fragility of the sensing elements and instrumentation complication. A cone pressure probe, as compact as seemed practical, was selected on the hypothesis that performance deviations from theoretical could be calibrated. Compromises were made with conventional cone pressure probe design practice to enhance its compactness.

A probe assembly was designed for use in JPL 21-in. Hypersonic Wind Tunnel (HWT) WT Test 21-141, to be mounted on the vertical traverse. The Mach numbers behind a model shock wave are significantly lower than free stream values. The probe was, therefore, calibrated in the undisturbed test section flow of the JPL 20-in. Supersonic Wind Tunnel (SWT) in April 1963, as Test C-47. The aerodynamic properties of the test section flow in this tunnel have been thoroughly investigated (Ref. 6), and are frequently recalibrated. A limited amount of calibration data were also gleaned from the performance of this probe in the HWT, when its sensing elements were located between the model shock wave and the tunnel wall boundary layer.

II. PROBE GEOMETRY AND INSTRUMENTATION

The physical geometry of the aerodynamically significant portions of the probe is given by Fig. 1. Figure 2 presents a photograph of the complete probe assembly, and Fig. 3 is an enlarged close-up photograph of the probe tip. The selection of the geometry illustrated by these figures was somewhat arbitrary, based on the following considerations:

1. A cone total angle greater than 60 deg would have caused probe bow shock wave detachment at a higher Mach number, thereby reducing the confidence level in data obtained at the lower supersonic Mach numbers.
2. A cone total angle less than 60 deg would have lengthened the conical portion of the probe, thereby degrading the definition of the effective location of a measurement in the non-uniform flow field. Increased over-all probe length would have further restricted flow measurements close to the toe of the model-stabilizing flare (see Fig. 2).
3. The required pressure transducers were most conveniently located external to the wind tunnel test section, due to cooling, flow blockage, and vibration considerations. This resulted in about a 12-ft length of connecting pneumatic tubing, consisting mainly of $\frac{1}{16}$-in.-OD stainless steel. The conical surface pressure ports, which operate at a lower pressure level than the tip pitot pressure port, were made larger than the latter (see Fig. 1).
4. The cone static pressure ports were located (radially) as close as reasonable, from fabrication considerations, to the central pitot pressure port. The design feature of drilling these cone pressure ports normal to the local surface was also deleted in the interest of compactness. Reference 1 recommends "the ratio of the distance between the probe tip and the static orifices to the diameter of the blunt tip" be in excess of 15; for the geometry under discussion this ratio is only 1.54 to the leading edge and 3.11 to the trailing edge of the cone static pressure ports.

Figure 3 also shows an opening below the cylindrical portion of the probe; this was provision for an electrical grounding contact to accurately establish the vertical position of the probe with reference to the model in the presence of air-load elastic deflections. This provision was not used during the calibration.

For calibration purposes, this probe was mounted approximately in the center of the 20-in. SWT test section in such a manner that it could be rotated in a vertical plane about its tip.

Statham Instruments, Inc., Type PM131 pressure transducers of ½-in. nominal diameter were used. One 25-psia transducer was connected to the central port to read absolute pitot pressure, P_t'. A 15-psia transducer was

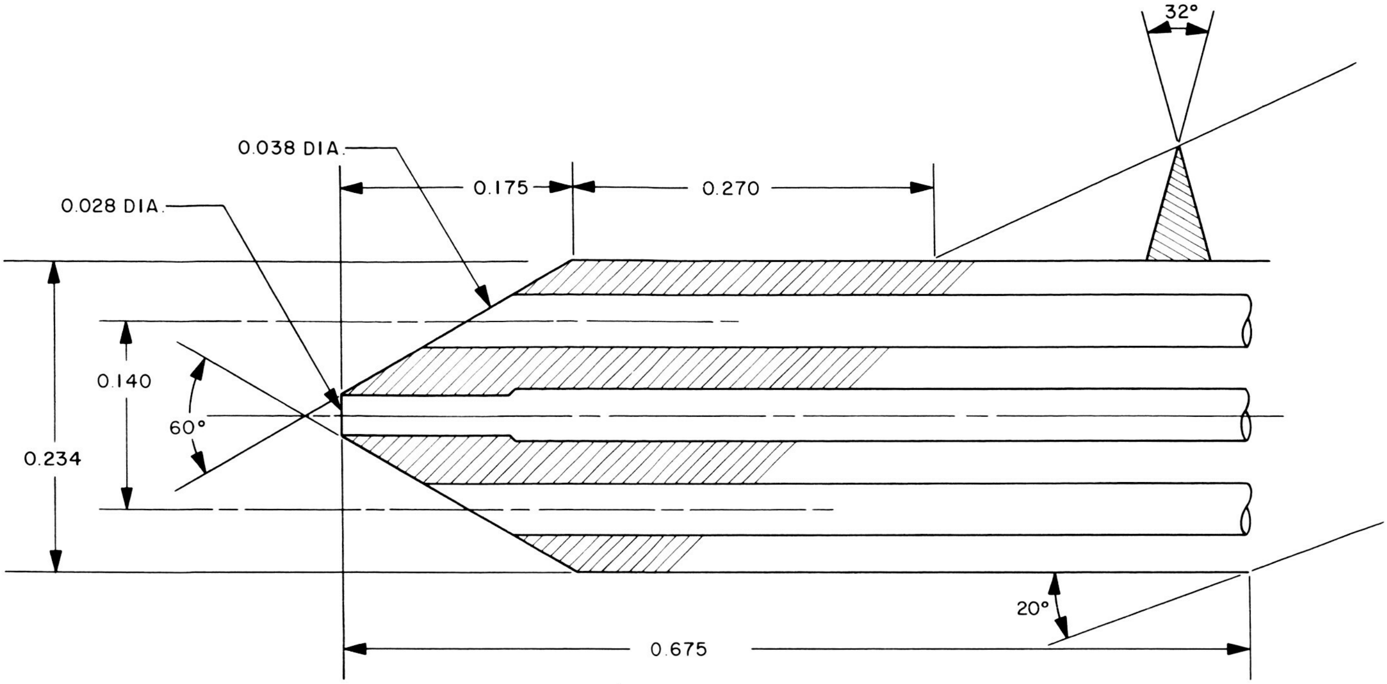


Fig. 1. Geometry of probe

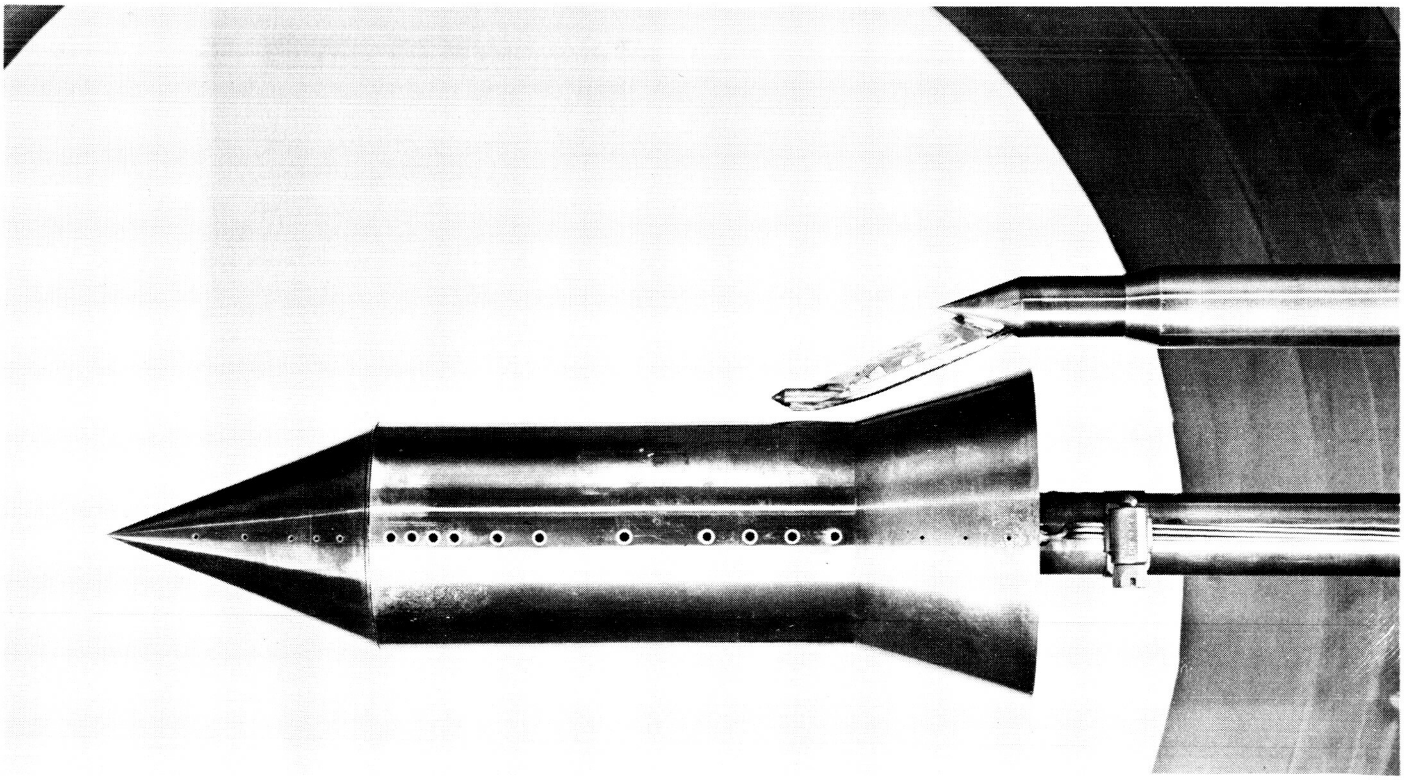


Fig. 2. Probe assembly adjacent to model (Test 21-141)

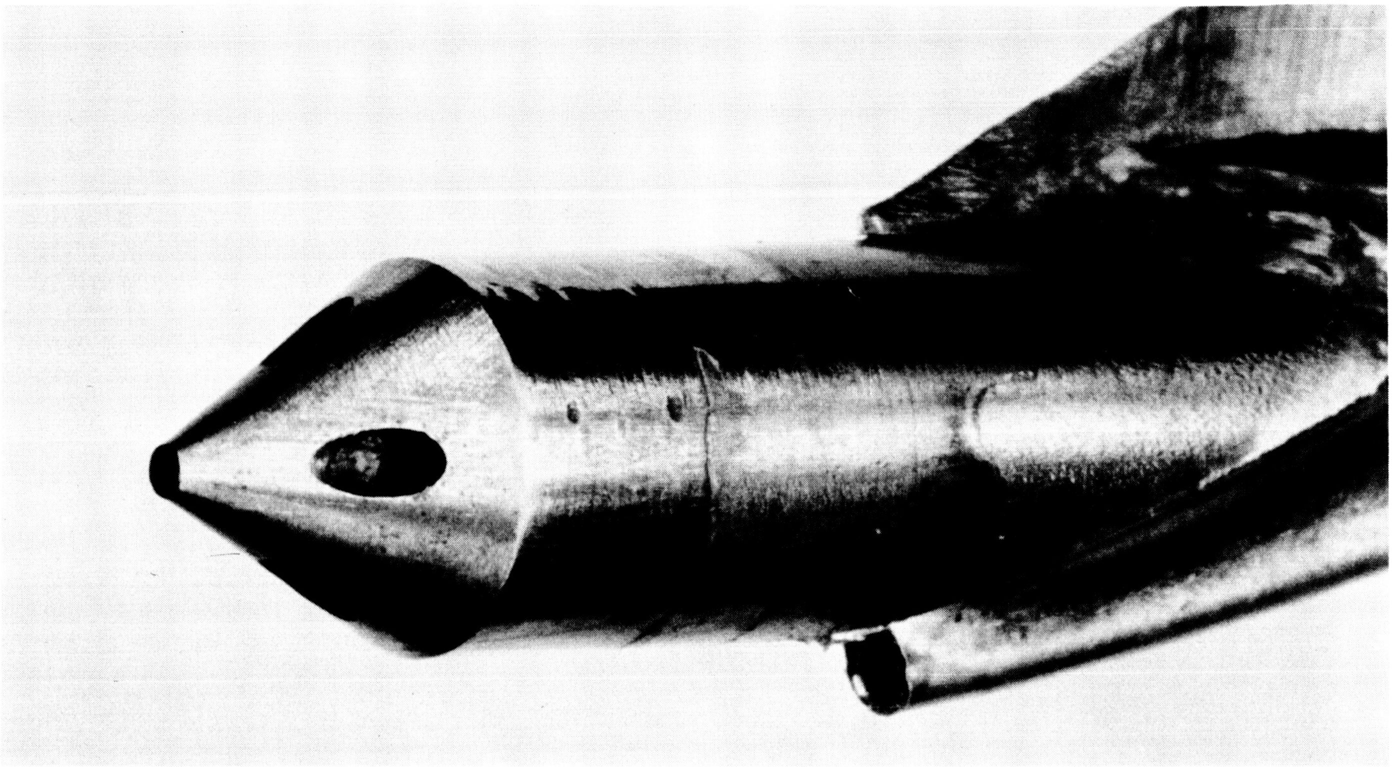


Fig. 3. Probe tip

connected to the two side cone static ports, siamesed together external to the tunnel, to read average cone static absolute pressure, $\overline{P}_c$. A 12.5-psia transducer was connected between the upper and lower cone static ports, to read a pressure difference, ΔP_c, related to the relative flow angularity. The electrical signals from these transducers were read from Brown round-dial instruments, with step-wise zero suppression, and recorded by hand.

III. CALIBRATION DATA AND DISCUSSION

Figure 4 presents enlarged shadowgraph photographs of the probe at Mach numbers 1.33, 1.48, 2.01, 2.81, and 3.26 at zero flow inclination angle. Inspection of this figure shows the bow shock wave to be detached from the pitot-port-blunted nose in all cases, the stand-off distance decreasing with increasing Mach number. At Mach number 1.33, the bow wave is completely detached, as predicted by theoretical analysis. Starting at Mach number 1.48, the shock wave angle in the vicinity of the conical surface shows good agreement with theoretical predictions. At Mach number 1.48, the bow wave is on the detachment margin; the pressure data to be discussed later show it behaves as though detached. A slight reverse curvature of the shock wave may be observed just downstream of the pitot-orifice-blunted nose, which probably contributes to discrepancies from theoretical values in cone static pressures measured in this region.

The pitot pressures read by the probe were compared with values read from the normally installed test section traversing pitot pressure installation. The agreement most of the time was within two least counts, which is the accuracy customarily attributed to the system. In general the probe yielded a higher pitot pressure than the tunnel pitot, especially at the lower pressure levels. The Reynolds numbers are not sufficiently low to attribute this discrepancy to pitot tube viscous effects. Small leaks, instrumentation zero drift, or pneumatic system outgassing are more likely the causes. Any effect of pitot pressure sensitivity to the ±10-deg angle range was covered by data scatter with no corrections. An accuracy within ±1% is indicated for the pitot pressures.

Figures 5 and 6 present the probe Mach number calibration. These plots show the ratio of the cone static pressure (from the two side ports pneumatically siamesed together) to the probe pitot pressure, $\overline{P}_c/P'_t$, vs the calibrated tunnel Mach number. The data points on Fig. 5 show the sensitivity of this pressure ratio to flow angularity in the orthagonal plane. Figure 6 presents faired values of the same data for zero-flow angularity, and compares it with theoretical values.

The effect of both bow shock wave detachment and Reynolds number are apparent in both of these plots. At the higher Mach numbers, where the bow shock wave would be attached to a sharp cone, all the data lie above the theoretical value, by an increasing amount with decreasing Reynolds number. This effect is attributed to the Reynolds number effect on the boundary layer, increasing the effective cone angle. It is interesting to note that Stone's first order theory (Ref. 4) does not predict any effect of probe angle on $\overline{P}_c$, as shown by the curvature of lines fairing the data points on Fig. 5; his second-order theory (extrapolated to the 30-deg cone half-angle) somewhat overpredicts the angle effect shown by these data. For Mach numbers at and lower than theoretical bow shock wave attachment, the Reynolds number and angle effect trends are both reversed. The latter essentially transonic phenomenon is difficult to explain by theoretical analysis.

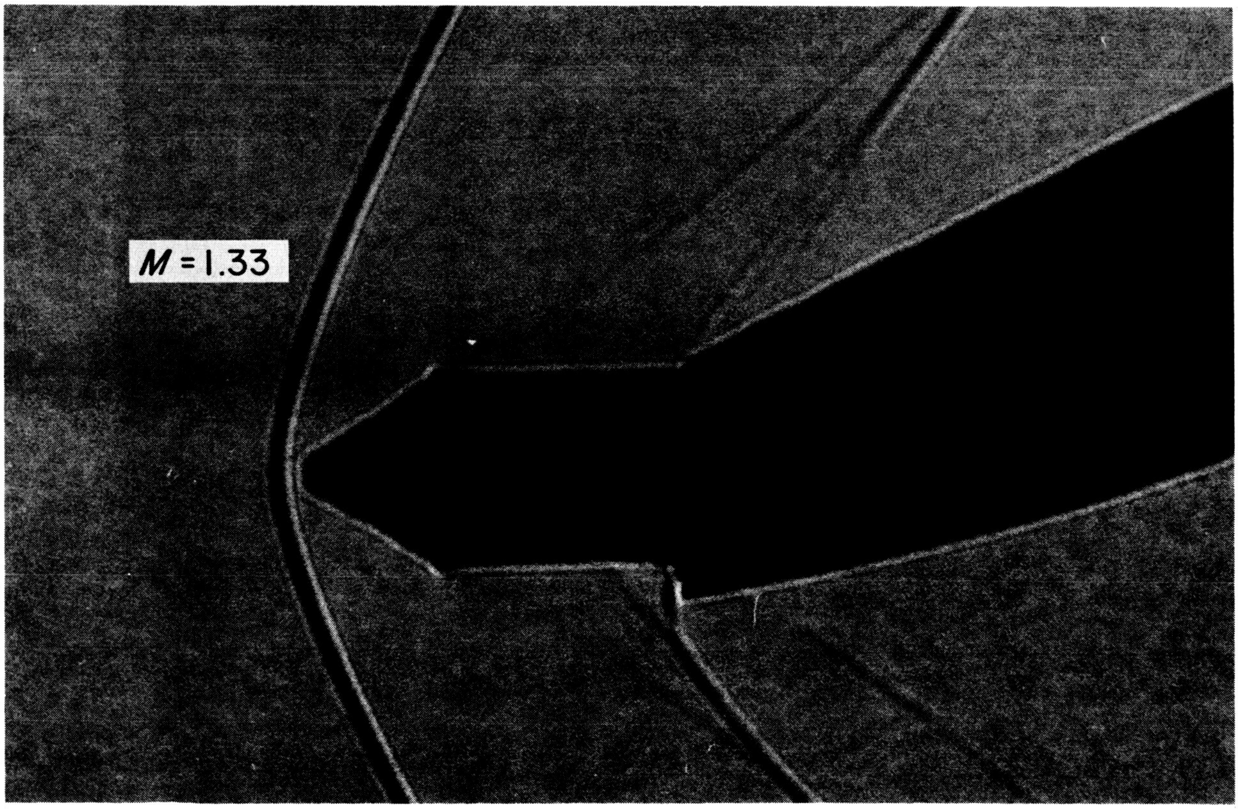
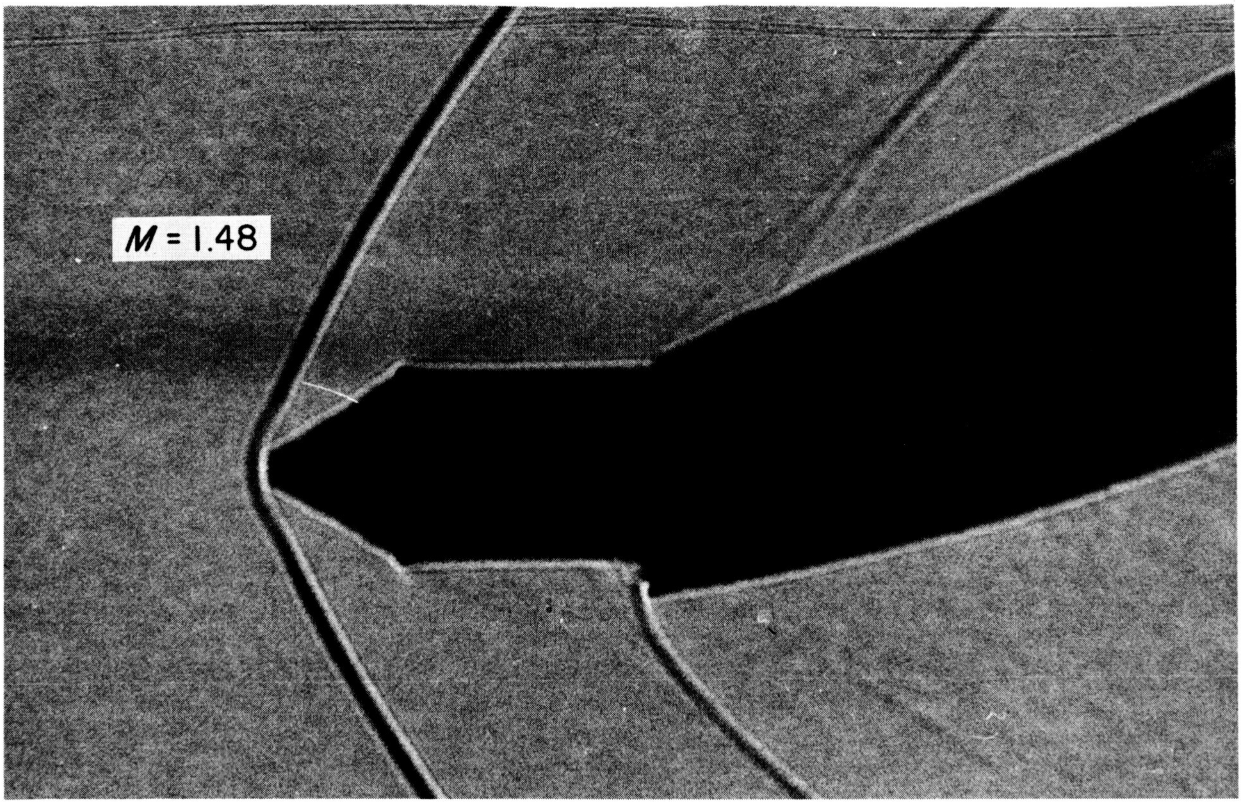


Fig. 4. Shadowgraph photographs of probe at various Mach numbers



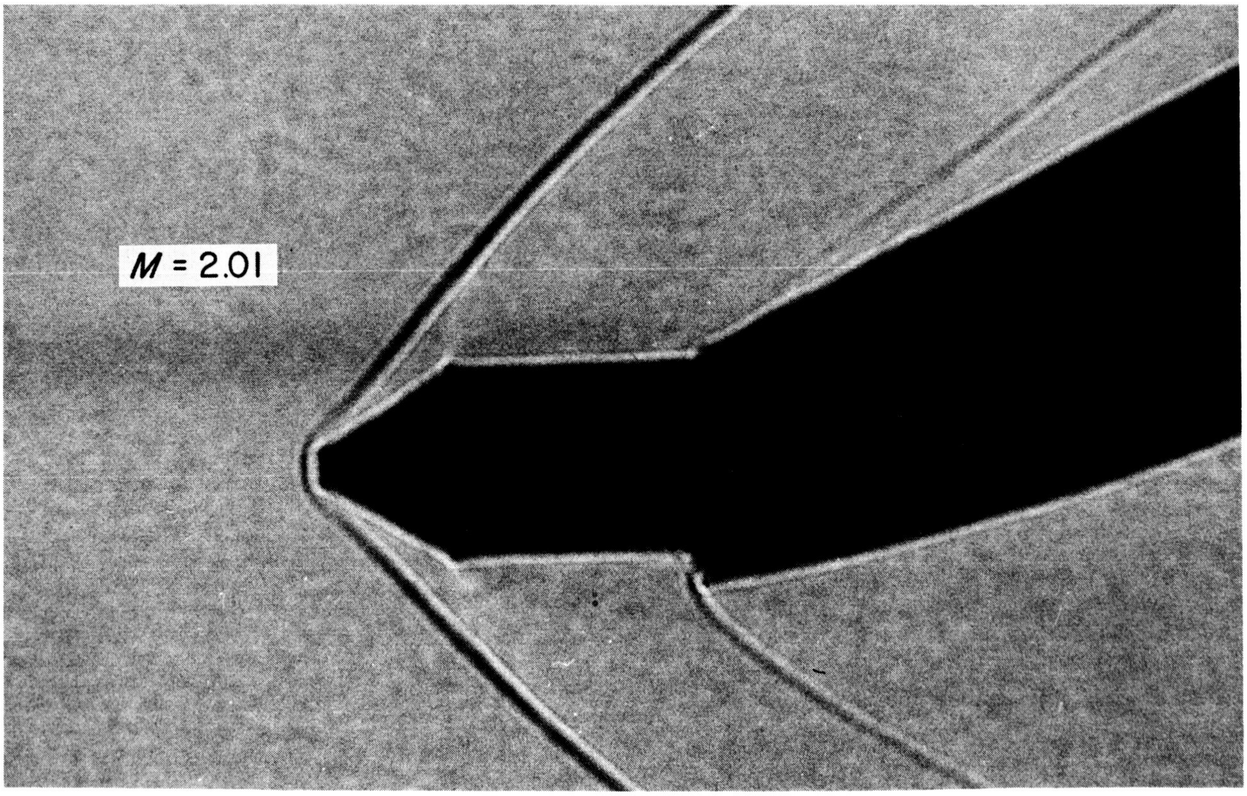
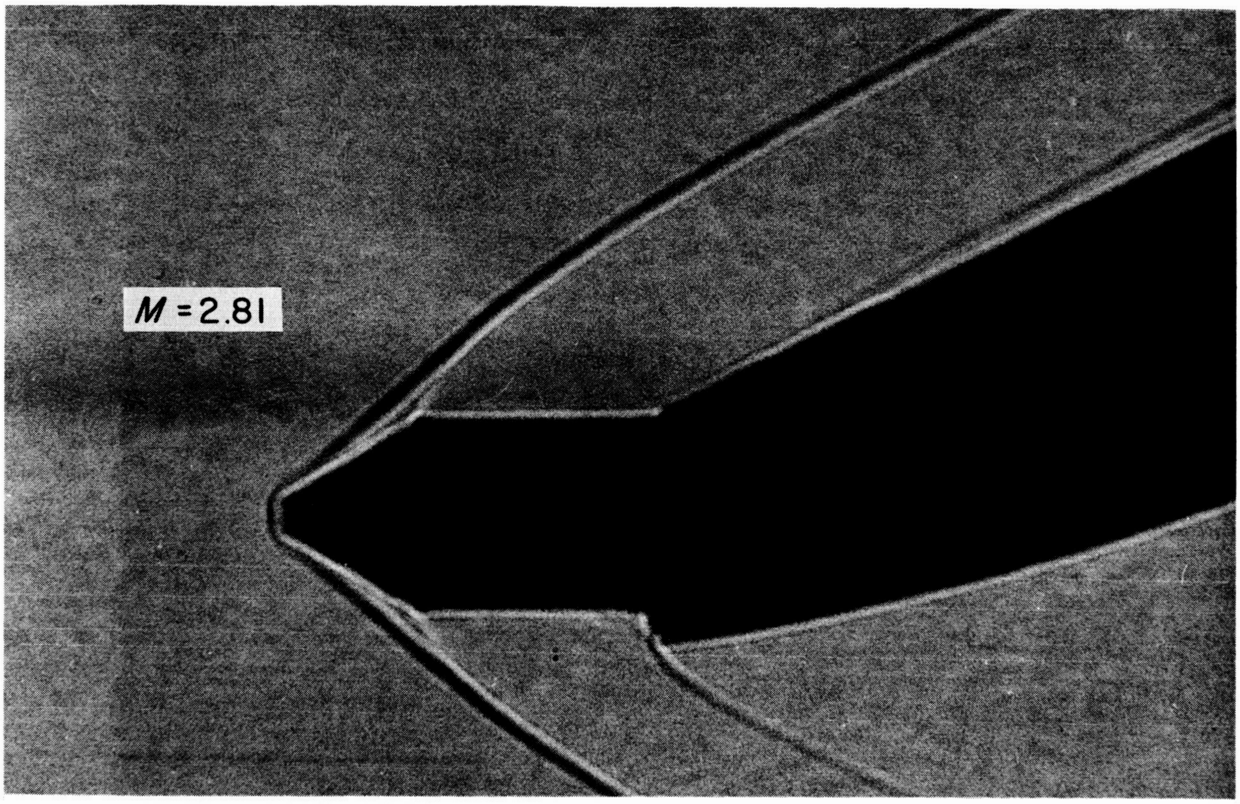


Fig. 4. Shadowgraph photographs of probe at various Mach numbers (Cont'd)



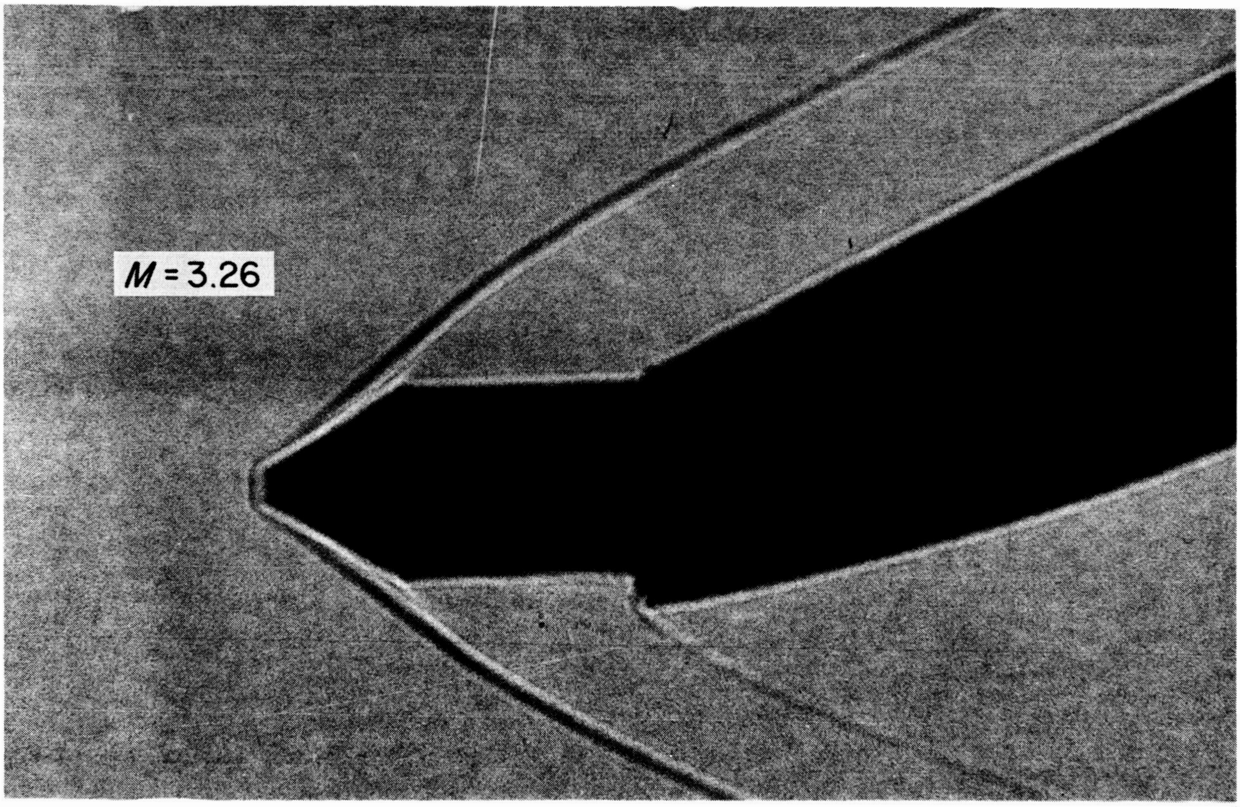


Fig. 4. Shadowgraph photographs of probe at various Mach numbers (Cont'd)

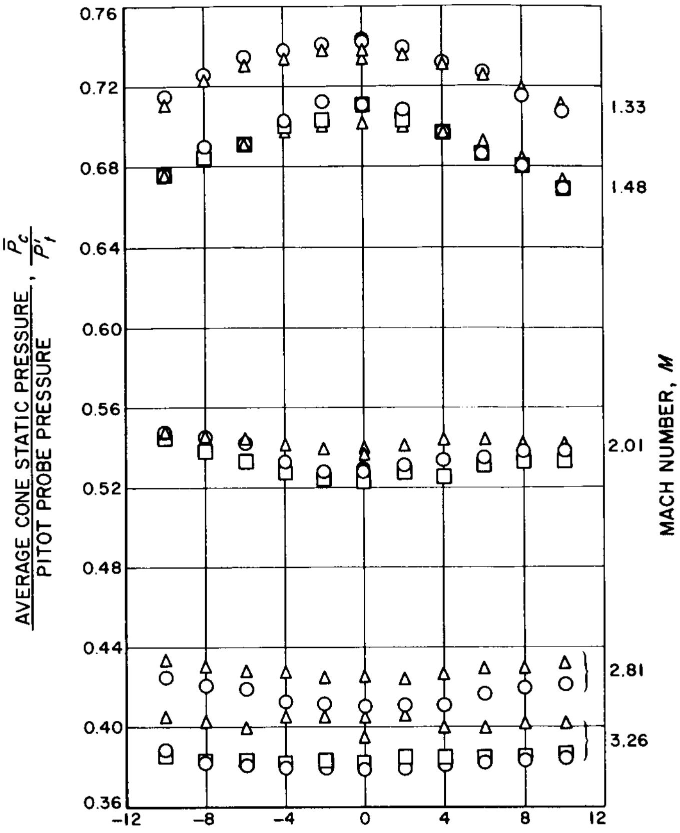


Fig. 5. Effect of flow angularity on probe Mach number calibration

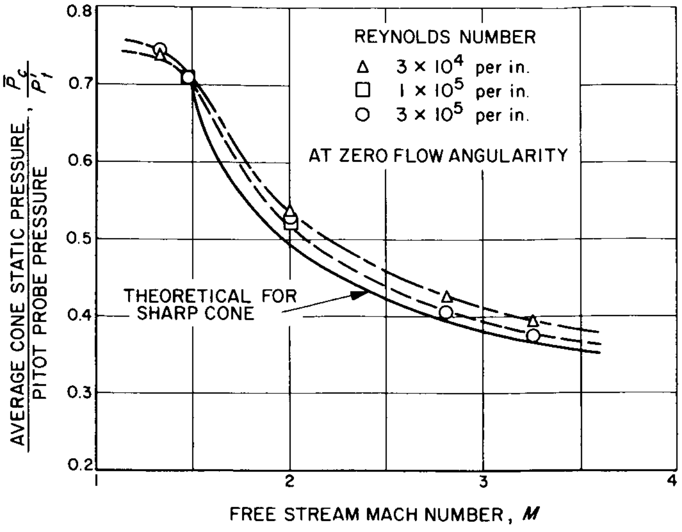


Fig. 6. Calibrated Mach number sensitivity

Figures 7 and 8 present the probe flow angularity calibration. These plots show the ratio of cone static pressure difference (top to bottom) to the probe pitot pressure, $\Delta P_c/P_t'$, vs flow angle. Figure 7 shows the data points as recorded; Fig. 8 summarizes this information as a sensitivity ratio vs Mach number and compares it to theoretical values.

Figure 7 shows the angular response of this probe reasonably linear over the ±10-deg range examined. However, a small but definite deviation pattern is apparent. Several anomalies are apparent in these data over and above the indicated data scatter, the most obvious being their failure to pass through the origin. The indicated flow angles for the zero value of $\Delta P_c/P_t'$ approaching 3 deg are greatest at the lower Reynolds numbers (lower pressures) and higher Mach numbers. It is difficult to imagine the test section flow angularity or geometric probe misalignment even approaching this magnitude; a more likely explanation is among the following:

1. The asymmetrical probe support (Fig. 2) may have had an influence upstream through the subsonic boundary layer, too small to be observed on the shadowgraphs. The low Reynolds numbers would aggravate this phenomenon.
2. Small manufacturing imperfections, such as asymmetry of the cone surface roughness or pitot-orifice-edge sharpness, influenced the cone boundary layer making the aerodynamically effective cone angle asymmetric. Both the relative shortness of the conical surface and the low Reynolds numbers would aggrevate this phenomenon, and could make it somewhat unpredictable.

A second anomaly, the fact that Reynolds number affects the probe angular sensitivity about ±20% semi-irregularly around the theoretical values (far greater than the apparent data scatter), tends to substantiate this hypothesis. A detailed examination of the data indicates that these anomalies were not caused by leaks or outgassing in the pressure instrumentation. While it appears there may be a pattern to these deviations, insufficient data were obtained to establish the cause. The probe was not checked in an inverted position to resolve the above analysis.

Observations during the calibration and application of this probe indicated the pneumatic time lag was not negligible. Particularly at the lower pressure levels, time approaching one minute was required to attain obvious data stabilization. All data were read several consecutive times to minimize errors from this source.

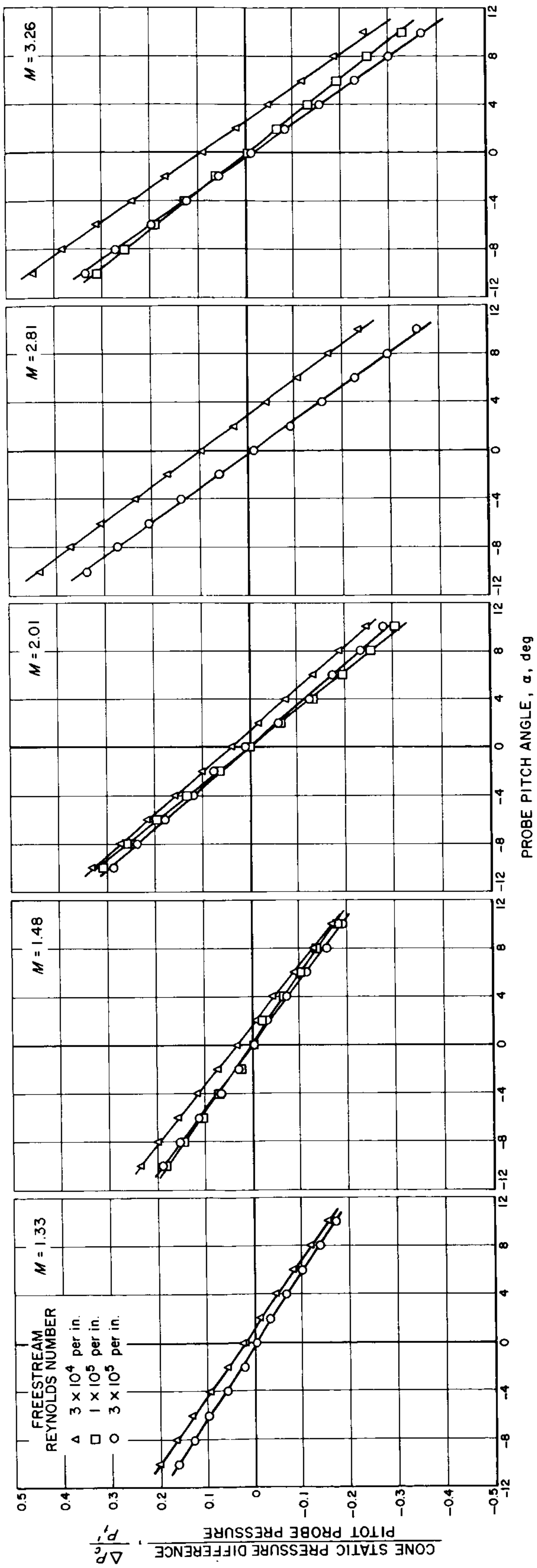


Fig. 7. Probe flow angularity calibration

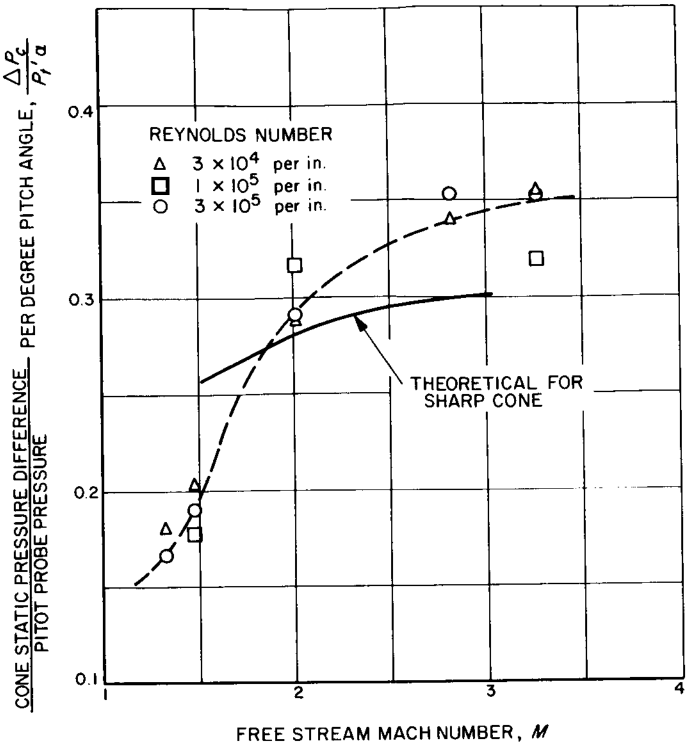


Fig. 8. Calibrated flow angularity sensitivity

IV. CONCLUSIONS

The data show that a cone pressure can be used through the bow shock wave detachment Mach number region when experimental calibrations are available. The effects of Reynolds number in the 10^3 region are apparent. This probe, the geometry of which was compromised in the interest of compactness, may be expected to yield the following accuracies when the calibrations are applied with care:

Pitot Pressure: ±1%

Mach Number: ±0.05

Flow Angle: ±0.3 deg if zero check can be made
±1.0 deg within the range of experimental calibration

It may be noted that, while the data of Ref. 2 applies to a 40-deg rather than a 60-deg total angle cone, the data trends and departures from theoretical values are quite comparable in the two cases.

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