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Miniature, Fast-Response Five-Hole Conical Probe for Supersonic Flowfield Measurements

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Five-hole probes have been used successfully for several decades to measure Mach number, total pressure, and flow angularity of complex, three-dimensional supersonic flowfields. However, the time response of conventional five-hole probes is typically on the order of seconds. A new probe design incorporating internally mounted miniature piezoelectric transducers has improved the time response by more than two orders of magnitude from 5 s to 20 ms, while maintaining better than 1-mm spatial resolution. This probe has been calibrated over the range Mach 2–4, and uncertainties in derived flowfield quantities have been shown to be small. Sample measurements of a supersonic vortex have been made to demonstrate the capabilities of the probe.

Nomenclature

D = nozzle exit diameter
M = Mach number
P = pressure
P^* = nondimensional pressure
q = dynamic pressure
t = time
v = velocity
x, y, z = Cartesian coordinates
θ = pitch angle
τ = time constant
ϕ = roll angle

Subscripts

a = average
f = final value after step function
i = initial value before step function
s = static conditions
x, y, z = Cartesian components
0 = stagnation or reference conditions
1, 2, 3, 4, 5 = pressure orifice number

Introduction

FIVE-HOLE flow angularity probes are popular for flowfield measurements because of their relatively low cost and proven ability to make accurate measurements in three-dimensional flows. However, in a conventional five-hole probe, where pressures are measured by transducers located outside the wind tunnel, a time response greater than 1 Hz is difficult to achieve. As a result, inexpensive, detailed flowfield measurements are difficult to perform.

Five-hole probes have been used successfully in supersonic, three-dimensional flowfields by many researchers. Early work by Centolanzi[1] and Andrews and Sawyer[2] showed that the five-hole conical probe is a reliable means of measuring Mach number, total pressure, and flow angularity. In addition, these researchers developed the methodology for the determination of these flowfield values from the raw pressure data. In recent years, five-hole probe development has focused on decreasing the probe size and determining the optimum geometry for the probe tip. Gaillard[3] calibrated a conical five-hole probe with a tip diameter of 1.5 mm. In addition, Gaillard[3] and Brodetsky and Shevchenko[4] investigated the effect of cone angle for different freestream conditions and independently found the optimum to be a 30-deg semivertex angle. However, both studies noted that this angle was a compromise. This implies that the best semivertex angle for a given study depends on the details of the flowfield being considered.

The optimization of five-hole probe time response has only recently been considered. The main obstacle has been reducing the distance between the orifices at the tip of the probe and the pressure transducers. In the past, this distance was determined by the length of tubing needed to carry the pressure signal to transducers outside the wind tunnel. Recently, commercially-available, miniature fast-response piezoelectric transducers have made it possible to mount pressure transducers closer to the probe tip. Matsunaga et al.[5] built a probe with such a design for use in low-speed water flows. They determined that the time response of their probe was sufficient to measure the fluctuating flowfield, thus yielding simultaneous values of fluctuating velocity and pressure. Of course, in supersonic flowfields, all turbulent fluctuations occur at much higher frequencies than such a probe can resolve. However, the faster time response possible with probes of this type can speed flowfield surveys significantly.

These factors provided the motivation to design a miniature, fast-response five-hole conical probe. Such a probe should be as small as possible to obtain excellent spatial resolution. However, the main motivation is to improve the time response so that detailed measurements in three-dimensional flows can be performed in a time-efficient manner. This is particularly important for intermittent facilities where measurements with traditional five-hole probes are not practical. The design, calibration, and accuracy of such a probe are described below.

Probe Design

Probe Tip and Body

A drawing and photograph of the conical probe tip are shown in Figs. 1a and 1b, respectively. The front view of the tip shows the numbering convention of the pressure orifices. The probe tip has a diameter of slightly over 1 mm with orifice spacing of 0.4 mm and a semivertex angle of 30 deg. This small tip provides excellent spatial resolution and is especially useful in flows with large gradients. Details of the fabrication process of such probe tips are given in Treaster and Houtz.[6] The body of the probe, shown in Fig. 2, is designed such that the distance between the five transducers and the probe tip is small. Mini-

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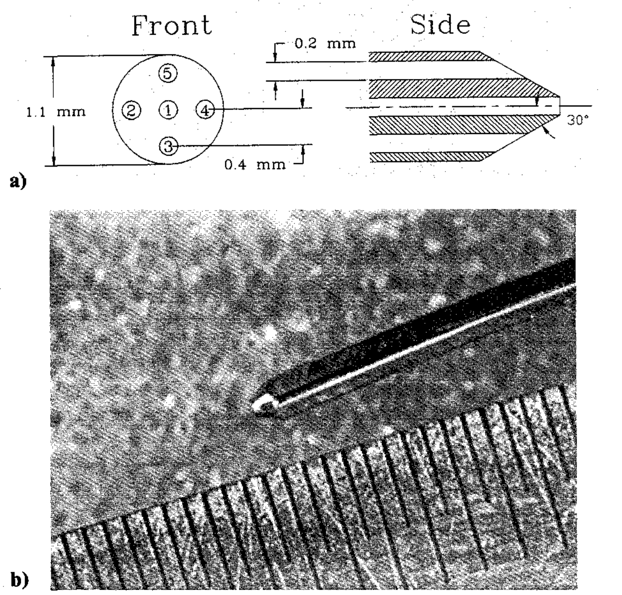


Fig. 1 Five-hole conical probe tip: a) pertinent dimensions and numbering convention of the pressure orifices; b) image of the probe tip (scale increment is 0.5 mm).

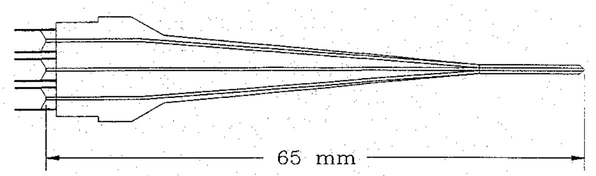


Fig. 2 Probe design minimizes the distance between the tip and the transducers.

mizing this distance is somewhat limited by the need to streamline the probe and to insure that the flow in the vicinity of the probe tip is not affected by the diameter increase downstream. The resulting design has a distance from the probe tip to the transducer face of approximately 65 mm.

In addition to minimizing the tip-to-transducer spacing, the "dead" volume at the transducer/hypodermic tube interface, as shown in Fig. 3, is also kept as small as possible. This is done because the theoretical time response improves as the dead volume decreases.[7]

Pressure Transducers

Five Endevco Model 8507-50 miniature piezoresistive pressure transducers were mounted in the probe body with RTV adhesive as shown in Fig. 3. Excitation to and signals from the transducers were carried via small shielded, grounded wires which were routed to the transducers from outside the tunnel. Similarly, reference pressures were supplied to these differential transducers by means of tubes connected to a vacuum pump located outside the tunnel. Pertinent characteristics of these transducers are listed in Table 1. Piezoresistive pressure transducers were chosen because they are commercially available in small sizes. Compared to other miniature piezoresistive pressure transducers, the selected transducers have high sensitivity and a large temperature compensation range. The latter is especially important when the transducers are used in blowdown facilities and flowfields with significant temperature variations.

Response-Time Characteristics

Benchtop tests were performed to determine the time response of the probe. The probe was mounted in a freejet downstream of a variable-speed, rotating chopper which generated a square-wave input pressure signal. The rise time of the square-wave signal proved to be much faster than the response time of the probe. The time history of the pressure from the central orifice P_1 was nondimensionalized using

$$P^* = \frac{P_1 - P_f}{P_i - P_f} \tag{1}$$

Figure 4, which shows the nondimensional pressure data plotted vs time, demonstrates that the probe has responded to 99% of the step input within 20 ms. Also shown in the figure as a solid line is a least-squares curve fit of the data to the step-input response function of a first-order system given by

$$P^* = e^{-(t - t_0)/\tau} \tag{2}$$

The curve fit yields a value of $\tau = 4$ ms. Normally, pressure probes are treated as second-order systems. However, in highly damped cases such as this, they reduce to first-order

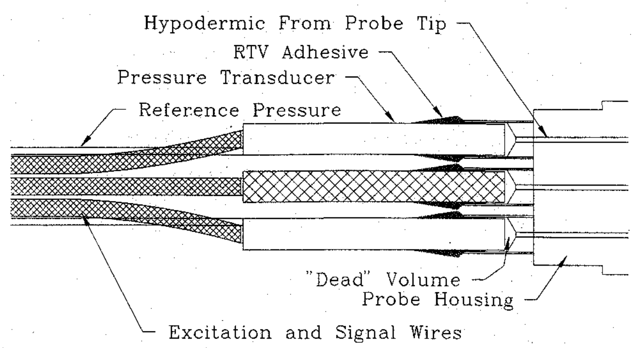


Fig. 3 Details of the installation of the pressure transducers.

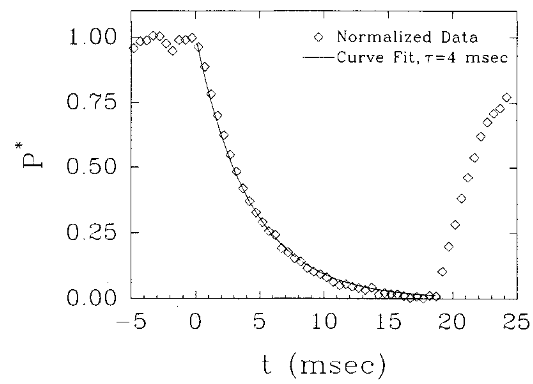
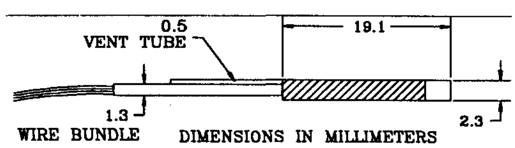


Fig. 4 Step input time response of the probe.

Table 1 Characteristics of the piezoelectric transducers used in the probe design



Model 8507-50

Range, psig	0–50
Compensated temperature range, °C	−54 to +121
Linearity	0.25% full scale
Dead volume, cm^3	0.0008
Excitation, V, dc	10
Resonant frequency, kHz	270
Electrical configuration	Piezoresistive bridge
Sensitivity, mV/psi	6

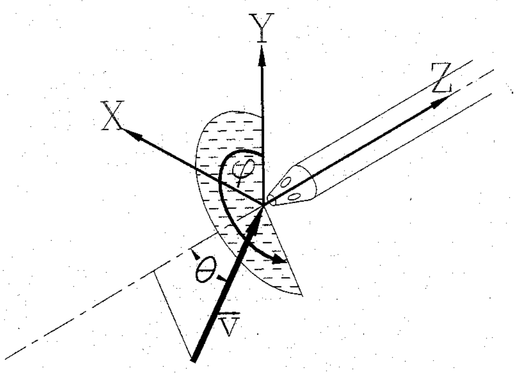


Fig. 5 Five-hole conical probe coordinate system.

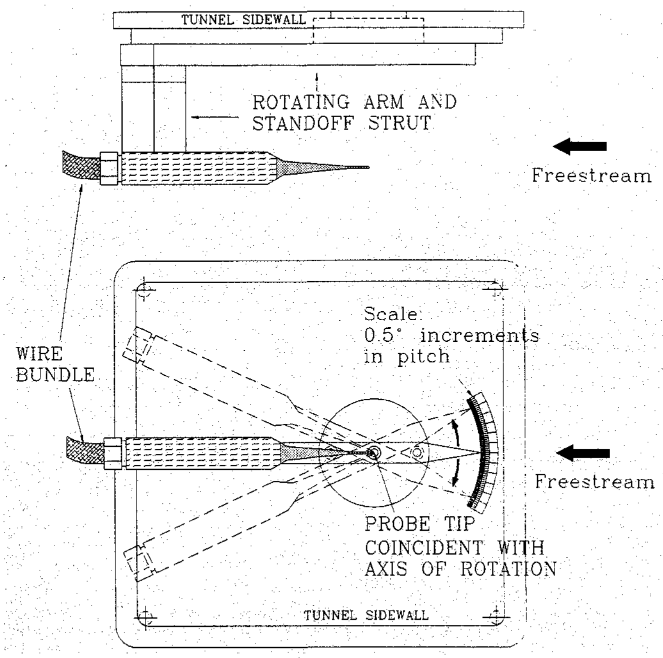


Fig. 6 Variable pitch probe support used for the five-hole conical probe calibration: upper schematic is the top view, and the lower schematic is the side view.

systems. Identical analyses of the pressure signals from the other orifices yielded similar results.

In comparison, the same five-hole probe tip was fitted with 2 m of vinyl tubing which was routed to conventional pressure transducers. The 99% time response in this case was 5 s. Thus, installing the transducers in the probe body yielded an improvement of more than two orders of magnitude in time response. This response is sufficient to allow mean-flow measurements to be made as fast as the probe can be repositioned. Thus, the time required for a flow survey becomes limited by probe positioning time rather than by the response time of the probe itself.

Calibration

The probe was calibrated in the supersonic wind tunnel facility of the Penn State University Gas Dynamics Laboratory. An asymmetric sliding block nozzle provides a continuously variable Mach number range of 1.5–4. The calibration requires that the orientation of the velocity vector v with respect to the probe axis be uniquely determined. A spherical coordinate system which uses pitch angle θ and roll angle ϕ, as shown in Fig. 5, was chosen for this purpose. Hence, the probe was subjected to known freestream conditions for various θ and ϕ combinations. Figure 6 shows a diagram of the probe support used in the calibration to vary θ, while adjustments in ϕ were made manually by rotating the probe about its axis. The calibration was carried out at Mach 3 over a range in θ from -25 to $+25$ deg in 2.5-deg increments and in ϕ from 0 to 350 deg in 10-deg increments. The results of this calibration are shown in Fig. 7. Here, the calibration data points, each of which represents a unique combination of θ and ϕ, are plotted vs flow angularity parameters, $(P_2-P_4)/q$ and $(P_5-P_3)/q$. Some asymmetry in this calibration is expected due to imperfections in tip construction. In addition to the Mach 3 calibration, a subset of the full θ, ϕ calibration was performed at Mach 2 and Mach 4 to assess Mach number variability. In Fig. 8, calibration data for eight discrete values of roll angle are compared at Mach numbers of 2, 3, and 4. The calibration points, for a

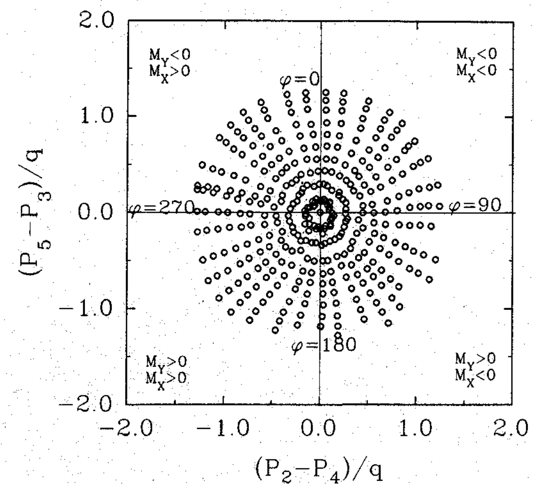


Fig. 7 Flow angularity map determined from calibration at Mach 3: each point is a unique θ, ϕ combination.

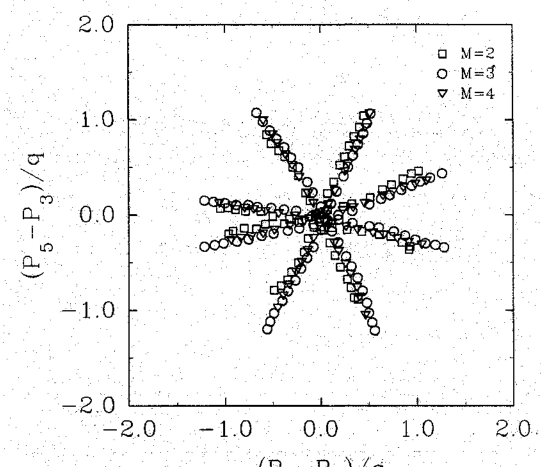


Fig. 8 Flow angularity calibration map is insensitive to Mach number variations over the range of 2–4.

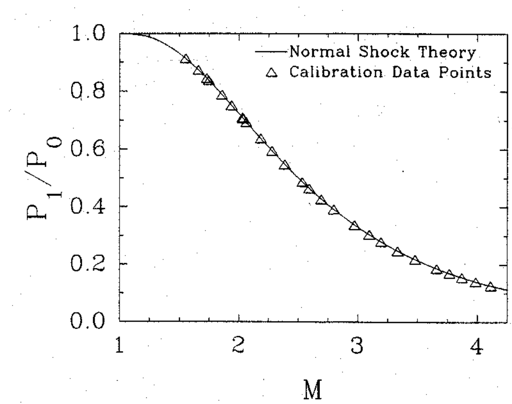


Fig. 9 Ratio P_1/P_0 agrees with normal shock theory.

fixed roll angle, lie essentially along the same line independent of Mach number. This indicates that normalizing the calibration data in this manner yields little variability due to Mach number as expected.[1,2]

Several measurements were performed with the probe aligned with the freestream velocity vector to determine the relationships between the measured five-hole probe pressures, the local Mach number M, and the local total pressure P_0. Figure 9 shows that the relationship between M and the ratio P_1/P_0 agrees with the total pressure ratio across a normal shock as predicted by theory. Figure 10 shows the relationship between M and P_a/P_1, where P_a is the average of the four peripheral "cone" pressures P_2, P_3, P_4, and P_5.

As mentioned previously, Figs. 9 and 10 were obtained with the probe aligned with the freestream velocity vector. In a general testing environment, however, the probe will not be at zero incidence with respect to the flow. Thus, as described in the next section, corrections to the values of P_a/P_1 and P_1/P_0 are necessary when θ is nonzero. An example of the correction factors for P_a/P_1 [i.e., $(P_a/P_1)_{\theta,\phi}/(P_a/P_1)_{\theta=0}$] and P_1/P_0 [i.e., $(P_1/P_0)_{\theta,\phi}/(P_1/P_0)_{\theta=0}$] vs flow angularity parameters at Mach 3 are shown in Figs. 11a and 11b, respectively. In general, these correction factors are functions of Mach number as well as flow angularity.

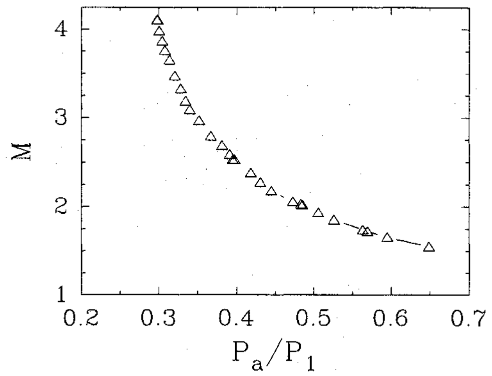


Fig. 10 M **is a function of the ratio** P_a/P_1**.**

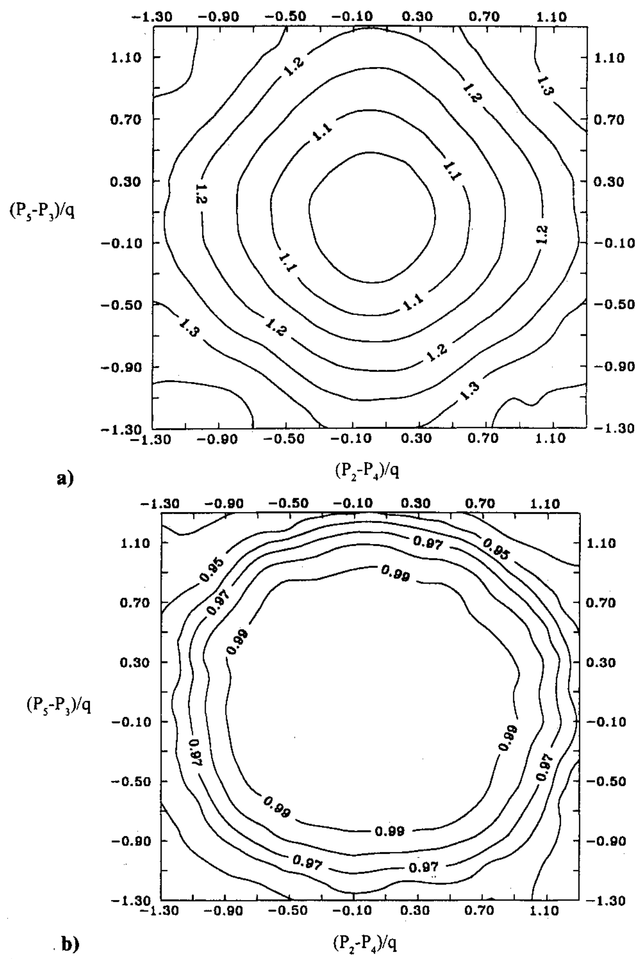


Fig. 11 Maps of flow angularity correction factors at Mach 3 for P_a/P_1 **and** P_1/P_0 **as a function of the flow angularity parameters: a)** $(P_a/P_1)_{\theta,\phi}/(P_a/P_1)_{\theta=0}$**, and b)** $(P_1/P_0)_{\theta,\phi}/(P_1/P_0)_{\theta=0}$**.**

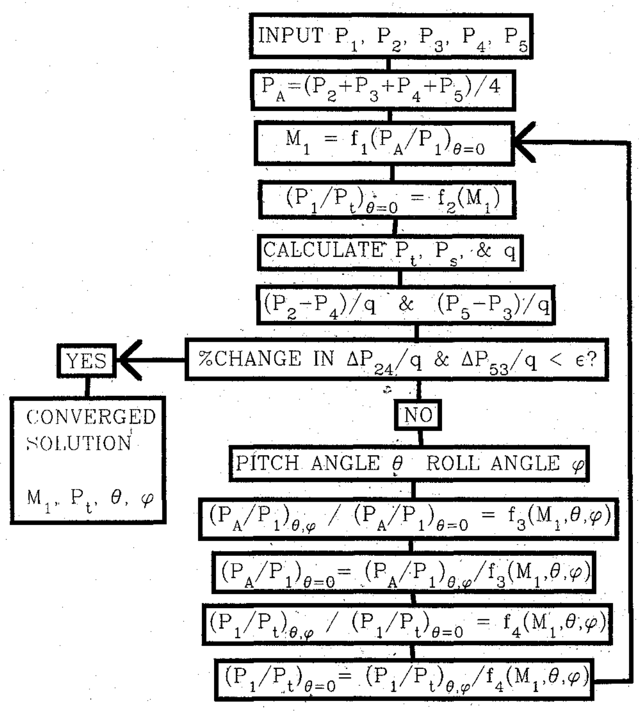


Fig. 12 Flowchart of five-hole conical probe data reduction scheme.

Data Reduction

Procedure

The reduction of test data follows the method of Centolanzi.[1] A flowchart of this process is shown in Fig. 12. In short, one first calculates P_a and the ratio P_a/P_1. Next, θ is initially assumed to be zero and an estimate of M is determined as a function of P_a/P_1 as shown in Fig. 10. From Fig. 9, P_1/P_0 is then determined from M, whereas P_0, P_s, and q are calculated using the isentropic relations. Then, the flow-angularity parameters $(P_5-P_3)/q$ and $(P_2-P_4)/q$ are computed and used to find θ and ϕ from the calibration map of Fig. 7. It is now necessary to correct the previous assumption that $\theta=0$. The correction factors for P_a/P_1 and P_1/P_0 are determined from the calculated flow angularity parameters with maps such as those in Figs. 11a and 11b. Corrected values of P_a/P_1 and P_1/P_0 are now used to recalculate the quantities M, P_0, P_s, and q. The updated value of q is then used to recompute the parameters $(P_5-P_3)/q$ and $(P_2-P_4)/q$. If these parameters have changed by more than a small tolerance, then the iteration process continues.

Upon convergence, the x, y, and z components of Mach number may be determined from the values of M, θ, and ϕ. These component Mach numbers are given by the following:

$$M_x = -M\sin(\theta)\sin(\phi)$$
$$M_y = -M\sin(\theta)\cos(\phi) \tag{3}$$
$$M_z = M\cos(\theta)$$

This data reduction procedure is automated in a Fortran code with look-up tables in place of the graphs described earlier. This code shows rapid convergence (typically four itera-

Table 2 Estimated rms uncertainties associated with the five-hole conical probe measurements

±Rms error	Mach number	Total pressure, %	Static pressure, %	M_x	M_y	M_z
$M=2$	0.07	6	5	0.02	0.02	0.07
$M=3$	0.07	4	6	0.03	0.03	0.06
$M=4$	0.11	8	7	0.04	0.04	0.10

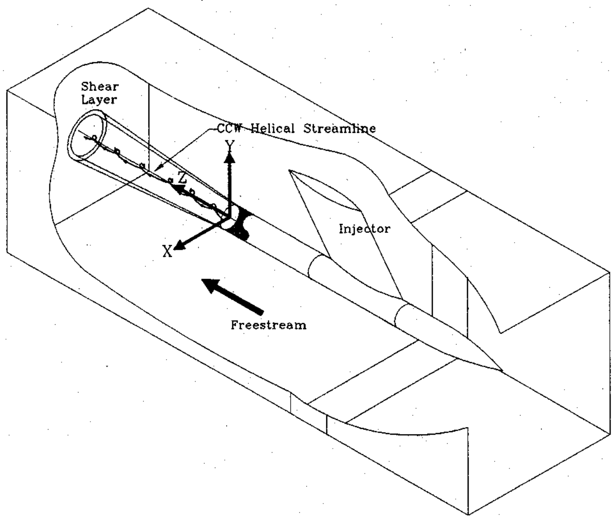


Fig. 13 Schematic of a supersonic streamwise vortex flowfield measured with the five-hole conical probe.

tions) so the computational overhead of the data reduction is not excessive.

Data Accuracy

The estimates of uncertainties inherent in the probe measurements and data-reduction scheme are summarized in Table 2. Root-mean-square uncertainties are given at freestream Mach numbers 2, 3, and 4 for M, P_0, and P_s, and the three Cartesian Mach number components (M_x, M_y, and M_z). These uncertainty estimates include both accuracy and repeatability, as well as transducer-calibration errors and interpolation errors inherent in the data-reduction process. The uncertainties of Table 2 were obtained by consideration of several example test cases over a range of conditions.

The pressure accuracy is on the order of ±5% at Mach 2 and 3, while the Mach number components may typically be measured with an accuracy of 0.05 or better. These values are somewhat higher at Mach 4 because the semivertex cone angle (30 deg for the present probe) is a compromise over the Mach number range. This leads to some deterioration of performance at the high Mach number end of the calibration.

The stated uncertainty estimates may be improved by a more detailed calibration, but are sufficient as shown for most purposes. However, note that certain local conditions may occur (such as an oblique shock wave intersecting the probe tip) which will result in much larger local errors than those indicated in Table 2.

Sample Data

Upon completion of the calibration, flowfield surveys of a Mach 3 streamwise vortex were taken with the miniature five-hole conical probe. A schematic of this flowfield is shown in Fig. 13. Figure 14 displays the results of a single 45 s traverse at a fixed Z/D location of 5.35. The probe was traversed in the x direction at a constant value of y such that the probe passed through the vortex core. Figure 14a shows the axial component of Mach number M_z, whereas Fig. 14b shows the M_x and M_y distributions. Since this survey is a horizontal cut through the core of an axisymmetric vortex, M_x and M_y may be interpreted as radial and tangential Mach numbers, respectively.

In addition to detailed, single traverses along a line, the fast time response of the probe allows for planar surveys of flowfields during a single 30 s test. For example, the vortical flowfield discussed was surveyed using a 5 × 15 grid measured over 50 s of testing time. Detailed contour plots of various quantities, such as the axial Mach number M_z shown in Fig. 15, can then be easily produced from the data.

These example surveys, taken in a flowfield with significant flow angularity, high radial gradients, and a range of Mach

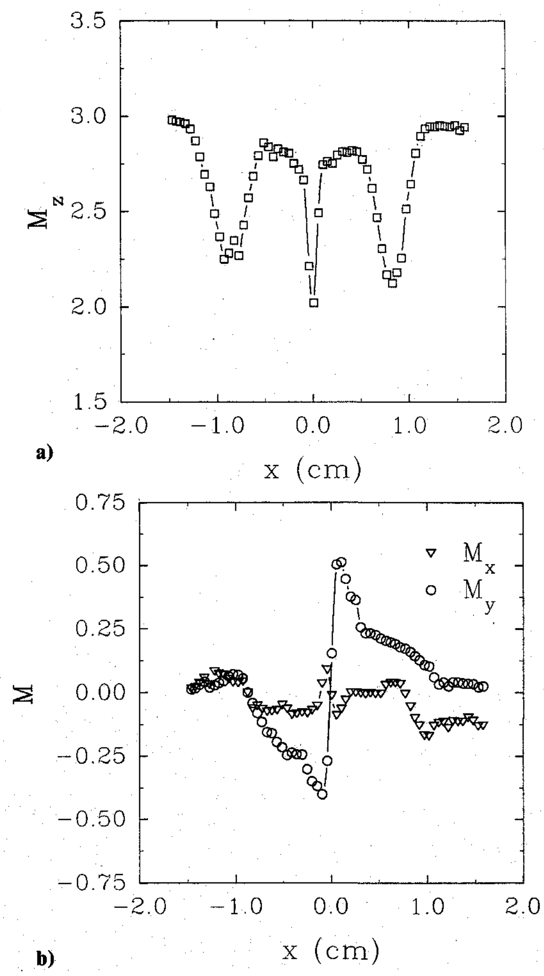


Fig. 14 Results of a single traverse of the five-hole conical probe through a supersonic vortex: a) M_z and b) M_x and M_y.

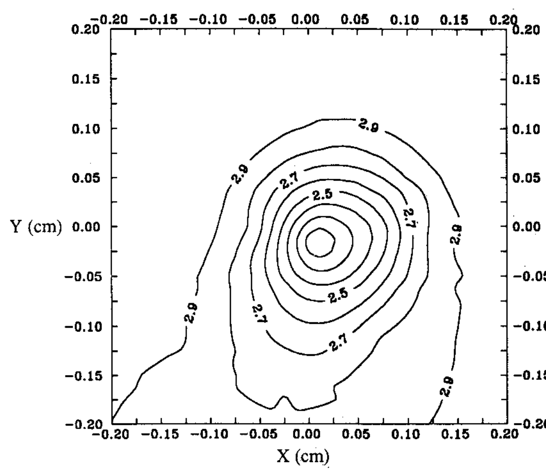


Fig. 15 Axial Mach number M_z contours obtained from a 5 × 15 grid of data points for a supersonic streamwise vortex.

numbers, serve to indicate the type of results which may be obtained with this five-hole probe. These sample data are taken from Cattafesta and Settles.[8] Note that these measurements, in conjunction with total temperature measurements, can also be used to determine density and flow velocity.

Conclusions

A miniature, fast-response five-hole conical probe which yields measurements of Mach number, total pressure, and flow angularity has been designed, calibrated, and used in flowfield surveys. The 30-deg semivertex angle conical probe has good spatial resolution (≈ 1 mm) and a time response ($\tau = 4$ ms) that is at least two orders of magnitude higher than that of conventional five-hole probes. This characteristic allows mean flowfield surveys to be completed rapidly, even in intermittent facilities. Thus, the added complexity in design and manufacture is justified by the significant reduction in testing time required. Furthermore, the uncertainties in the probe measurements have been shown to be small within the calibration range.

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