Velocity Vector Determination from Multiple-Sensor Pneumatic Probe Measurements

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Theme

DESIGN data for compressors are often derived from measurements made with multiple-sensor pneumatic probes. Although it is generally admitted that the presence of a probe alters the flow to some extent, few attempts have been made to evaluate and to correct probe readings for the interference that they produce. The goal of the present work was to measure the velocity distribution between blade rows of a small transonic compressor (11-in. o.d. and 2-in. blade height), operating subsonically. Different probes were used in the compressor annulus and were also applied to measure uniform temperature flows in pipes, free jets, and annular ducts. A useful method for representing probe characteristics and correcting for the presence of flow boundaries was devised. The probe calibration away from boundaries was represented by two interrelated polynomials for the pitch angle and velocity magnitude. In application, the probe-pressure measurements were reduced, using a computer off-line and distribution of temperature (measured separately) to velocity magnitude and pitch angle. The departure of probe measurements near a flow boundary was then treated as being a self-induced flow effect. The effect was examined in known flows and represented analytically. The analytic representation of the calibration and of the corrections allowed a routine reduction of probe data from compressor surveys. The method can be applied generally to probes having four or five sensors for the measurement of pitch angle, yaw angle, and velocity magnitude. The measurements made with different probes near to flow boundaries showed that errors could be surprisingly large or very small depending on particular design features. A new probe which also incorporated a temperature sensor was designed and used successfully to transonic Mach numbers.

Contents

We are concerned with probes that can be inserted through small appertures to determine flow velocity in both magnitude and direction. An approximately cylindrical probe for this purpose is shown in Fig. 1. The probe has five ports that are so arranged that one measures close to impact pressure (p_1), two side ports (p_2 and p_3) measure close to static pressure when the cylinder has been rotated so that the two pressures are equal, and the fourth and fifth (p_4 and p_5) measure pressures which depend largely on the pitch angle when p_2 and p_3 are balanced. A variety of tip geometries and sensor arrangements can be found; however, common in their application is the rotation to balance two side pressures in order to measure yaw angle on a calibrated scale, and the requirement to relate the probe pressures to velocity magnitude and pitch angle by calibration in a controlled flow. What is presented in Ref. 1 can be adapted to probes of different geometries in which these two features are present. It is not required that the probe measure true impact or true static pressure.

The calibration of the probe relates the measured pressures to the nondimensional velocity magnitude x and pitch angle ϕ through the relations

$$(p_1 - p_{23})/p_1 = F'_\theta(x,\phi) \tag{1}$$

and

$$(p_4 - p_5)/p_1 = F'_\phi(x,\phi) \tag{2}$$

The functions F'_θ and F'_ϕ were obtained as analytic approximations of measurements made in a large free jet over a controlled range of values of x and ϕ. However, the solution for x and ϕ when the values of F'_θ and F'_ϕ were known (as in the application of the probe in an unknown flow) proved to be difficult. Consequently the calibration data were used to establish polynomial approximations for

$$x = x(F'_\theta, \phi) \tag{3}$$

where the polynomial was in F'_θ with coefficients that were polynomials in ϕ, and for

$$F'_\phi = F'_\phi(x,\phi) \tag{4}$$

where the polynomial was in ϕ with coefficients that were polynomials in x. Newtonian iteration was used to obtain the values of x and ϕ from Eqs. (3) and (4) from measured values of F'_ϕ and F'_θ. An initial estimate of zero pitch angle gave convergence in less than five iterations. Calibration data were represented analytically to within the accuracy of the data.

In compressor applications, the influence of the presence of flow boundaries on the probe behavior must be evaluated. This was demonstrated clearly in the results of tests in which six different probes were used to survey across a 7-in. diam

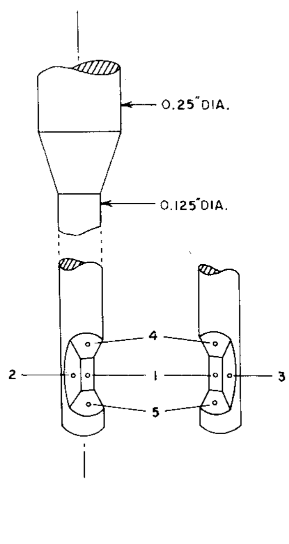

Fig. 1 Schematic showing the arrangement of pressure sensors on a typical cylindrical multiple-sensor probe.

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Index categories: Airbreathing Propulsion; Subsonic Flow; Research Facilities and Instrumentation.

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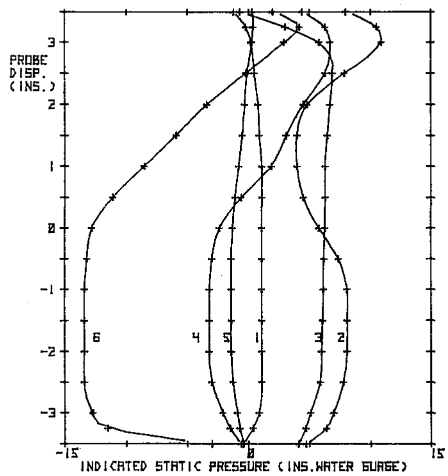

Fig. 2 Radial surveys of a 7-in.-diam free jet. Test conditions: exit pressure = atmospheric; stag. pressure = 60 in. water gage; and stag. temperature = 570°R. Probe description: 1) Prandtl probe; 2) United Sensor Corp. DA-125 (cylindrical); 3) United Sensor Corp. DC-125 (cone); 4) United Sensor Corp. WT-250 (35 deg cyl. wedge); 5) NASA 8 deg wedge probe; and 6) NASA P-T probe (60 deg cyl. wedge).[2]

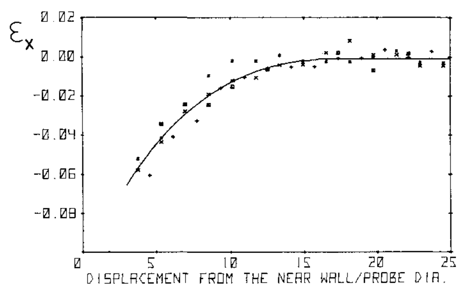

Fig. 3 Correlation of the ratio of the probe-induced to actual velocity ϵ_x in a 10-in.-diam pipe flow. (Symbols are for centerline Mach numbers ranging from 0.14 to 0.24).

axisymmetric free jet at atmospheric pressure. The measured profiles of "indicated" static pressure ($p_2 = p_3$ for the probe in Fig. 1) are shown in Fig. 2. The stagnation pressure was 60 in. of water (gage) over a 5-in.-diam uniform core. It can be seen that cone, wedge, and Prandtl probes indicated a constant static pressure across the core to within 1% of the dynamic head. The Prandtl and 8-deg wedge probes also indicated the correct static pressure to within 1% of the dynamic head. In contrast, the three cylindrical probes designed for velocity vector determination, and to the constraint of using a ¼-in.-diam access port, indicated much larger variations in static pressure. All three probes, however, recorded impact pressures that were uniform and agreed with the Prandtl probe over the core.

The feature that was common to the three cylindrical probes was that the "indicated" static sensors were located on a lateral continuation of the probe shaft. Referring to Fig. 2, there was a geometrical similarity between probe 4 and probe 6.[2] Both probes had sensors located on the side of a blunt wedge near the probe tip. The characteristic behavior of the probes was correspondingly similar. The probe shown in Fig. 1 (probe 2 in Fig. 2) gave less total variation across the core and measured the mean value approximately on the centerline. On this probe, the sensors were located further from the tip and in a shallow groove in the probe surface.

What should be noted is that the effect of flow boundaries can be large for probes with sensors located on and not forward of the probe shaft. It is suggested that the effect is the result of cross flow, perhaps associated with vortex shedding at the probe tip. It is consequently difficult to perform a calibration of a cylindrical probe that is truly free of boundary effects. It is noted that probe 6 in Fig. 2 was inserted fully 3 in. across the uniform jet core before a uniform flow was indicated. Very similar results were obtained in surveys of the flow in an 8-in.-diam pipe.[1] Recently, probes have been designed for which the effect of flow boundaries is small.[3]

Two approaches are reported in Ref. 1 to correct for the effect of flow boundaries. Subsonic measurements in a shallow annulus (2-in. deep) downstream of a transonic axial compressor rotor were made with two different probes. The velocities derived using calibrations established in a 7-in.-diam free jet disagreed by about 13% over the complete profile. Calibrations of the two probes were then obtained as functions of radial displacement in a steady axial flow in a geometrically similar annulus. The calibrations were represented as a function of the normalized displacement and applied to reduce the compressor measurements. Agreement in the velocities derived from the two probes was obtained to within 3% over 70% of the profile.

A second approach was taken for measurements made in a large compressor annulus (36 in. o.d. by 7.2. in. deep). In this case, the effect of flow boundaries was of importance only for some distance from the hub and tip walls. It was argued that near to the wall, the probe itself induces a change in the velocity and the pitch angle, which it then measures. The ratio of the induced to the actual values of the velocity ϵ_x and pitch angle ϵ_ϕ were measured as a function of the probe displacement in a 10-in.-diam pipe flow, and in an axial flow in the large compressor annulus. The results for different velocities in the pipe flow were analytically correlated as shown in Fig. 3 for the near-wall region, and the correlation was found to represent well the measurements made in the compressor.

Further measurements in different flows are required to determine the usefulness of these approaches for other flow geometries. However, the computational techniques now generally available permit the routine use of multiple-sensor probes with nonlinear and interrelated characteristics. As a consequence, a reasonable evaluation of corrections for flow boundaries has been shown to be possible.

Acknowledgment

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