AIAA JOURNAL
Vol. 45, No. 6, June 2007

Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes should not exceed 2500 words (where a figure or table counts as 200 words). Following informal review by the Editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Development of a 12-Hole Omnidirectional Flow-Velocity Measurement Probe

Vijay Ramakrishnan* and Othon K. Rediniotis†
Texas A&M University, College Station, Texas 77843-3141

DOI: 10.2514/1.27459

I. Introduction

MULTIHOLE pressure probes are widely used in aerodynamic flow studies. Their general design and working principles have been widely studied and are well documented [1–5]. The most popular ones, the five- and seven-hole probes, measure flow velocity up to 55 and 70 deg, respectively, from the probe axis. A spherical probe with 18 holes [6] was developed recently that considerably reduced the range limitation by measuring flows up to nearly 160 deg from the probe axis.

The 18-hole probe was essentially an extension of the five-hole probe design. Its design was driven by the necessity to use the reduction method of a conventional five-hole configuration, the only method available at the time. Consequently, over a large region of its measurable range, there are more than four ports available with valid (attached-flow) pressure data. Because there are typically only four unknown variables during flow measurement, there is a redundancy in the number of ports in the 18-hole probe. When new calibration and reduction algorithms were developed by the authors [7] for tackling any generic arrangement of ports, it became possible to consider designing an optimized version of the omnidirectional probe, which would be free of redundancy. These algorithms do not depend on the axisymmetry of the port distribution pattern to define the nondimensional pressure coefficients.

In this work, an optimal spherical-probe design for omnidirectional flow measurement is presented. The calculation of the four unknown flow quantities (two flow angles, flow speed, and static pressure) is achieved with the minimum necessary number of ports on the probe tip. This has significant implications in the instrument's spatial resolution, frequency response as well as cost of interfacing, and usage. A prototype probe was fabricated with a spherical tip diameter of 0.375 in. (9.53 mm) and a sting diameter of 0.122 in. (3.1 mm). The probe was calibrated and its measurement accuracy assessed in a calibration facility.

Received 23 August 2006; revision received 22 January 2007; accepted for publication 27 January 2007.

*Graduate Research Assistant, Department of Aerospace Engineering.
†Professor, Department of Aerospace Engineering. Associate Fellow AIAA.

II. Design and Fabrication

A classic question in physics (known as Thomson's problem) consists of finding the equilibrium arrangement of N unit charges on a sphere such that the Coulombic potential is a minimum [8]. The design of the 12-hole probe (i.e., the pressure-port arrangement on the spherical probe surface) is based on this principle. In other words, the goal of the design was to find the smallest N such that for any stagnation point on the sphere, there are always four ports within ~85 deg (the laminar flow separation angle for a sphere) from it. This is achieved with $N = 12$, with the ports located at the vertices of an icosahedron. In such a configuration, the highest possible angular separation of the stagnation point from any of its nearest four ports is 81.2 deg. If we consider a distribution of $N = 11$ ports (distributed "uniformly") around a sphere, such a probe will have regions where the stagnation point does not have four ports in attached flow. Hence the 12-hole design is optimal. The geometric definition of the icosahedron helps in easily defining the port locations.

The probe is designed such that the cylindrical sting (Fig. 1) is located at the geometric center of any two adjacent ports. The locations of the tip ports (on the spherical surface in Fig. 1) is given in Table 1 in terms of their Θ and Φ coordinates (probe coordinate system shown in Fig. 2). The probe head is a brass sphere of 3/8 in. (9.53 mm) diameter with 0.014 in. (0.36 mm) holes precision drilled at the specified locations. Each one of the tip holes/ports is routed through the sting. Each hole in the sting base (see Fig. 2) mates with a metal tube, which ultimately connects each of the tip ports to its corresponding pressure sensor. The selection of the tip hole diameter was based on our experience with the 18-hole probe in terms of the minimum possible tip hole diameter that will not suffer from port clogging problems and will yield a reasonable measurement frequency response. Once 0.014 in. (0.36 mm) was selected as the tip hole diameter, this automatically dictated a minimum of 0.020 in. (0.52 mm) sting hole diameter, based on the availability of stainless steel tubing in the market (i.e., tubes with 0.014 in. inner diameter). Based on the hole sizing chosen earlier and due to the fact that, for fabrication reasons, there has to be a minimum separation of 0.005 in. (0.13 mm) between the edges/walls of adjacent sting holes, the hole configuration shown at the base of the cylindrical sting in Fig. 1 is the most optimal (in terms of minimizing sting diameter). The ratio of sting diameter to tip diameter for this probe is 0.32. An alternate configuration with the sting at the geometric center of three adjacent ports was considered but discarded due to its lower gains in probe and sting sizing.

III. Advantages

The 33% reduction in the number of ports (compared to an 18-hole probe) augurs many advantages for this probe. Consider, for example, an 18-hole and a 12-hole probe, both with the same spherical tip diameter. If the sting port (or hole) diameter is maintained the same for both probes, the smaller the number of ports, the smaller the sting diameter necessary to accommodate them and thus the smaller the sting interference. This in turn leads to a larger measurable flow angularity. Alternately, if the sting diameter is maintained the same, the pressure conduits in it can be made bigger in diameter for the case of the 12-hole probe. This in turn can result in some gains in the measurement frequency response of the probe [9]. As an illustration, consider a probe with internal tubing of 0.014 in. inner diameter (i.d.) and 5 in. (0.13 m) length and external tubing

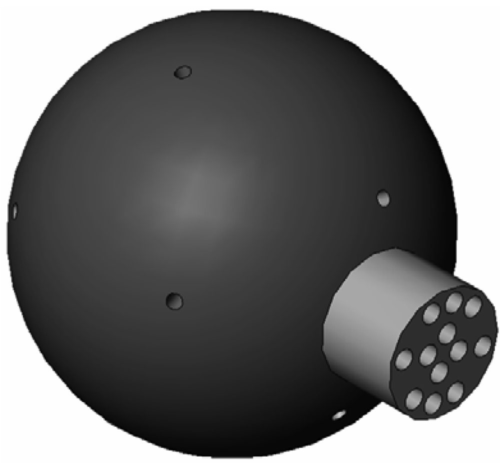

Fig. 1 Solid model of the probe depicting pressure ports on the surface and sting hole pattern.

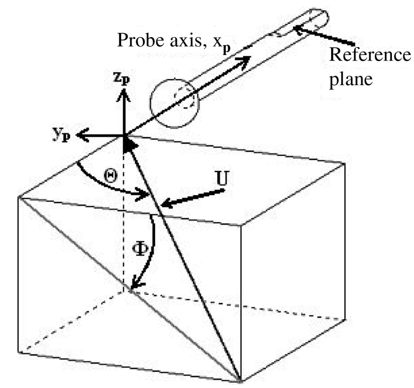

Fig. 2 Probe coordinate system.

(to the pressure sensors) of 0.020 in. i.d. and 12 in. (0.3 m) length. It should be noted that the i.d. of the external tubing considered here is not arbitrary; it is equal to the outer diameter (o.d.) of the stainless steel tubes described in the preceding section. The response (at the sensors) of this tubing assembly to a step pressure input (at the probe surface) of unit magnitude would yield a response time [9] (to 90%) of 10.2 ms. If we consider a probe with 0.012 in. i.d. internal tubing and 0.016 in. i.d. external tubing (all of the same lengths as earlier), the time response (to 90%) of this tubing would be 13.2 ms: a considerably slower response.

In another scenario, if one maintains the same ratio of sting diameter to tip diameter and the same diameter of sting holes for both probes, a smaller 12-hole probe can be manufactured. This results in higher spatial resolution than the corresponding 18-hole probe without sacrificing measurable angularity range or frequency response. Additionally, because every port has to be interfaced with a pressure sensor, significantly fewer pressure sensors are required for the operation of the 12-hole probe. This advantage is enhanced if an electronic pressure scanner (ESP) from PSI, Inc. is used. The 16-channel ESP can be used for this probe, whereas for an 18-hole probe, a 32-channel unit, at nearly double the price, would be necessary (units with a number of channels between 16 and 32 are not available). The same argument applies to the choice of an A/D board interfaced with the sensors for acquisition of data: a 16-channel board would suffice for the former. The reduction in the number of ports from 18 to 12 also results in a reduction of the probe manufacturing time. However, the reduction in complexity, size, and cost of instrumentation is by far the most desirable property of this probe. Further, as is described in the next section, there is no tradeoff in the new design's measurement accuracy.

IV. Calibration and Error Estimates

Experimental calibration of multihole probes has become a necessity for high-accuracy flow measurements. This is because the uncertainty in the port locations (due to machining limitations) and unevenness of the probe surface can introduce unacceptable errors when the probe is used based on theoretical flow assumptions. The probe was calibrated at the subsonic jet calibration facility of Aeroprobe Corporation at Mach numbers of 0.05, 0.1, 0.3, 0.5, 0.6, and 0.7. With calibration, one can obtain an extensive database of port pressures at different known angular orientations of the probe (with respect to the known velocity vector in the wind tunnel). The cone Θ and roll Φ ranges of the calibration facility are 0–155 deg and 0–360 deg, respectively. At each Mach number, data were recorded for every 3.6 deg in roll angle and every 2.7 deg in cone angle. This translates into a total of about 5600 calibration points (per Mach number). The pressure data were acquired using an ESP from PSI, Inc.

Before the probe was ready for application, its calibration data were preprocessed using new techniques (or new calibration coefficient definitions) developed by the authors for a generic arrangement of ports. These calibration and reduction techniques were employed in an earlier work [7] for the 18-hole probe with excellent results. To assess the prediction capability of the calibration (and hence the probe), in lieu of a full-blown uncertainty analysis, a calibration validation is performed, in which test data are also collected immediately following each calibration. Test data are composed of pressure data at several known orientations, none of them coincident with any of the orientations used for calibration. These pressures are fed into the reduction routines, and the predicted flow variables (calculated with the help of the calibration database) are compared with the actual values to estimate the calibration accuracy. About 1800 test points throughout the angular range of the probe were collected at each Mach number for this purpose.

The probe's final measurement accuracy is only as good as its calibration. Therefore, before we analyze the error data from

Table 1 Tip port coordinates (refer to Fig. 2 for Θ and Φ definitions)

Port No.	Θ, deg	Φ, deg
1	31.7	0.0
2	31.7	180.0
3	58.3	270.0
4	58.3	90.0
5	90.0	148.3
6	90.0	211.7
7	90.0	328.3
8	90.0	31.7
9	121.7	90.0
10	121.7	270.0
11	148.3	0.0
12	148.3	180.0

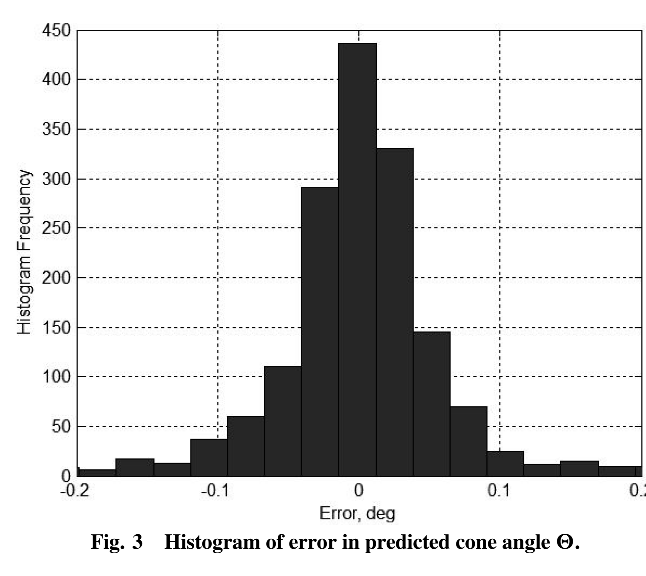

Fig. 3 Histogram of error in predicted cone angle Θ.

Table 2 Error data (standard deviations) for predicted flow variables

Flow variable	$M = 0.05$	$M = 0.1$	$M = 0.3$	$M = 0.5$	$M = 0.6$	$M = 0.7$
Θ, deg	0.18	0.32	0.15	0.22	0.28	0.29
Φ, deg	0.34	0.57	0.29	0.47	0.53	0.59
U_{mag}, %	0.30	0.42	0.25	0.35	0.36	0.54

calibration validation, it is worthwhile to identify and quantify sources of errors in the calibration process. The ESP, which is used to measure the tunnel dynamic pressure, has an accuracy of 0.1% of its full-scale span. A unit with appropriate range was employed for calibration at each Mach number. The calibration of the unit itself was checked before probe calibration and it was zeroed frequently (every 30 min) during probe calibration to minimize effects of voltage drifts. The accuracy of the ESP is an indication of the accuracy of the tunnel dynamic pressure measured at each calibration Mach number.

The cone and roll angles have unavoidable errors (albeit of magnitudes of 0.5 deg or less) when aligning the probe with the tunnel reference planes. These (bias) errors can be corrected postcalibration (as described in Zeiger and Schaeffler [10]) and reduced to the order of ± 0.1 deg. The positioning (random) errors themselves in Θ and Φ are very small, on the order of 0.001 deg, due to position encoders that are used with the stepper motors that rotate the probe. After correction of the alignment errors and due to the low contribution of the calibration process to the overall errors (in Θ, Φ, and U_{mag}), the error data from the calibration validation process are a good indication of the probe's accuracy.

For the sake of analyzing the probe's prediction capability, errors in the two flow angles (Θ and Φ) are defined here as the difference between predicted and "true" values, and the error in velocity magnitude (U_{mag}) is defined here as the relative difference (with respect to the true value) expressed as a percentage. The error standard deviations obtained for all calibration Mach numbers (using the test data for calibration validation) are shown in Table 2. Test points that turned out as outliers using Chauvenet's criterion [11] were removed before calculating the error estimates. All mean errors were very close to zero, indicating negligible bias (systematic) errors within the calibration or the reduction routine. Error histograms were also plotted in each case (sample plot of error in Θ for $M = 0.05$ is shown in Fig. 3) and it was satisfied that Gaussian distributions are indeed consistently observed. As can be seen in Table 2, the standard deviations for all calibrations are comparable, although there is a weak dependence on Mach number. The standard deviations, when compared to similar data [7] of an 18-hole probe, are comparable and in some respects better.

V. Conclusions

A new multihole probe for omnidirectional flow measurement has been successfully developed. The probe was designed with a spherical head of 0.375 in. (9.53 mm) and fabricated in brass with stainless steel internal pressure tubing. It was calibrated at multiple Mach numbers in a jet facility and tested to assess its accuracy of prediction of flow variables: three velocity components and static pressure. Only four pressure ports are used at any measurement point, thus avoiding redundancy. This optimum design was made possible by new definitions previously developed by the authors for nondimensional coefficients in multihole probes, which obviate the necessity for a symmetric arrangement of ports. The new probe has the same functionality as an earlier 18-hole design but with many more advantages in terms of spatial resolution, frequency response, and cost, and hence is a persuasive upgrade. The probe can be employed in the entire subsonic regime. Error estimates with experimental data show good prediction capability: 0.5 deg in Θ, 0.7 deg in Φ, and 0.6% in velocity magnitude (95% confidence).

Acknowledgments

The authors thank Aeroprobe Corporation for funding this project and for providing calibration data. The authors also thank Rick Allen of Texas A&M University for his help with the design and for building the probe.

References

[1] Everett, K. N., Gerner, A. A., and Durston, D. A., "Seven-Hole Cone Probes for High Angle Flow Measurements: Theory and Calibration," *AIAA Journal*, Vol. 21, No. 7, 1983, pp. 992–998.

[2] Rediniotis, O. K., Hoang, N. T., and Telionis, D. P., "The Seven-Hole Probe: Its Calibration and Use," *Forum on Instructional Fluid Dynamics Experiments*, Vol. 152, American Society of Mechanical Engineers, New York, 1993, pp. 21–26.

[3] Houtman, E. M., and Bannink, W. J., "Calibration and Measuring Procedure of a Five-Hole Hemispherical Head Probe in Compressible Flow," Delft University of Technology, Report No. LR-585, The Netherlands, April 1989.

[4] Zilliac, G. G., "Modelling, Calibration, and Error Analysis of Seven-Hole Pressure Probes," *Experiments in Fluids*, Vol. 14, No. 1/2, 1993, pp. 104–120.

[5] Johansen, E. S., Rediniotis, O. K., and Jones, G., "The Compressible Calibration of Miniature Multi-Hole Probes," *Journal of Fluids Engineering*, Vol. 123, No. 1, 2001, pp. 128–138.

[6] Rediniotis, O. K., and Kinser, R. E., "Development of a Nearly Omnidirectional Velocity Measurement Pressure Probe," *AIAA Journal*, Vol. 36, No. 10, 1998, pp. 1854–1860.

[7] Ramakrishnan, V., and Rediniotis, O. K., "Calibration and Data-Reduction Algorithms for Nonconventional Multihole Pressure Probes," *AIAA Journal*, Vol. 43, No. 5, 2005, pp. 941–952.

[8] Edmundson, J. R., "The Distribution of Point Charges on the Surface of a Sphere," *Acta Crystallographica Section A: Foundations of Crystallography*, Vol. 48, Part 1, 1992, pp. 60–69.

[9] Rediniotis, O. K., and Pathak, M. M., "A Simple Technique for Frequency Response Enhancement of Miniature Pressure Probes," *AIAA Journal*, Vol. 37, No. 7, 1999, pp. 897–899.

[10] Zeiger, M. D., and Schaeffler, N. W., "Correcting Multi-Hole Probe Alignment Bias Errors Post-Calibration," AIAA Paper 2001-0900, Jan. 2001.

[11] Coleman, H. W., and Steele, W. G., "Statistical Considerations in Measurement Uncertainties," *Experimentation and Uncertainty Analysis for Engineers*, 2nd ed., Wiley–IEEE, New York, 1999, p. 34.

F. Coton
Associate Editor