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Calibration of A Five-Hole Probe in Null and Non-Null Technique

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ABSTRACT
The analysis of fluid flow is encountered in almost all engineering applications. Flow measurements, particularly velocity and its direction, turbulence quantities are needed in order to improve the understanding of various complex flow phenomena and to validate and further refine the computer flow models. Pressure probes find wide application in the measurement of fluid flows both in the laboratory and in the industry. A five-hole pressure probe is calibrated in both null and non-null technique. An algorithm for five-hole probe in non-null method is developed which utilizes a database of calibration data and a local least-squares interpolation technique is used for interpolation of flow properties. It is also found out that the non-null method was superior in ease of use and prediction of flow measurement variables than the null method.
Keywords: five-hole probe, non-null method, interpolation technique, regression model, sector scheme.

Nomenclature

C_α	Pitch angle coefficient
C_β	Yaw angle coefficient
f1, f2, f3, F(α), k	Calibration constants
G	Acceleration due to gravity(m/s^2)
U	Mean velocity (m/sec)
U_X	Velocity in x-direction (m/sec)
U_Y	Velocity in y-direction (m/sec)
U_Z	Velocity in z-direction (m/sec)
C_{Ptotal}	Total pressure coefficient
$C_{Pstatic}$	Static pressure coefficient
P	Pressure sensed by different holes
α	Pitch angle (°)
β	Yaw angle (°)
ρ	Density (kg/m^3)
ρ_m	Density of manometric fluid (kg/m^3)
ρ_{air}	Density of air (kg/m^3)

Subscripts

1, 2, 3, 4, 5, 6, 7	Hole numbers
I	ith data point in a given sector
°	Degree

Superscripts

‾	Average

I. INTRODUCTION

Multi-hole pressure probes have, over the years, been used to resolve the three-dimensional velocity vector and static and total pressures at the point of measurement in a flow field. Such devices include three-hole, five-hole and seven-hole probes and other combination of more tubes/holes. There are of course other types of pressure probes such as pitot-static probes and yaw probes, which, however, are not of interest here, since they cannot resolve all three components of the velocity vector.

The application of five-hole probe was developed in 1915 by Admiral Taylor. However, Pien [1] was first to show theoretically that for a spherical probe the velocity component in any plane in space can be obtained independently from three pressure measurements in that plane. Kjelgaard [2] developed a theoretical relationship and generalized it for a hemispherical tipped five-hole probe. Treaster and Yocum [3] reported the non- nulling calibration technique and the interpolation procedure for commercially available prism and angle tubes probes made of five 1.27mm diameter hypodermic tubes. Mukhopadhya et. al. [4] conducted experiments on hemispherical, conical and open ended five-hole probes to determine the effect of calibration coefficients on each of the probe tip shapes.

Pisasale and Ahmed [5] assumed potential flow theory across a spherical probe tip and presented a theoretical basis for extending the range of flow angles of a five-hole probe. The method assists in overcoming the singularity in calibration of five-hole probes for different geometrical shapes, but the prediction errors remains of same magnitude as of the conventional method. A simplified method for measurement of 3-D flow using 4-hole pressure probe has been discussed by Sitaram and Treaster [6].

II. EXPERIMENTAL SET UP AND ALGORITHM FOR NON- NULL METHOD WITH SECTOR SCHEME

Schematic diagram of the experimental set up used for this study is shown in Fig.1. The main components of the experimental set up include an air supply unit, flow control arrangement, settling chamber, contraction cone and a straight test section. Every component, except the air supply unit and the straight test section were made of wood. The straight test section was made of transparent plexiglass. However, calibration is done in the open jet of air coming out from the test section. Ambient air is used as flowing fluid during calibration. A hemispherical tip five-hole pressure probe as shown in Fig.2 has been used for the calibration. It consists of five stainless steel tubes of outer diameter 1.2mm and inner diameter of 0.9mm glued together. The length of the five-hole pressure probe is 0.25m. A probe traversing gear has been designed for the present study, which allows the rotation of the probe in both pitch and yaw plane [8].

A simple regression method of matrix terms as discussed by Netter and Washerman [7] has been used in the present study for determining the different calibration coefficients as required.

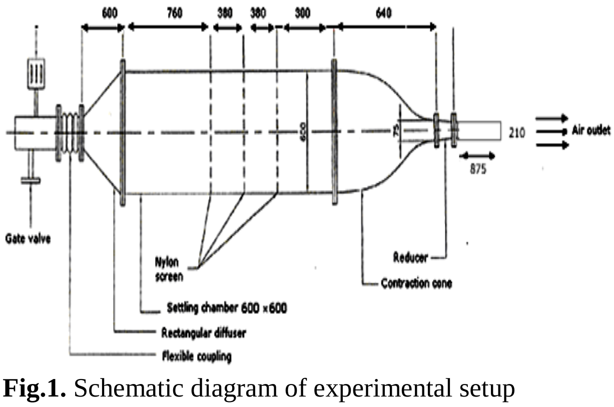


Fig.1. Schematic diagram of experimental setup

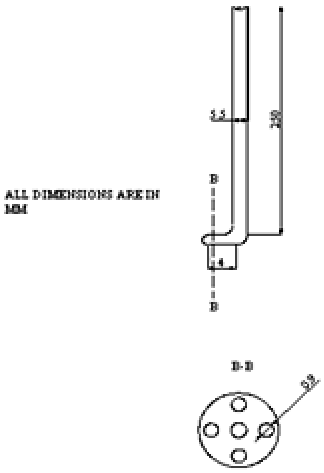
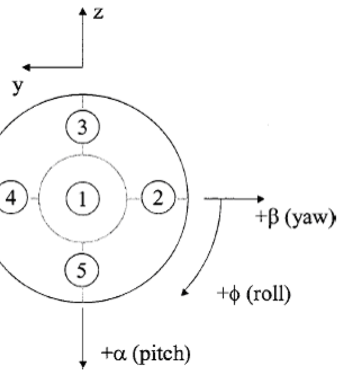
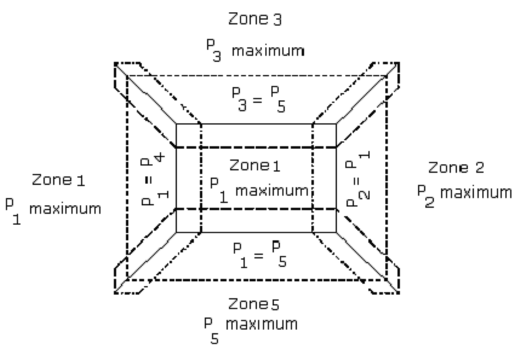


Fig.2. Schematic diagram of the pressure probe

The sector method divides the entire calibration zone into five parts, one central zone and four side zones .The zones are chosen based on the highest pressure sensed by the holes e.g. when center hole senses maximum pressure, zone 1 is taken. Detailed view of the probe with zonal discrimination is given in Fig. 3(a-b).



(a) Section view with hole nomenclature



(b) Different sectors chosen

Fig.3. Sectoring scheme chosen for five-hole probe (hole numbers 1to 5)

The calibration coefficients in various zones are defined as follows.

$ZONE1$

$$\bar{P} = (P2 + P3 + P4 + P5)/5$$
$$D = P1 - \bar{P}$$
$$C_\alpha = (P3 - P5)/D$$
$$C_\beta = (P2 - P4)/D$$
$$C_{pstatic} = (P_{static} - \bar{P})/D$$
$$C_{ptotal} = (P_{total} - P1)/D$$

$ZONE2$

$$\bar{P} = (P1 + P3 + P5)/5$$
$$D = P2 - \bar{P}$$
$$C_\alpha = (P2 - P4)/D$$
$$C_\beta = (P3 - P5)/D$$
$$C_{pstatic} = (P_{static} - \bar{P})/D$$
$$C_{ptotal} = (P_{total} - P2)/D$$

$ZONE3$

$$\bar{P} = (P1 + P4 + P5)/5$$
$$D = P3 - \bar{P}$$
$$C_\alpha = (P2 - P4)/D$$
$$C_\beta = (P3 - P1)/D$$
$$C_{pstatic} = (P_{static} - \bar{P})/D$$
$$C_{ptotal} = (P_{total} - P3)/D$$

$ZONE4$

$$\bar{P} = (P1 + P3 + P5)/5$$
$$D = P4 - \bar{P}$$
$$C_\alpha = (P1 - P4)/D$$
$$C_\beta = (P3 - P5)/D$$
$$C_{pstatic} = (P_{static} - \bar{P})/D$$
$$C_{ptotal} = (P_{total} - P4)/D$$

$ZONE5$

$$\bar{P} = (P1 + P2 + P4)/3$$
$$D = P5 - \bar{P}$$
$$C_\alpha = (P2 - P4)/D$$
$$C_\beta = (P1 - P5)/D$$
$$C_{pstatic} = (P_{static} - \bar{P})/D$$
$$C_{ptotal} = (P_{total} - P5)/D$$

For all the above equations the value of D should not be negative or too small.

The first step is to determine the pressure hole that gives the maximum reading and accordingly to determine the zone where the probe lies. While calibrating the value of P_s and P_T are recorded and C_α C_β, Cp_{static} and Cp_{total} are thereby calculated for each zone. A full fourth order multiple regression model [8] with two independent variables, C_α C_β, that would predict four different variables (α, β, Cp_{static} and Cp_{total}) depending on the coefficient set selected. The described regression model also applies for compressible flow and the nature of equation can be varied as order of the curve fit or the accuracy level by comparing the predicted data with the measured data. The multiple regression model does predict α and β explicitly but predicts the total pressure and static pressure implicitly via a pressure coefficient Cp_{static} and Cp_{total}, which are defined in each zone separately. This method of zonal division reduces large errors due to extrapolation. The zonal demarcation angles are chosen such that zones overlap e.g. hole 1 is maximum within yaw angles of ± 18° at a pitch angle of -9°.

The actual data prediction equations for the multiple regression model is defined as follows.

$$\alpha = K\alpha_0 + K\alpha_1 \times C_\alpha + K\alpha_2 \times C_\beta + K\alpha_3 \times C_\alpha^2 + K\alpha_4 \times C_\alpha \times C_\beta + K\alpha_5 \times C_\beta^2 + K\alpha_6 \times C_\alpha^3 + K\alpha_7 \times C_\alpha^2 \times C_\beta + K\alpha_8 \times C_\alpha \times C_\beta^2 + K\alpha_9 \times C_\beta^3 + K\alpha_{10} \times C_\alpha^4 + K\alpha_{11} \times C_\alpha^3 \times C_\beta + K\alpha_{12} \times C_\alpha^2 \times C_\beta^2 + K\alpha_{13} \times C_\alpha \times C_\beta^3 + K\alpha_{14} \times C_\beta^4 \quad \ldots\ldots\ldots\ldots (1)$$

$$\beta = K_{\beta 0} + K_{\beta 1} \times C_\alpha + K_{\beta 2} \times C_\beta + K_{\beta 3} \times C_\alpha^2 + K_{\beta 4} \times C_\alpha \times C_\beta + K_{\beta 5} \times C_\beta^2 + K_{\beta 6} \times C_\alpha^3 + K_{\beta 7} \times C_\alpha^2 \times C_\beta + K_{\beta 8} \times C_\alpha \times C_\beta^2 + K_{\beta 9} \times C_\beta^3 + K_{\beta 10} \times C_\alpha^4 + K_{\beta 11} \times C_\alpha^3 \times C_\beta + K_{\beta 12} \times C_\alpha^2 \times C_\beta^2 + K_{\beta 13} \times C_\alpha \times C_\beta^3 + K_{\beta 14} \times C_\beta^4 \quad \ldots\ldots\ldots\ldots (2)$$

$$Cp_S = K_{CPS0} + K_{CPS1} \times C_\alpha + K_{CPS2} \times C_\beta + K_{CPS3} \times C_\alpha^2 + K_{CPS4} \times C_\alpha \times C_\beta + K_{CPS5} \times C_\beta^2 + K_{CPS6} \times C_\alpha^3 + K_{CPS7} \times C_\alpha^2 \times C_\beta + K_{CPS8} \times C_\alpha \times C_\beta^2 + K_{CPS9} \times C_\beta^3 + K_{CPS10} \times C_\alpha^4 + K_{CPS11} \times C_\alpha^3 \times C_\beta + K_{CPS12} \times C_\alpha^2 \times C_\beta^2 + K_{CPS13} \times C_\alpha \times C_\beta^3 + K_{CPS14} \times C_\beta^4 \quad \ldots\ldots\ldots (3)$$

$$Cp_T = K_{CPT0} + K_{CPT1} \times C_\alpha + K_{CPT2} \times C_\beta + K_{CPT3} \times C_\alpha^2 + K_{CPT4} \times C_\alpha \times C_\beta + K_{CPT5} \times C_\beta^2 + K_{CPT6} \times C_\alpha^3 + K_{CPT7} \times C_\alpha^2 \times C_\beta + K_{CPT8} \times C_\alpha \times C_\beta^2 + K_{CPT9} \times C_\beta^3 + K_{CPT10} \times C_\alpha^4 + K_{CPT11} \times C_\alpha^3 \times C_\beta + K_{CPT12} \times C_\alpha^2 \times C_\beta^2 + K_{CPT13} \times C_\alpha \times C_\beta^3 + K_{CPT14} \times C_\beta^4 \quad \ldots\ldots\ldots (4)$$

The calibration coefficients are determined using matrix operations which automatically involves a least-square curve fit.

The following matrices were defined

$$\begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \\ . \\ . \\ . \\ . \\ A_n \end{bmatrix} = \begin{bmatrix} 1 & C_{\alpha 1} & C_{\beta 1} & C_{\alpha 1}^2 & C_{\alpha 1}C_{\beta 1} & C_{\beta 1}^2 & C_{\alpha 1}^3 & \ldots\ldots & C_{\beta 1}^4 \\ 1 & C_{\alpha 2} & C_{\beta 2} & C_{\alpha 2}^2 & C_{\alpha 2}C_{\beta 2} & C_{\beta 2}^2 & C_{\alpha 2}^3 & \ldots\ldots & C_{\beta 2}^4 \\ 1 & C_{\alpha 3} & C_{\beta 3} & C_{\alpha 3}^2 & C_{\alpha 3}C_{\beta 3} & C_{\beta 3}^2 & C_{\alpha 3}^3 & \ldots\ldots & C_{\beta 3}^4 \\ 1 & C_{\alpha 4} & C_{\beta 4} & C_{\alpha 4}^2 & C_{\alpha 4}C_{\beta 4} & C_{\beta 4}^2 & C_{\alpha 4}^3 & \ldots\ldots & C_{\beta 4}^4 \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ 1 & C_{\alpha N} & C_{\beta N} & C_{\alpha N}^2 & C_{\alpha N}C_{\beta N} & C_{\beta N}^2 & C_{\alpha N}^3 & \ldots\ldots & C_{\beta N}^4 \end{bmatrix} \begin{bmatrix} K_1 \\ K_2 \\ K_3 \\ K_4 \\ . \\ . \\ . \\ . \\ K_N \end{bmatrix}$$

Where, A is one of the flow properties like α, β, Cp_{static} or Cp_{total}. A sample set of N data points are taken for each of the given zone (a minimum of 15 sample points are required for uniquely defining the 15 K's). The K's are the calibration constants where the subscript identifies the term in expansion. The above equation could be abbreviated as follows

$$[A]=[C][K] \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

Where, [N×1], [A] matrix contains N values of one of the four flow properties, the [N×15], [C] matrix contains the corresponding expanded pressure coefficient variables, and the [20×1], [K] matrix contains the calibration coefficients.

During calibration the quantities within the A matrix are determined for every zone i.e. for α=10° and β=5°, the value of C_α and C_β at that point corresponding to Cp_{static} and $Cp_{total.}$ The calibration constants are unique for every probe and are determined by solving the above matrix equation as outlined by Netter and Wasserman [8].

$$[K]= [C^TC]^{-1}[C]^T[A] \qquad \ldots\ldots\ldots\ (6)$$

Equations (1) to (4) is then solved which gives the interpolated values of α, β, Cp_{static} and Cp_{total} values. All data points obtained during calibration were cross checked to ensure the effectiveness of the calibration constants obtained by using the pressures and calibration constant as inputs and flow angle as outputs. The interpolated values are then compared with the measured points and any questionable data points found are neglected. The calibration constants are again determined until a ±0.6° accuracy level was reached for both pitch and yaw angles.

Resolving the velocity vector in the mutually perpendicular plane the velocities in three directions can be determined using the following equations.

$$\overline{U} = \sqrt{(P_T - P_S)\times(\rho_m \times g \times 2/\rho_{air})}$$

$$U_x = \overline{U}\times\cos\alpha\times\cos\beta$$

$$U_y = \overline{U}\times\sin\beta$$

$$U_z = \overline{U}\times\sin\alpha\times\cos\beta$$

III. RESULTS AND DISCUSSIONS

3.1. *Null Technique*

In this method, yaw angle is set to zero by aligning the probe with the incoming flow (null setting).The Fig. (4a-c) shows the calibration curves of the five-hole probe obtained by the null technique. The calibration constant and methods adopted are according to Byre and Pankhurst [9**].** Fig.4a shows the variation of pitch angle (α) versus the ratio of pressure (P_4-P_2 / P_3-P_5). A first order polynomial function is generated to interpolate the pitch angle on the basis of the pressure sensed by holes 2, 3, 4 and 5 when the probe is inserted to an unknown flow.

Fig.4b shows the variation of pitch with the constant 'k'. A second order polynomial function is generated to define 'k' with respect to pitch angle. When the probe is inserted to an unknown flow the value of pitch angle interpolated earlier will thus provide the value of 'k'.

Fig.4c shows the variation of F(α) with pitch angle. F(α) represents the dimensionless pressure coefficient. A second order polynomial function is generated to define the F(α) with respect to pitch angle. When the probe is inserted to an unknown flow the value of pitch angle interpolated earlier will thus provide the value of F(α).

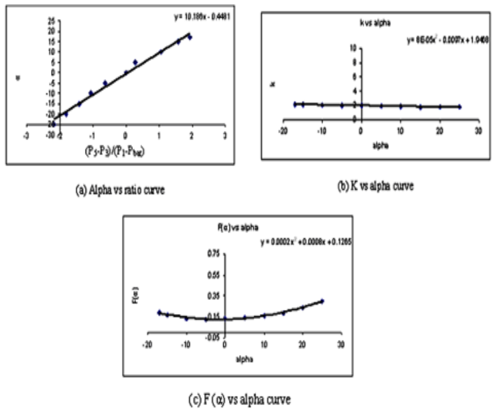


Fig.4. Calibration curves of five-hole probe in null technique

3.2. *Sector Scheme*

The Fig.5 shows the pitch and yaw angle map of sectors chosen by the calibration scheme. The symbol indicates the hole registering the maximum pressure. The flow angle α and β are taken within ± 30°. Fig.5 also indicates the range of α and β for various sensing holes of the probe. It shows that the centre hole (hole 1) covers the most wide range of α and β among all the holes. However, at larger angles of α and β other holes are likely to sense the total pressure and hence pressure sensed by the holes at their location is maximum. Further, the centre hole or other holes at this position will become stalled.

The contours show lines of increasing pressure as the holes of the probe is oriented to the flow. The curvature of the lines increases as the pressure increases, since the flow is more directly into the hole and exhibits grater dependence upon the inclination of the hole with respect to the mean flow

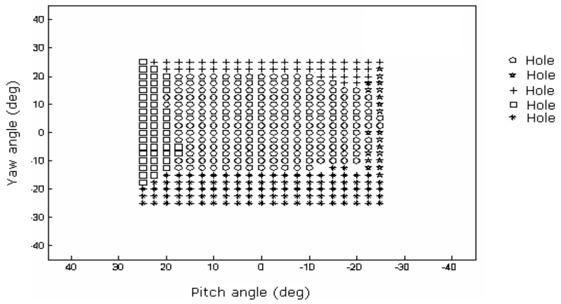
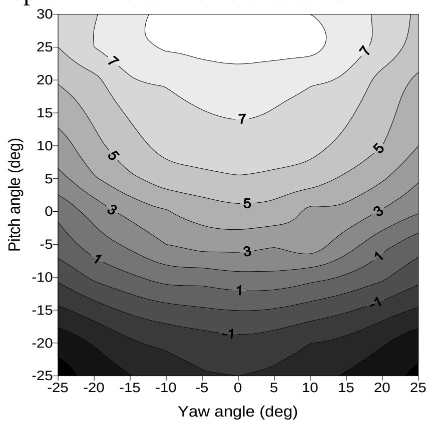
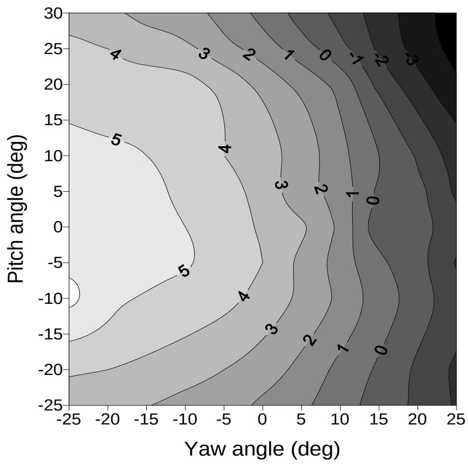


Fig.5. Sector map of pitch and yaw angle of five-hole probe

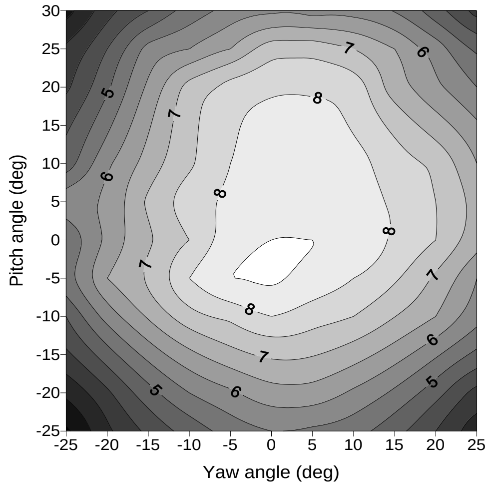
The Fig.6(a-e) shows the contours of the response of the individual five pressure holes. They are representative of the pressure distribution obtained from the perimeter holes for the probe. The contours as seen are non-symmetric in nature, which may be due to non-symmetry of the holes with respect to the centre hole occurred



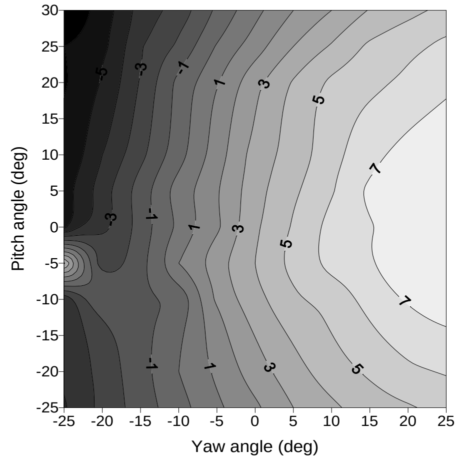
(a) Pressure hole 3

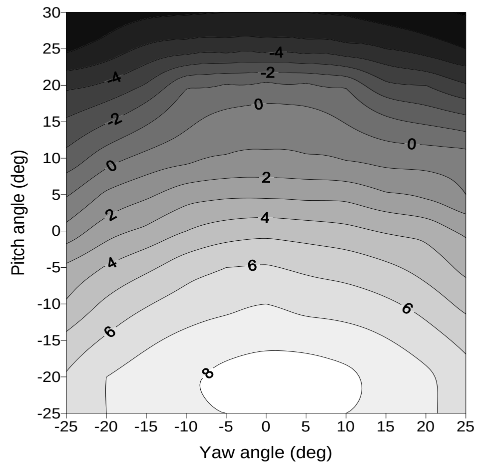


(b) Pressure hole 4



(c) Pressure hole 1





(d) Pressure hole 2

Fig.6. Pressure holes of Five-hole probe response to pitch and yaw angle

IV. CONCLUSION

The following conclusions are made based on the present study:

1. Null technique is simple during calibration but time consuming at the time of actual measurement.
2. Non-null method, particularly sector scheme is very useful where rotation of the probe is not possible.
3. Errors in null technique are more as perfect null depends on the least count of the scales associated as well as human skill.
4. For larger flow angle, sector technique to be a better option. For flow angles within ±30°, five-hole probe in non-null technique is very useful. The data reduction technique yielded an accuracy of ±1.5° both in pitch and angle and ±1.5 m/s in velocity.

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