

Fabrication and Calibration of Five Hole Pressure Probe

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ABSTRACT: In the field of aerodynamics, flow measurement is very important. The quality of the flow influences the design and performance of the various aerodynamic components like compressors, blowers, fans and turbines. More and more research work is available in the field of flow measurement. Many techniques had been developed for measurement of flow like LDV, PIV and Hot wire anemometry. All these techniques are effective but are very costly. In the present work, calibration of five hole pressure probe is carried out. Literature review reveals that the flow measurement by probe is very effective since it can measure flow parameters such as static and stagnation pressure, velocity of fluid stream. In this work, probe is fabricated and then calibrated by using continuous type wind tunnel. The probe is subjected to known flow field for calibration. The velocity of the fluid stream is maintained at 25 m/sec and the probe is calibrated for different yaw and pitch angle. The graphs obtained for the calibration are compared with [11]. From these graphs, it had been found that suitable range for yaw and pitch angle is -20° and $+20^{\circ}$. The calibrated probe can be extensively used for three dimensional flow measurements. It provides good alternative to same costly techniques of flow measurement.

I. INTRODUCTION

In the aerodynamics research, the classical Pitot-static tube was extensively used to measure the velocity in a stream. The pressure manometers have been employed to measure the difference between stagnation and static pressure, and thus allow the calculation of the velocity, if the density of the fluid was known. A Pitot-static tube can generate accurate measurements, if the flow is uniform and the probe is nearly aligned with the direction of the flow velocity. Both requirements represent significant limitations for the measurement of the velocity at a point within a flow field. But Pitot-static probes are still extensively used in situations where the direction is known a priori, or if the direction of the flow does not change significantly locally. To overcome above limitation there is need to design Multi-Hole Probes (MHP) for the measurement of flow velocity. It is based on the principle of operation of a Pitot-static tube.

Five-hole probes are used to measure the three components of velocity, inflow angles, static and total pressures simultaneously for a point in a flow field. Measurement by such probe is categorized into two methods; the balancing one (null method) and the fixed one (non-null method). In the null method, the probe is rotated so that the pressures from the holes are balanced in order to measure the flow direction, static and total pressure. This method, however, requires a complex probe traversing mechanism for the rotation of the probe, which often causes difficulty to install the measurement unit into the given flow field. In the non-nulling method, the probe does not require any rotation.[7]

Pneumatic probes are still a useful tool when investigating flow fields within turbo machines, cascades or any other aerodynamic facility. Due to the fact that flow velocity and flow direction cannot be measured directly by the probes as well as due to some inaccuracies when manufacturing the probe's head, a calibration process is necessary. Pressure probes are instruments to measure the local velocity and the pressure value in a flow. Calibration of a five-hole probe requires subjecting the probe to a known flow field at different combinations of yaw and pitch angles.

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Pressures at all five holes are measured for each angular position of the probe. The measured data are represented as dimensionless pressure coefficients. They are usually preferred over other sophisticated optical devices due to their maintenance and relatively low cost, and their robustness and simplicity of operation in a number of research and industrial purposes. In fact, pressure probes are widely used in turbo machinery applications.[4]

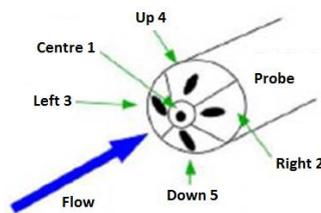


Fig. Nomenclature of Five-hole probe[4]

Calibration is a significant element of MHP and the difficulties associated with it are discussed here. Generally, calibration is carried out in wind tunnel. The tunnel was run at a constant velocity of 25 m/s, which was recorded by a pitot-static tube placed in the flow. The total and static pressure of the free stream were recorded, and the five-hole probe was set up in the flow, with arrangements to change its pitch and yaw angles in relation to the free stream direction.



Fig. Fabricated Five Hole Probe

A wind tunnel is a specially designed and protected space into which air is drawn or blown, by mechanical means in order to achieve a specified speed and predetermined flow pattern at a given instant. The flow so achieved can be observed from outside the wind tunnel through transparent windows that enclose the test section and flow characteristics are measurable using specialized instruments. An object, such as a model, or some full-scale engineering structure, typically a vehicle, or part of it, can be immersed into the established flow, thereby disturbing it. The objectives of the immersion include being able to simulate, visualize, observe, or measure how the flow around the immersed object affects the immersed object.

II. LITERATURE SURVEY

The papers deal with design, analysis and performance of probe with different holes. Some papers and reports are given below as a part of literature survey.

S.J. Lien, et al [1], authors studied the problems of misalignment to flow direction and the need to drill a tapping hole on a measurement surface to obtain total and static pressures make the use of Preston probe in skin friction measurement in a turbulent flow a cumbersome task. The suitability of a multi-hole pressure probe in a non-nulling mode to overcome these problems was, therefore, investigated. The near-wall effect on multi-hole pressure probe readings was examined both experimentally and theoretically. The results indicate that the presence of the wall had negligible overall effect. Experiments were carried out in a pipe, on a flat plate and on a swept forward facing step to simulate one, two, and three-dimensional turbulent flows. The skin friction coefficient determined using the multi-hole pressure probe was found to have good agreement with published data. Since the technique is based on similarity principle with probe diameter as a characteristic parameter, it is expected that the method would be effective with

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M. Yasar , et al [2], author investigated a multi-tube pressure probe calibration method for measurements of mean flow parameters in swirling flows. A simple and sensitive measurement method of multi-tube pressure probes applicable in swirling flow fields is presented in this paper. Determination of flow direction associated with local pitch, α , and yaw, Ψ , angles, magnitudes of local static and dynamic pressures can be achieved through a calibration method used with 3- and 5-tube versions of a multi-tube pressure probe. The 5- tube probe was tested in a conventional air cyclone where a strong rotational flow prevailed while the 3-tube probe was used in a low swirl flow field in a pipe internally fitted with a helical coiled wire insert. The method is based on the rotational sensitivity of the pressure probe handled through non-dimensional calibration parameters.

He conclude that in comparison with LDV and Hot-wire probe measurements, the presented method is simple and cheap with not much difference in measured quantities. However, the difficulty in data reduction from the calibration charts needs further computational work to make the utilization of probes somehow more practical and rapid.

L.J. Fingersh, et al [3], This research shows that the Wind Tunnel Calibration of 5-Hole Pressure Probes for Application to Wind Turbines. A method to quantify the local inflow vector on a rotating turbine blade using a 5-hole static pressure probe was developed at the National Wind Technology Center. The technique permits quantification of dynamic pressure, angle-of-attack and cross-flow-angle to magnitudes of $\pm 40^\circ$ in any inflow direction parallel to the probe centerline. A description of the static and dynamic calibration procedure, iteration sequence for data reduction, and field results are included.

A. R. Paul, et al [4], author performed a novel calibration algorithm for five-hole pressure probe. Five-hole pneumatic pressure probes are used to carry out the steady-state measurements of three components of velocity, inflow angles, static and total pressures simultaneously for a point in a flow field. Various calibration algorithms for five-hole probes are studied in this paper as reported in the literature. Authors have defined non-dimensional pressure coefficients in different ways. Based on certain limitations, a new set of pressure coefficients are proposed in this paper, which overcome the limitations in the literature and gives less computational errors in calculating the flow parameters. In this method, the influence of pressure recorded by central hole is considered in defining these coefficients. From 4th order regression analysis, the average values of r^2 parameters for all zones are 0.9979 and 0.9910 for α and β respectively, and which are even better than that reported in the all existing methods.

Demetri Telionis.et.al,[5] Multi-hole probes are fluid flow instruments that measure pressure along pressure ports arranged on their tips. With proper calibration, this information can then return three components of the fluid velocity as well as static and dynamic pressure. With the development of modern methods like laser-Doppler velocimetry, particle-image velocimetry and others, the use of these probes has declined. But the emergence of miniature pressure sensors and modern electronics new multi-hole probes were designed and tested to match some of the features of other methods.

Moreover, multi-hole probes are robust, and can sustain harsh environments, like very high temperatures, opaque fluids, flows carrying particulates and others. Moreover, they are easier to use and less expensive. In the present paper we review recent developments in multi-hole probe technology, namely, instrumentation and calibration methods that increase the probe's frequency response, allow them to take data in wide ranges of the Mach number, and correct for inertial effects. We also present examples of using these probes in many industrial settings.

A. J. Main, et al [6], author Calibrate the four-hole pyramid probe and area traverse measurements in a short-duration transonic turbine cascade tunnel. A four-hole pyramid probe has been calibrated for use in a short-duration transonic turbine cascade tunnel. The probe is used to create area traverse maps of total and static pressure, and pitch and yaw angles of the flow downstream of a transonic annular cascade. This data is unusual in that it was acquired in a short-duration (5 s of run time) annular cascade blow down tunnel. A four-hole pyramid probe was used which has a 2.5 mm section head, and has the side faces inclined at 60° to the flow to improve transonic performance. The probe was calibrated in an ejector driven, perforated wall transonic tunnel over the Mach number range 0.5-1.2, with pitch angles from -20° to $+20^\circ$ and yaw angles from -23° to $+23^\circ$ A computer driven automatic traversing mechanism and data collection system was used to acquire a large probe calibration matrix of non- dimensional pitch, yaw, Mach number,

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and total pressure calibration coefficients. A novel method was used to transform the probe calibration matrix of the raw coefficients into a probe application matrix of the physical flow variables (pitch, yaw, Mach number etc). The probe application matrix is then used as a fast look-up table to process probe results. With negligible loss of accuracy, this method is faster by two orders of magnitude than the alternative of global interpolation on the raw probe calibration matrix. The blow down tunnel (mean nozzle guide vane blade ring diameter 1.1 m) creates engine representative Reynolds numbers, transonic Mach numbers and high levels of inlet turbulence intensity. Contours of experimental measurements at three different engine relevant conditions and two axial positions have been obtained. An analysis of the data is presented which includes a necessary correction for the finite velocity of the probe. Such a correction is non trivial for the case of fast moving probes in compressible flow.

B. O. Johnson [7], He research on A Multi-Holed Pressure Probe Accuracy Analysis. A Cobra Probe is a four-holed dynamic pressure probe that uses empirical relations to ascertain the local three velocity components and the total pressure of a flow at a point. The objectives of this thesis are to assess the accuracy of a newly acquired Cobra Probe (Series 100 manufactured by Turbulent Flow Instrumentation (TFI)) up to velocities of 90 m/s, develop a MATLAB graphical user interface (GUI) to analyze Cobra Probe data, and to provide a detailed description of how to setup and operate the probe in a closed-circuit ELD wind tunnel. TFI provides automated data acquisition and reduction software and claims the Cobra Probe output is accurate up to velocities of 90 m/s at pitch and yaw angles of $\pm 45^\circ$. The measurements are said to generally be within ± 0.5 m/s for velocity and $\pm 1^\circ$ for pitch and yaw measurements. Previously, the Cobra Probe was demonstrated to be accurate at velocities up to 30 m/s to within $\pm 3^\circ$ for pitch and yaw measurements and ± 2 m/s for velocity measurements by E. A. Deem in an internal group report "TFI 4-hole Cobra Probe Calibration and Performance". The first goal of this research is to analyze the accuracy of the Cobra Probe for velocities exceeding 30 m/s and approaching 90 m/s, where the limits of the assumed incompressibility assumption begin to break down. The results demonstrate that as velocity approaches 90 m/s, the velocity measured by the Cobra Probe is unreliable for 17.6 % of the designed range of use. As velocity approaches 90 m/s, 20.9 and 12.1 % of the test region has unacceptable error for pitch and yaw measurements respectively.

A.J. Pisasale, et al [8], His study illustrate the A novel method for extending the calibration range of five-hole probe for highly three-dimensional flows. Five-hole probe used in a non-nulling manner to find unknown flow properties is limited to a low range of acceptance angles due to singularity encountered in the calibration procedure. A novel method to extend this range by avoiding singularity is developed allowing calibration of a five-hole probe up to much larger angles of pitch and yaw. The method has been tested using experimental calibration data of a five-hole probe that were obtained employing the 18in. \times 18in. subsonic closed circuit wind tunnel of the University of New South Wales at the wind tunnel speed of 15 m/s. The new procedure shows that the calibration range can be successfully extended to angles of up to $\pm 75^\circ$. A step-by-step procedure of using the new technique is also detailed in this chapter

From this literature it is observed that, The design of modern Multi-Hole Probes (MHP) for the measurement of flow velocity in x ,y and z direction is based on the principle of operation of a Pitot-static tube.

- Multi-hole probes are robust, and can sustain harsh environments, like very high temperatures, opaque fluids, flows carrying particulates and others.
- Review recent developments in multi-hole probe technology, namely, instrumentation and calibration methods that increase the probe's frequency response.

III. METHODOLOGY

Design and fabrication of Probe:

The five hole pressure probe which is calibrated for the purpose of measuring the stagnation pressure. As the name implies, five-hole probes are characterized by five pressure sensing holes lying in two perpendicular planes with the line of intersection of the two planes passing through the central hole. The design specification of Five hole probe is given below table 1.

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Particular	Dimension
Diameter of outside tube	7mm
Diameter of inside tube	1mm
Total length	300mm
Numbers of inside tube	5
Head width	2.8mm

Table1 Design specification of five hole probe

The material used for the probe is stainless steel. Five tubes of 1mm diameter are inserted into the tube of diameter 7mm. The gap between the inside and outside tube is filled with the araldite solution which holds all the tubes in proper position. The Probe has four ports equally spaced in a circular configuration around a central port. The outside holes are located on planes that are at 45° angles with respect to the plane on which the central hole is located, as seen in Figure 1. The geometry of the five hole probe facilitates its use in aerofoil, turbo machinery research which can be easily inserted through casings and used to detect the pressure at the surface of blades.



Fig 1. Fabricated five hole probe with 90° bend

Tube Bender Mechanism:

A pipe and tube bender is a machine which bends tube, pipes and solid metals. Pipe bending machines can either be human powered, hydraulic assisted or hydraulic motor driven. In the pipe bending operation the tube may be supported internally or externally to preserve the cross section of the pipe. In operations where there is flexibility in the shape of the pipe, the pipe does not need to be supported; however there will be some deformation in the cross section of the pipe.

This machine is used to bend steel tube into curve or other curvature shape. The size of the machine is very convenient for portable work. It is fully made by steel. Moreover it is easy to be carried and used at any time and any place.



Fig 2. Tube bender mechanism

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Details of Wind Tunnel:

Wind tunnel for probe calibration. Wind tunnels used to calibrate probes must meet the following design specifications.

The air shall be confined within a rectangular duct. The cross-sectional area of the tunnel must be large enough to ensure fully developed flow in the presence of both the calibration pitot tube and the tested probe. The test section of the wind tunnel shall have a minimum width of 30.5 cm (12 in.) on the shorter side for rectangular cross-sections. Wind tunnels shall meet the probe blockage provisions of this section and the qualification requirements. The projected area of the portion of the probe head inside the wind tunnel during calibration shall represent no more than 4 percent of the cross-sectional area of the tunnel. The projected area shall include the combined area of the calibration pitot tube and the tested probe if both probes are placed simultaneously in the same cross-sectional plane in the wind tunnel, or the larger projected area of the two probes if they are placed alternately in the wind tunnel. Specifications of existing wind tunnel facility are as follow.

- Length of wind tunnel- 5.0m
- Height of wind tunnel- 2m
- Size of test section- 30 X 30cm
- Contraction ratio- 6.25:1
- Maximum Reynolds no. achievable- 2500000 per

U –Manometer:

U- tube manometer are generally used to measure the pressure difference at two point. To measure the pressure of the fluid through five port probe, vertical U-tube manometer is used. Fig shows the U-manometer used in this study. The diameter of the tube is 10mm and length is 0.5 m. The working fluid used is water.



Fig 3. U tube manometer set-up

IV. RESULTS AND DISCUSSION

The important thing with calibrating a five-hole probe is producing graphs with reduced errors. Ideally, the graph should remain same every time the probe is calibrated. But there are many sources of errors. The main reason of the errors in calibration is changes in calibration flow quality that can be caused by laboratory disturbances or unwanted air currents during a calibration. Another source of error can occur when the probe is first aligned with the flow. The probe was initially aligned by hand and it leads to human error. In the calibration of the probe, five manometers were used to sample pressure from all five-pressure measurement points. Five tubes were required for the five hole probe ports and two channels were needed for the simple pitot probe which gives the tunnel velocity, total pressure and static pressure in the test section. This method helped to eliminate some of the calibration errors. The following values in table and graphs can be plotted using Equation 2 to Equation 5.

Pitch -30	Pitch -20	Pitch -10	Pitch 0	Pitch 10	Pitch 20	Pitch 30							
-4.1	-3.8	-3.8	-1.8	-3.4	-0.65	-3.2	0.4	-3.4	1.5	-3.6	3	-3.8	5.4
-2.3	-3	-2.1	-1.5	-2.4	-0.5	-2	0.3	-2	1.2	-2.15	2.3	-2.25	4
-1.1	-2.8	-1.1	-1.3	-1.1	-0.4	-1.1	0.2	-1.1	1	-1.15	2	-1.05	3.3
-0.4	-2.5	-0.2	-1.3	-0.1	-0.4	0	0.1	0.1	0.9	0	1.9	0	3
0.8	-2.6	0.9	-1.35	0.8	-0.45	0.7	0.1	0.8	0.9	0.9	1.9	0.9	3.1
1.9	-2.9	1.8	-1.4	1.6	-0.6	1.6	0.1	1.7	1	1.8	2.1	2	3.8
3	-3.4	2.8	-1.8	2.9	-0.8	2.9	0.1	3.1	1.1	3.4	2.4	3.6	4.7

Yaw -30	Yaw -20	Yaw -10	Yaw 0	Yaw 10	Yaw 20	Yaw 30							
-4.05	-3.75	-2.2	-3.1	-1.15	-2.8	-0.4	-2.5	0.85	-2.6	1.9	-2.81	3.12	-3.4
-3.85	-1.7	-2.15	-1.55	-1.1	-1.2	-0.2	-1.3	0.9	-1.3	1.89	-1.4	2.8	-1.86
-3.3	-0.6	-2.34	-0.55	-1.11	-0.4	-0.1	-0.4	0.83	-0.45	1.6	-0.69	2.75	-0.8
-3.26	0.47	-2.1	0.32	-1.05	0.25	0	0.1	0.7	0.17	1.51	0.1	2.9	0.19
-3.34	1.6	-2.08	1.28	-1.1	1.2	0.1	0.9	0.75	0.9	1.7	1.09	3.18	1.1
-3.51	3.2	-2.1	2.24	-1.25	2.05	0	1.9	0.9	1.86	1.88	2.1	3.4	2.31
-3.85	5.15	-2.21	4.1	-1.15	3.3	0	3	0.96	3.1	2	3.73	3.52	4.7

Table 2 : The value of Pitch and Yaw Angle calibration constant.

Figure 4 shows that the center of the crosses indicates the average value, while the four points surrounding each cross indicates the data individually collected from each run. Almost all points in the range of $\pm 20^\circ$ are very close to the average value. It is on the outlying areas, those greater than $\pm 20^\circ$, that the blocks start to get bigger and small errors, such as a misalignment start to become more pronounced. The star formed carpet map as shown in Figure is not perfectly symmetrical because a dimensionally perfect and symmetrical five-hole probe is very difficult to obtain during the even the best hand manufacturing process used.

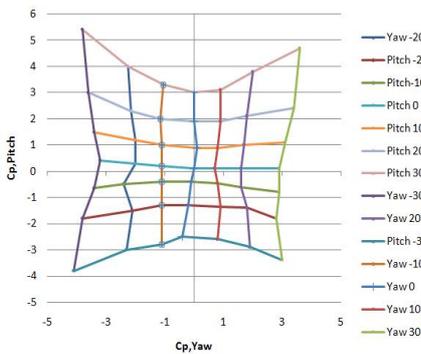


Fig 4. Average Value Calibration Map Cp, Static Calibration Map

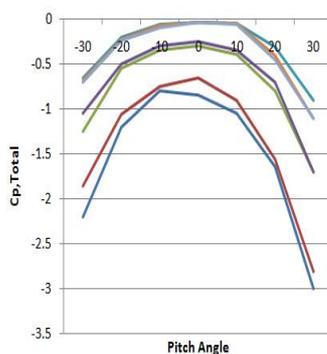


Fig 5. Average Value Cp, Total Calibration Map

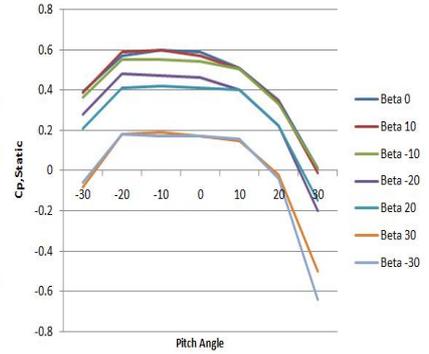


Fig 6. Average Value Cp, Static Calibration Map

Figure 5 shows a typical averaged carpet map produced by readings obtained by the probe. This map is used for finding the best suitable range of pitch and yaw angles during a five-hole probe measurement. From the figure it is observed that the best range of yaw and pitch angle for measurement of probe is $\pm 20^\circ$.

Figure 6 shows the variation of total pressure coefficient with respect to pitch and yaw angle. Total pressure coefficient can be obtained from Figure by using the pitch and yaw angle deduced from Figure. It is observed that total pressure coefficient first increases with pitch angle and after certain value of pitch angle the total pressure coefficient decreases for each value of yaw angle.

This figure gives the static pressure coefficient as a function of pitch and yaw angle. Local static pressure from the five-hole probe measurement can easily be recovered from Figure after determining the pitch and yaw angle. The

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nature of the graph shows that static pressure coefficient increases initially with pitch angle. It is remaining constant for the range of -20° to 10° of pitch angle and then decreases.

All these graphs are closely matches with the results of Jason Town who calibrated the five hole pressure probe. [11]

V. CONCLUSION

In this work, the calibration of probe is carried out. The calibration of the probe was carried out in a blow down type of wind tunnel. In wind tunnel calibration, it was found that the probe gives the correct readings at the centre position of test section. This was because of the fully developed flow at the centre. Near the walls of test section, the effect of the boundary layer predominates and hence probe was not tested at such location.

The probe used for calibration was tested for different positions of yaw and pitch angle. From the results as states above, it can be said that the best suitable range of yaw and pitch angle for the measurements of pressure is $+20^{\circ}$ to -20° .

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