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Experimental Investigation of Multi Hole Probe in Aircraft Air Data Sensors

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ABSTRACT

A Multi Hole pressure Probes (MHP) with five holes and conically shaped was designed for Air craft data sensors for calibrating the total pressure, static pressure, flow angle and flow speed. The main principle of five-hole probe is based on the notion that Mach number, pressure and directionality of the incoming stream may correlated with the combination of pressure readings. The general aspects of the five-hole conical probe were studied by various research papers and concluded with the final design of conical probe with 60^0 included angles which is applicable Air craft data sensors and also for both subsonic and supersonic wind tunnel test sections. Numerical calibration using ANSYS FLUENT 14.0 is done.

Introduction

Air Data System (ADS)

The function of an air data system (ADS) is to acquire mission critical aerodynamic quantities, such as static pressure, local angle of attack, local side slip angle, indicated air speed, pressure altitude, flight Mach number, static temperature and rate of climb. Air data is required for monitoring flight safety, stall warning, navigating the aircraft through complex maneuvers, in-flight calibration and research.

Aircraft air data sensors

Main component of the ADS is probe which collects the information from the environment. Mostly Pitot - static tube is used for this purpose.

The size and geometry of pressure probes shows considerable variation according to their particular use and the number of flow quantities that are required at the same time. Fundamentally, however they all exploit the distribution of pressure which occurs over a body when it is immersed in a moving fluid. These pressure variations depend mainly on wind speed so that with suitable choice of body shape and location of holes to serve as pressure tappings, a probe may be calibrated in a known wind stream; the relationship between pressure and wind speed can then be established over a range of speeds. The design of certain probes involving simple shapes, such as cylinders or spheres, can have some basis in theory, but the final design usually becomes a compromise aimed at minimizing the effect of factors such as Reynolds number, Mach number and stream turbulence. Ideally calibration should be unaffected by these, but in practice, this is not usually attainable although probes can be designed so that extraneous effects are insignificant over large ranges of stream conditions.

For many purposes the measurement of wind speed alone is not sufficient. A knowledge of flow direction as defined by two angles, together with total pressure and static pressure, are common additional requirements, and can be catered for either singly, in groups or in a single instrument. The degree of complexity of both probes and its method of operation will depend on how many flow quantities are to be derived from one set of operations, and in general, the number of flow quantities which can be derived from single probe is related to the number of pressure tapings and the number of attitudes at which it is presented to the flow. Compared with probes intended specially for the measurement of only one quantity, multipurpose instruments, because they involve some degree of compromise in sensitivity to all the quantities that they are intended to degree, are often somewhat less accurate and tend in addition to have larger minimum dimensions. Nevertheless, the first of these advantages is usually far outweighed by errors arising from sequential positioning of single purpose probe, where a number of quantities are required at any one position in the flow.

General features which are desirable in probes selected for the measurement of flow quantities at a point in a fluid can be summarized as follows:

(a) Small size offering a minimum of disturbance to the flow.
(b) Rapid response.
(c) Robust and simple construction.
(d) Calibration both infrequent and unaffected by flow conditions.
(e) All measurements close to one point.

No special significance attaches to the order in which the above properties are given, the importance of each being dependent on the particular application envisaged. It can be seen that some of the properties are incompatible as in the case of (a) and (b) where some lag in pressure response is inevitable in probes of very small size. It follows that practical limits enforce a compromise design expect where the need for any one feature is over-riding: for example, in certain boundary-layer applications, considerable pressure-response lag must be tolerated in order to provide a probe of sufficiently small dimensions.

Here we first discuss

The principles and the geometrical configurations of different MHP designs

Difficulties associated with calibration of MHP next, it is important to mention here that MHP calibrations do not have to be repeated, unless the probe tip is damaged

Discussions of probe interference with the flow, with surface walls and with multiple probes

Also, turbulence measurements and examples of applications are presented

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The paper is organized as follows section 2 provides the brief about related activities, section 3 describes design issues, numerical analysis and results and section 5 concludes the paper.

Related works

A spring 1997 test section calibration program is scheduled for the NASA Glenn Research Center Icing Research Tunnel following the installation of new water injecting spray bars. A set of new five-hole flow angle pressure probes was fabricated to properly calibrate the test section for total pressure, static pressure, and flow angle. The probes have nine pressure ports: five total pressure ports on a hemispherical head and four static pressure ports located 14.7 diameters downstream of the head. The probes were calibrated in the NASA Glenn 3.5-in.-diameter free-jet calibration facility. After completing calibration data acquisition for two probes, two data prediction models were evaluated. Prediction errors from a linear discrete model proved to be no worse than those from a full third order multiple regression model. The linear discrete model only required calibration data acquisition according to an abridged test matrix, thus saving considerable time and financial resources over the multiple regression model that required calibration data acquisition according to a more extensive test matrix. Uncertainties in calibration coefficients and predicted values of flow angle, total pressure, static pressure, Mach number, and velocity were examined. These uncertainties consider the instrumentation that will be available in the Icing Research Tunnel for future test section calibration testing.

As a result of this test, the following conclusions were acquired,

- General observations of the calibration data revealed constant values of total pressure recovery, static pressure recovery, total pressure coefficient, and dynamic pressure coefficient over a ±2° pitch-yaw angle range.
- A linear discrete model for predicting pitch angle, yaw angle, total pressure coefficient, and dynamic pressure coefficient was just as accurate as a full third-order multiple regression model.
- Coefficients were generated for the discrete linear model using least-squares curve fitting and data averaging techniques.
- The linear discrete model coefficients were generated so that pitch and yaw angles could be accurately predicted over a ±5° pitch-yaw range.

Numerical Calibration of a Conical Five-Hole Probe for Supersonic Measurements

A miniature conical five-hole probe of 30^0 half-angle was numerically calibrated for measurements of flow properties at supersonic mach numbers in order to circumvent ther traditional experimental approach vastly demanding on resources. There principle of the multi-hole conical probe is based on the notion that Mach number, pressure and directionality of the incoming stream may be correlated with the combination of pressure readings on the conical probe surface and a Pitot port situated at the flat tip. Using a three- dimensional thin layer Navier-Stokes solver, calibration data were generated for the range of Mach numbers and pitch angles of interest. The validity of the computed pressure distributions on the probe surface was subsequently confirmed in a series of wind tunnel tests including low Mach number and high angularity flow-field. The current study also demonstrated the profound influence of the blunt tip on the nearby static pressure ports, its relevance to the ultimate modeling strategy and the resulting calibration charts.

The earlier experimental investigation by Centolanzi with a 20^0 half angle conical probe demonstrated that accurate and simultaneous measurements of the Mach number components, pressures and flow angularity in three dimensional supersonic flows could be achieved with such an instrument.

The calibration procedure involved positioning the probe at numerous combinations of pitch and roll angles and at free stream Mach numbers of 1.72, 1.95 and 2.46.those calibration data were then cast in to charts so that the Mach number and flow angularity could be obtained from the pressure orifice readings using an iterative procedure.

As a result of this numerical calibration of a conical five-hole probe, the following conclusions were acquired,

- Due to the considerable nose bluntness and the proximity of the surface pressure taps to the flat tip, modeling strategy and numerical approach had to be more elaborate than those reported in the literature.
- Using a three dimensional thin layer Navier-stokes solver, the calibration data were generated for the range of mach numbers and pitch angles of interest.
- The validity of the computed pressure distributions on the probe surface was subsequently confirmed in wind tunnel tests.
- The calibration phase also demonstrated the profound influence of the blunt tip on the nearby static pressure ports, its relevance to the ultimate modeling strategy and the resulting calibration charts.

Windtunnel Calibration of 5-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 2 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.

Obtaining an accurate prediction of aerodynamic rotor performance is key to wind turbine design. The effects of design permutations in airfoil shape, solidity, twist and taper are evaluated using empirical codes based on momentum theory and 2-D wind tunnel empirical data. Such analyses fail to accurately model performance of the airfoils in the highly 3-D, turbulent and unsteady operating environment of an ordinary wind turbine.

As a result of this wind tunnel calibration of a conical five-hole probe, the following conclusions were acquired,

✓ After numerous comparisons, the 5-hole probe was shown to be far superior to the flag probe for measuring local flow angle on a wind turbine.

✓ It resolved the 3-D inflow velocity vector providing a complete quantification of the local turbine blade inflow condition.

✓ The probe has also proven to be a robust device in the hostile turbine operations environment.

With high-resolution angle-of-attack data. It will now be possible to resolve 3-D unsteady separated flow events experienced by turbines in field operation as well as gain some insight into 3-D rotational flow effects.

Recent Development in Multi-Hole Probes

In the first few decades of aerodynamics research, the classical Pitot-static tube was extensively used to measure the velocity in a stream. And for decades again, 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 if 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. The design of modern Multi-Hole Probes (MHP) for the measurement of flow velocity is based on the principle of operation of a Pitot-static tube. The multi-hole pressure probe is a proven and mature measurement technology to resolve the 3-dimensional velocity vectors in steady flow fields (Bryer and Pankhurst 1971, Everett and Gerner 1983, Rediniotis et al. 1993, Zilliac 1989). What could not be measured until very recently is the pressure in midfield. But today, many years after the development of sophisticated methods of measurement like Hot-Wire Anemometry (HWA), Laser-Doppler Velocimetry (LDV) and Particle-Image Velocimetry (PIV), we turned again to the principles of a Pitot-static tube to return the in-field static pressure. This can now be achieved with multi-hole probes properly calibrated.

Multi-Hole Probe

In fact MHP are the only probes that can provide the local value of all three components of the velocity, both static and dynamic pressure and with the appropriate modifications the total and static temperature and the local composition of the fluid. The present article is devoted to recent developments in multi-hole probe technology. Multi-hole probes are based on the fact that the static pressure varies over a solid surface immersed in the flow, from the maximum value, which is equal to the stagnation pressure to low values the order of the base pressure in the wake of the body. Measuring the pressure at distinct points over the body of a probe can provide all the necessary information on velocity components and in-field pressures. This requires careful calibration. Many different shapes have been employed for the tip of a MHP as for example cones, spherical or cylindrical surfaces or faceted surfaces. These probes must be inserted in the flow at the point where a measurement is required. They therefore provide point measurements. And they interfere with the flow. Probe interference is in principle calibrated out, but as discussed later, there are limitations that depend on the dimensions of the tip and the local spatial variations of the flow. Point instruments require traversing along the domain of interest to map out a velocity field. Of all these methods, the hot wire anemometer is the most vulnerable to particulates in the flow and can easily be damaged if not handled properly. It is therefore not appropriate for industrial applications. LDV and PIV require optical access to the point of measurement, which is a limitation to the experimental rig, as well as the range of working media. MHP are robust and reliable tools most appropriate for many industrial applications, that can be operated in opaque fluids that could carry some particulates, and do not need optical access to the point of measurement. But in some cases they may introduce some local or even global interference to the flow.

Design issues in the Proposed work

Basics of Probe Calibration

The unique relationship which exists between pressure and velocity is steady in compressible flow and upon which all pressure-probe methods rely, namely that, neglecting viscosity, change in Kinetic pressure are accompanied by equal and opposite changes in static pressure.

The static pressure defined for present purposes as the pressure sensed by a measuring device at rest relative to the fluid (i.e. moving with the fluid). The total pressure defined as the pressure obtained when the fluid is brought to rest relative to the probe.

It follows that the kinetic pressure can be determined directly by measuring (H-P).If we require the velocity V itself, we need to determine the density as well. This is usually done by measuring the (absolute) pressure and temperature at some point in the flow field, and invoking the perfect gas equation: in practice the pressure changes arising from the motion in incompressible flow are negligible in comparison with the absolute pressures.

Design of 5-Hole Probe

Basic Theory of 5-Hole Probe

The figure (1) shows the schematic representation of a five-hole probe. The probe calibration procedure for the non-nulling method is to place the probe in a known flow and vary the pitch and yaw of the probe over a matrix of angles which exceed the flow angles expected in the flow field to be measured. At each location in the matrix, the five-hole probe measures the direction as well as magnitude of the flow using pressure P1. In case of the non-nulling method, total pressure, static pressure, the angle of attack and side slip angle are calculated by measured pressure: P1, P2, P3, P4, P5. Each pressure is a function of velocity, AOA and AOS. There are four coefficients which are used to calibrate, as follows;

$$Cp_{pitch} = (P_5 - P_4)/(P_1 - \overline{P}),$$

$$Cp_{yaw} = (P_3 - P_2)/(P_1 - \overline{P}),$$

$$Cp_{total} = (P_5 - P_T)/(P_5 - \overline{P}),$$

$$Cp_{static} = (\overline{P} - P_S)/(P_1 - \overline{P}),$$

$$\overline{P} = (P_2 + P_3 + P_4 + P_5)/4.$$

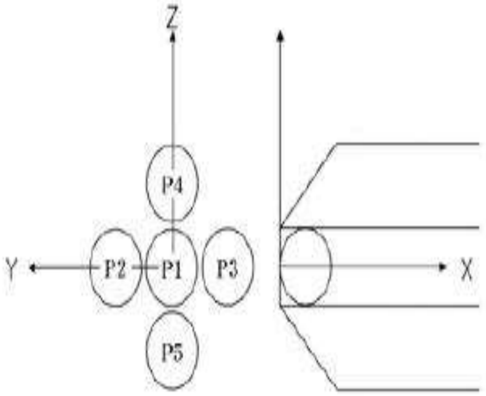

Fig 1. Simple schematic representation of 5- hole probe

Calibration Equations

The static pipe and flow uniformity tests provide the calibration tables to correct the facility's institutional total and static pressure measurement to the true total and static pressure in the test section. The tables provide one correction factor for static pressure, $C_{PS,cor}$, and a second factor for total pressure, $C_{PT,cor.}$ These factors are defined as follows:

$$C_{PS,cor} = \left(\frac{P_{S,pipe} - P_{S,pc}}{q_c} \right)$$

And,

$$C_{PT,cor} = \left(\frac{P_{T,probe} - P_{T,sc}}{q_C}\right)$$

During the test project, this table was used to obtain correction factors for $P_{T,ts}$ and $P_{S,pc}$. For intermediate points between the calibrated test conditions, linear interpolation was performed on both $P_{T,sc}$ and Mc to arrive at the proper correction factors. Linear extrapolation was used to determine the correction factors for points outside the calibrated test conditions.

The correction factors were used to generate corrected test conditions as follows:

$P_{S,ts} = P_{S,pc} + C_{PS,cor} \times q_c$

And,

$P_{T,ts} = P_{T,sc} + C_{PT,cor} \times q_c$

The calibrated tunnel Mach number and dynamic pressure were then computed from $P_{S,ts}$ and $P_{T,ts}$ using standard compressible flow equations.

Flow Uniformity Equations

Local A-plane and B-plane flow angles:

The local flow angles in the A-plane and B-plane were defined by

$$\alpha_m = \left[K_{\alpha 1} \times \left(\frac{P3 - P1}{q_{probe}}\right) + K_{\alpha 2}\right] \times K_{\phi}$$

And,

$$\beta_m = \left[K_{\beta 1} \times \left(\frac{P4 - P2}{q_{probe}}\right) + K_{\beta 2}\right] \times K_{\phi}$$

The local flow angularity was then adjusted for the probe angle of attack and sideslip to give the flow-angularity properties in the tunnel coordinate system.

$\alpha = \alpha_m - \alpha$ probe

and,

$\beta = \beta_m - \beta$ probe

Co-Ordination System Of Probe

In order to establish any angular parameters, such as angle of attack and roll angle, the probe's position needs to be identified with a coordinate system. During the wind tunnel test and data collection, the probe's position is assumed to be fixed in space. The velocity vector's orientation will be measured with respect to the probe's fixed coordinate system. In Figure, the probe coordinate system is shown with axes Xp, Yp, and Zp with

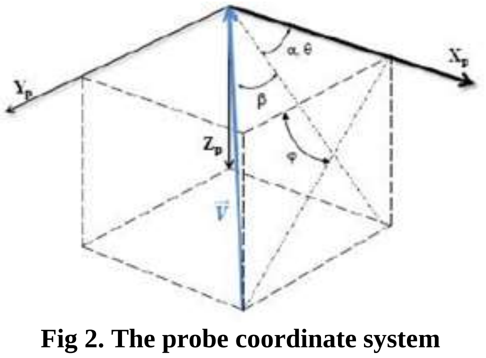

Fig 2. The probe coordinate system

The probe aligned along the Xp-axis. The probe tip meets with the incoming local velocity vector, at the origin. Several angles that indicate the position of the probe in relation to the local velocity vector include angle of attack, α, sideslip angle, β, pitch angle, θ, and roll angle, φ. The angle of attack or the pitch angle is the angle that the probe makes with respect to the oncoming flow about the Yp-axis. The sideslip angle or the yaw angle is the angle that the probe makes with the local velocity vector about the Zp-axis.7 finally; the roll angle is the angle that the probe twists about its centerline on the Xp-axis.

Materials Selection

The materials used for the fabrication of probe and mounting section and their properties are as follows.

i) 5-hole probe - stainless steel 316 (SS 316)
ii)Probe adapter - stainless steel 304 (SS 304)
iii) Probe holder - mild steel
iv) Tapered section - mild steel

Pressure tapping's - SS tube

SS 316 – The Probe:

Grade 316 is the standard molybdenum-bearing grade, second in importance to 304 amongst the austenitic stainless steels. The molybdenum gives 316 better overall corrosion resistant properties than Grade 304, particularly higher resistance to pitting and crevice corrosion in chloride environments. It has excellent forming and welding characteristics. It is readily brake or roll formed into a variety of parts for applications in the industrial, architectural, and transportation fields. Grade 316 also has outstanding welding characteristics. Post-weld annealing is not required when welding thin sections.

Chemical composition: Fe, <0.03% C, 16-18.5% Cr, 10-14% Ni, 2-3% Mo, <2% Mn, <1% Si, <0.045% P, <0.03% S

Mild Steel:

Mild Steel is one of the most common of all metals and one of the least expensive steels used. It is to be found in almost every product created from metal.

It is weldable, very durable (although it rusts), it is relatively hard and is easily annealed.

Numerical Simulation

Two Dimensional Analysis:

In order to get accurate and precise results on the yawmeter theoretical analysis have been made by flow analysis programs like Gambit and Fluent.

The following are the graphical representation of the results obtained under several sonic speeds.

The various input velocities and parameters which are initiated before analyzing are as follows:

Table 1. Input Data (2D Analysis)

S.No	Velocity	Ambient Pressure	Ambient Temperature
1	30 m/s	1.01325 bar	288 K
2	45 m/s	1.01325 bar	288 K

The analysis of the results is shown in the following figure from fig 3 to fig 8.

i) Contour of Static pressure (30m/s)

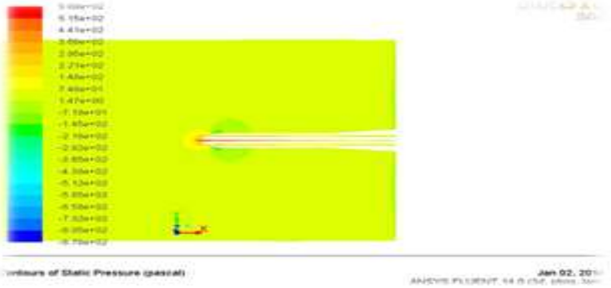

Fig 3. The Contour of Static presure-30 m/s

ii) Contour of Total pressure (30m/s)

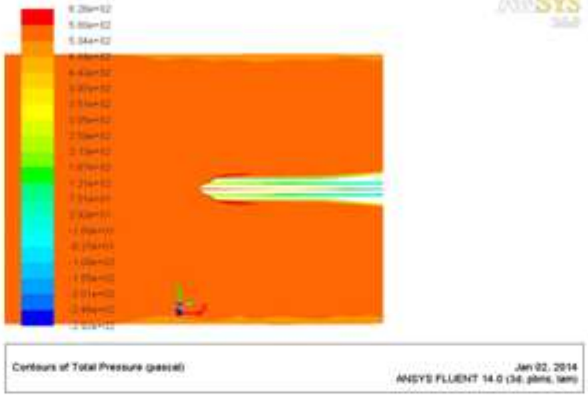

Fig 4. The Contour of Total pressure- 30 m/s

iii) Contour of Velocity magnitude (30m/s)

Fig 5. The Contour of Velocity magnitude- 30 m/s

2. i) Contour of Static presure (45m/s)

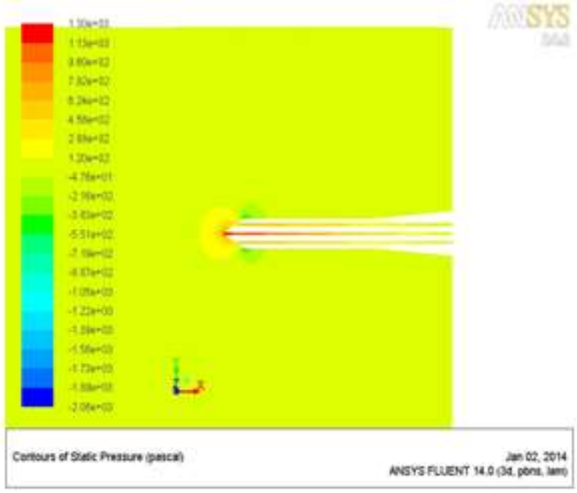

Fig 6. The Contour of Static pressure-45 m/s

ii) Contour of Total presure (45m/s)

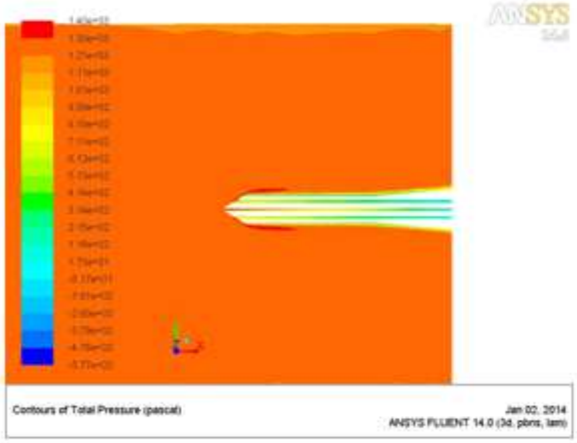

Fig. 7. The Contour of Total pressure-45 m/s

iii)Contour of velocity magnitude (45m/s)

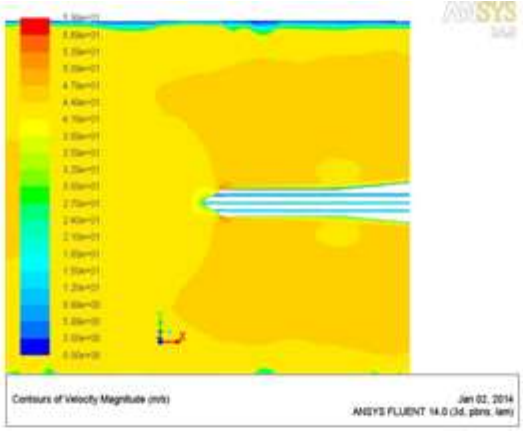

Fig. 8. The Contour of Velocity magnitude- 45 m/s

Conclusion

The simple, more effective and accurate alternate for conventional pitot-tube in Air Data System has been implemented and tested numerically with ANSYS FLUENT 14.0. The probe has been numerically calibrated for four different velocities viz. 15 m/s, 30 m/s, 45 m/s and 60 m/s from which the contours of static, total pressure and velocity magnitude were derived. Of these a sample analysis results for the velocities 30 m/s and 45 m/s has been depicted.

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