Five-Hole Pitch+Yaw Probe Manual

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Aeroprobe Corporation
1700 Kraft Drive, Suite 2350
Blacksburg, Virginia 24060

Voice: (540) 951-3858   FAX: (540) 951-8618

http://www.aeroprobe.com
tech-support@aeroprobe.com

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1.0 Construction, Calibration and Application of Multi-Hole Probes

Fluid mechanicians have employed a variety of multi-hole probes in flow diagnostics. The most common is the well-known Pitot-static probe, which can provide flow speed information, but only if the flow direction is known beforehand. Three-hole pitch or yaw probes can provide information on one flow angle in addition to the flow speed, but only to a flow angles where the center port ceases to exhibit the highest pressure of the three ports. Five-hole probes have been used extensively to provide velocity magnitude and direction (i.e. the velocity vector) and the local total and static pressures, but the range of this instrument is limited to velocity vectors inclined by less than 55°- 60° with respect to the probe axis. Seven-hole probes provide the same information as five-hole probes, but with higher accuracy for angles as high as 70°-75° with respect to the probe axis.

Multi-hole probes are rugged, requiring only one calibration (per flow speed) at the end of the manufacturing process. Application is straightforward and accuracy is typically better than 1% of the flow speed and 0.5° in flow angles.* However, the frequency response for standard-response probes is low (typically less than 50 Hz), and (simply by the nature of their operation) they present some interference with the flow. Multi-hole probes are normally among the most cost-effective methods for examining flow, providing data accurate at a reasonable cost.

Construction

Aeroprobe multi-hole probes are typically constructed with a stainless steel tip. The probe tip is typically machined to form either a cone with a half-angle of 30°, or a hemisphere. The pneumatic tubing connecting the tip ports to the pressure sensors are soldered to the tip and then fit into a larger tube (the shaft of the probe). The space between the tubes is filled with epoxy to prevent tube displacement. A probe mount is usually manufactured to be integral with the probe shaft. This is important to fix the probe in calibration and testing, and sometimes necessary in order to provide a roll reference surface (in the case of straight probes).

Calibration

No two probes can be machined exactly the same, therefore, the calibration process must be performed for every probe. During calibration, the probe is mounted in the wind tunnel on a positioning mechanism, capable of independent positioning in two degrees of freedom. The probe tip is constrained to remain at the same point in the test section. A system of stepper motors positions the probe at a series of predetermined orientations with respect to the free stream. At each one of these orientations, the multi-hole probe pressures along with the free-stream total pressure are recorded. In almost all cases, the pressures are differential with respect to the local static pressure. The collected data are used to generate the probe calibration map, and/or reduction functions. Probes are calibrated at many flow angles for one calibration flow speed. More information about probe calibration, bias angle removal and related topics may be found in the literature listed in the reference list.

Mach and Reynolds Number Effects

Calibrations at additional flow speeds may be used to interpolate test data between calibration maps at several Mach and Reynolds numbers. Recommended Mach number spacing for multiple calibrations is $\Delta M = 0.1 - 0.15$. If the probe is going to be tested at low flow speeds (typically less than 17 m/s in air), then additional calibrations might be required in order to effectively cover the Reynolds number effects.

Testing and Data Reduction

The principle idea of operation is the following: The pressure over a bluff body is the highest at the stagnation point and lowest near separation. If the flow direction forms small angles with the axis of the probe (below 20°), the center hole registers the highest pressure. If however, the flow is steeply inclined with respect to the probe, then one of the peripheral holes on the windward side of the probe tip registers the highest pressure, while on the leeward side of the probe, the flow is separated. The pressure information that is provided by any hole(s) in the separated region is not

* Accuracy is Dependent on Use of Accurate Pressure Transducer of Appropriate Range. Stated Accuracy is with Use of Transducers Accurate to 0.1% Full Scale.

useful in reduction. Careful calibration, involving the recording of the pressure data for many different flow angles allows the construction of a calibration map, relating the pressures to the flow direction and speed.

When thinking about probe calibration and data reduction, it is useful to think about how many independent pieces of information are available, and therefore how many unknown quantities can be determined. In addition, there are some assumptions that must hold for each type of probe so that accurate data is acquired. Flow variables, independent quantities and assumptions for each probe are given in Table 1. Note that the flow speed ($|\mathbf{V}|$) can be determined from the total and static pressure (p_t and p_s, respectively) and knowledge of stagnation thermodynamic quantities.

Table 1: Probe Capabilities for Various Multi-Hole Probes

Probe Type	**Number of Ports (Usable)**	**Variables Determined**	**Angular Limitation**	**Assumptions**
Pitot-Static	2 (2)	P_t, P_s	5°-10°	Flow Direction Already Known
Pitch or Yaw	3 (3)	P_t, P_s, α or β	15°-25°	Calibration Holds for Small (< 10°) Deviation in Other Angle
Pitch and Yaw	5 (5)	Pt, Ps, α and β	15°-25°	Calibration Holds for Small (< 10°) Deviation in Other Angle
5-Hole	5 (5 Low-Angle, 4 High-Angle)	P_t, P_s, α, β	55°-60°	Ports in Separated Region not Usable
7-Hole	7 (7 Low-Angle, 4 High-Angle)	P_t, P_s, α, β	70°-75°	Ports in Separated Region not Usable
Omniprobe	18 (5)	P_t, P_s, α, β	155°-160°	Ports in Separated Region not Usable

Flow Interference

Due to the size of the probe, the user may anticipate some interference with the flow. Ideally, the probe should be utilized in the same manner as it was calibrated. This means that the probe should not be placed closer than 4-5 diameters to another body. Errors may be expected if one attempts to measure too close to a solid wall or model. Boundary layer measurements therefore are normally not reliable.

In the same way, the probe may interfere with the flow and cause unwanted effects. Fluid mechanics phenomena that are very sensitive to external disturbances have also been known to be affected by the probe. This includes, but is not limited to:

(i) Inserting the probe near the core of a columnar vortex, like the tip vortex of an airfoil, may induce vortex breakdown.

(ii) Inserting the probe in a laminar shear layer or a laminar boundary layer at moderate Reynolds numbers may induce transition.

(iii) Inserting the probe in a region over a wall with adverse pressure gradient may induce separation.

Frequency Response

Another limitation in the use of a multi-hole probe is the relatively low uncorrected frequency response. Like many methods of measuring air pressure via a pressure tap and a flexible hose, the multi-hole probe have an uncorrected frequency response of 20 to 50 Hz. Higher frequency oscillations of the pressure attenuate and phase-shift in the tubes and therefore cannot be measured correctly without knowing more about the acoustic properties of the tubing system. One cannot expect to measure turbulent flow quantities like turbulence level or RMS of the velocity fluctuations. However, transient phenomena which develop within a time span as small as 50 milliseconds can be captured by multi-hole probes, provided the tubing used to connect the probe to the pressure sensor itself is not longer than 10 inches. Note that frequency response attenuation and phase shift of the pressure signal is not an issue in an incompressible fluid such as water, because rapid pressure changes in a tubing system filled with such a fluid cause very little or no relative motion between the fluid and the walls of the tubes, and thus no frictional loss.

Aeroprobe has the ability to calibrate any probe and tubing system to determine the acoustic properties. In addition, Aeroprobe offers software that can apply the acoustic calibration to a time series of pressures in order to correct the pressures and recover the actual pressures at the probe tip. This process can increase the frequency response of the probe into the hundreds of Hz for a standard probe/tubing/sensor system, or into kHz for fast-response probes with embedded sensors.

2.0 Connecting the Probe to Pressure Sensors

Port numbers are normally indicated by the tube length of the exposed tubes on the back of the probe (**in some custom cases, labels will be used to indicate the port correspondence**). The longest exit tube corresponds to port 1, and the remaining ports are numbered sequentially based on length. For probes with an optional static chamber, the takeoff from that chamber corresponds to the shortest exit tube.

Since the multi-hole probes depend on the measurement of the port pressures to operate, the exit tubes of the probe must be connected to pressure transducers in some manner. In almost all cases, Aeroprobe probes are designed to be connected to pressure sensors in a one-to-one fashion. Aeroprobe recommends robust and flexible tubing to connect the probe to the pressure sensors. Aeroprobe can meet your tubing needs, and can recommend the appropriate tubing type and size for your application. Aeroprobe also supplies compact tubing reducers so that tubing of different diameters may be connected.

Using Probes with AeroAcquire

When using probes with the Aeroprobe data acquisition package (AeroAcquire), it is assumed that the probes are connected to the available pressure transducers in the following manner. The first probe, with N_1 ports is connected to the first N_1 transducers, whether these are individual sensors or the first N_1 sensors of a pressure scanner. Any remaining probes should be consecutively connected to the next available sensors, until all probes have been connected. It is not necessary that all probes have the same number of ports, but at this time AeroAcquire supports only 5-hole, 7-hole, 12-hole, and 18-hole probes, in addition to one Pitot-static probe for measurement of the freestream speed. Once the probes are mounted, oriented correctly and connected to the sensors, the remaining setup for data acquisition is handled through AeroAcquire. This setup will require knowledge of how the probes are connected, the number of ports for each probe, and the pre-processed calibration files for each probe.

3.0 Orienting the Five-Hole Pitch/Yaw Probe

The two five-hole probe coordinate definitions are shown in Figure 1 for a straight probe and Figure 2 for bent (cobra/L-shaped) probes. The coordinates are always defined into the tip of the probe where the x_p axis is along the axis of the tip. The z_p axis is always normal to the reference surface of the probe, which is the plane of the probe for a cobra or L-shaped probe, and is the reference flat (marked with an “R”) on the hexagonal mount of a straight probe. The probe coordinates are defined only by the axis of the probe and the reference surface or flat. There is no predefined relationship between port numbering and the probe coordinate axes.

For a five-hole probe, the probe will be aligned so that the five holes are aligned both horizontally or vertically. The holes aligned horizontally are used to measure the yaw angle in an aerodynamic sense, and the holes aligned vertically are used to measure the pitch angle. The yaw angle is normally denoted by the Greek letter β, and the pitch angle by the Greek letter α. This is how the angles are defined in Figures 1 and 2. In most cases, port 1 is the center port, and all three ports will be aligned with either the y_p or z_p axis. Also, port 2 is typically (though not necessarily) the port that will exhibit increasing pressure with increasing yaw angle. Port 4 is typically (though not necessarily the port that will exhibit increasing pressure with increasing pitch angle.

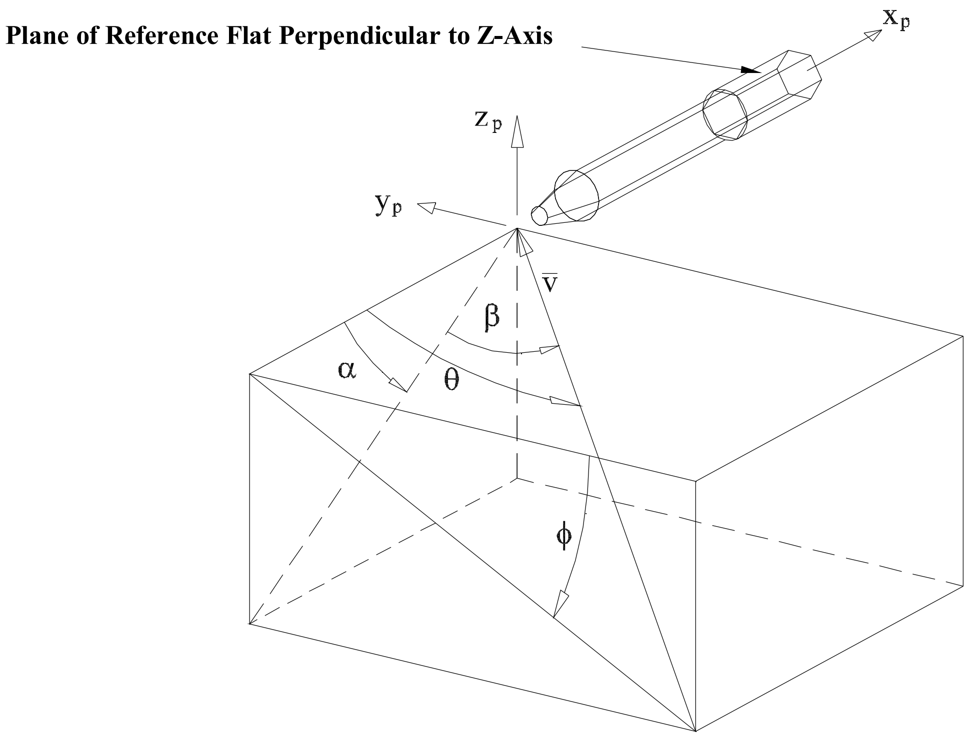

Figure 3
Coordinates for Straight Probe

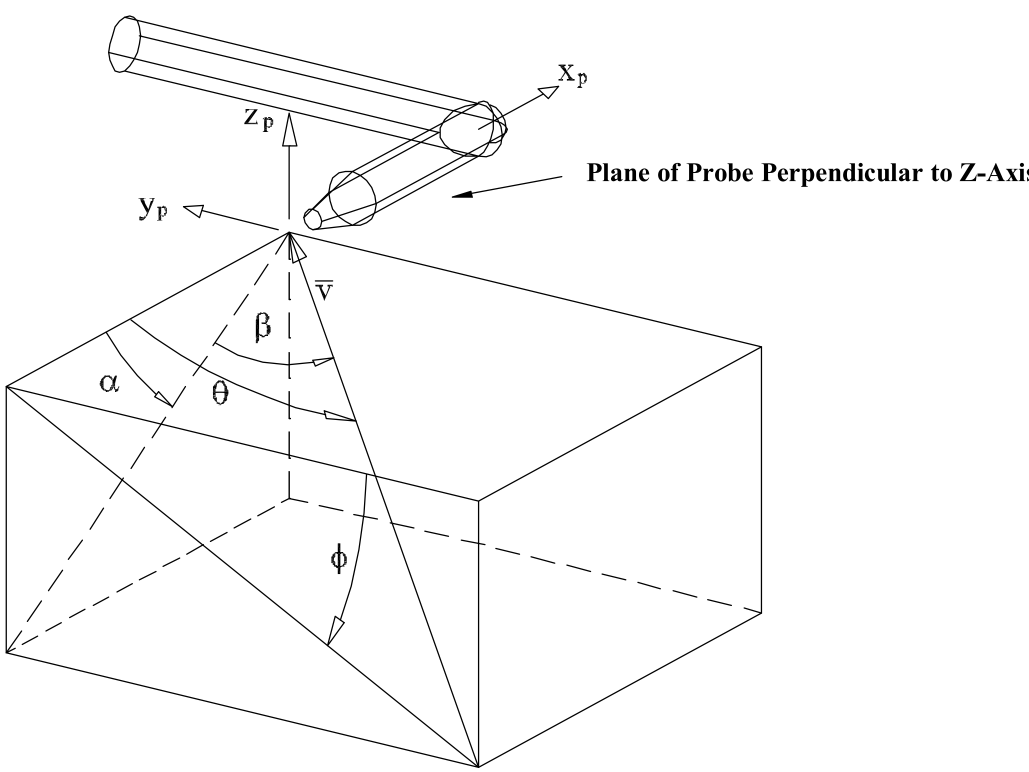

Figure 4
Coordinates for Cobra/L-Shaped Probe

4.0 Calibration File (Spreadsheet) Contents

The calibration spreadsheet is designed to enable the user of the yaw/pitch probe to understand how the raw calibration data is used to determine the calibration functions, and how the resulting functions are used to reduce test data in the flows of interest. There are essentially five parts to the calibration file:

1 – Variables and Conventions Defined

On the first sheet of the calibration template, the various parameters and angle conventions are defined.

Definitions and Equations (Airflows Only, $\gamma = 1.4$):

P_n, n = 1-6	Port Pressures, Measured
P_6	Probe Manifold Static Pressure, Measured
T_o	Total Temperature, Measured
P_o	Total Pressure, Absolute, Measured
$P_s = P_o - (P_{t,\ Measured})$	Static Pressure
$P_{t,\ Measured}$	Total Pressure, Measured, Referenced to Ps
$M = \{(2/(\gamma-1))[(P_o/P_s)^{((\gamma-1)/\gamma)} - 1]\}^{0.5}$	Mach Number
$T = T_o/(1 + 0.5(\gamma-1)M^2)$	Temperature
$a = (\gamma RT)^{0.5}$	Speed of Sound, R = 287.04 J/kg/K
$V = aM$	Temperature
$q = 0.5\gamma P_s M^2$	Dynamic Pressure
$Qbar = P_1 - P_6$	Dynamic Pressure Coefficient
$C_\beta=(P_2 - P_3)/Qbar$	Yaw Coefficient
$C_\alpha=(P_4 - P_5)/Qbar$	Yaw Coefficient
$C_t = Qbar/(P_{t,\ Measured} - P_s)$	Total Pressure Coefficient
$C_s = (P_6 - P_s)/Qbar$	Static Pressure Coefficient

2 – Calibration Data

The raw calibration data is displayed in the left part of this sheet. There may be calibration data for several speeds, and additional data for offset analysis (see below). In addition, there is normally data for angular sweeps perpendicular to the port arrangement. This latter data is acquired to document the sensitivity of the probe to the flow angle that the probe was not designed to measure. On the right side of this sheet are the calculated data. This includes the updated angles (from the offset analysis) and the pressure coefficients and pseudo-dynamic pressure coefficients (as defined in the section on data reduction below).

3 – Offset Removal

The removal of the bias angle from the calibration is performed with a standard method. The idea is that the probe is aligned to the oncoming stream if the tip of the probe can be rotated 360° about its axis and the pressures do not change. Therefore, it is sufficient to show that the probe can be placed at 180° from its original state without changing the pressure coefficients. Essentially, this is what is shown in the graph. The point where the two lines meet and cross is the location where the probe is aligned with the flow. The angular location is the bias angle, and it is removed from the data by subtracting it from the original angular quantities in the calibration data sheet (compare right side calculated data to original data on the left side). For more information, refer to the paper on bias angle removal in the references.

4 – Graphs and Curve Fits

After bias offset removal, the required nondimensionalized parameters are calculated and plotted. The data from the right side of the Yaw Data sheet is used as a basis for the graphs. Each sheet contains graphs corresponding to one calibration speed. In the first set of graphs, two coefficients (C_q and C_α or C_q and C_β) are shown as a function of the independent angles alpha or beta. C_q relates the velocity to the angle, and C_α or C_β are nondimensionalized angle coefficients. In the next set of graphs, three coefficients are shown as functions of the angle pressure coefficient (C_α or C_β). Depending on the data reduction method, either the C_q curves or the C_t, C_s curves will be used. In the reduction process, C_β and/or C_α are used independently to define the angle and the velocity magnitude.

5 – Data Reduction

In this section, the methods for the reduction of the raw pressure data (via the calibration data) to useful velocity and angle information will be discussed. Three sheets in the calibration data workbook show examples of how to perform the pressure-to-velocity reduction, depending on how the port pressures are measured. These last three sheets, titled "Sample Reduction Method (1, 2, or 3)" are all the user needs to properly reduce data for the probe.

The "Sample Reduction Method1" sheet shows how to reduce the pressure data if all of the tip ports are measured independently with respect to the probe static ring (i.e. P1-P6, P2-P6, P3-P6, P4-P6 and P5-P6) using differential transducers and if the absolute static ring pressure is measured with an absolute sensor. This method can also be modified if the user does not wish to measure the static ring pressure absolutely. In lieu of this measurement, the user can estimate the actual static pressure of the flow and insert this value into the "Ps" column directly before the "Pt" column.

The "Sample Reduction Method2" sheet shows how to reduce the pressure data if only the differences between the tip ports are measured (i.e. P1-P6, P2-P3, P4-P5) using differential transducers and if the absolute static ring pressure is measured with an absolute sensor. This method can also be modified if the user does not wish to measure the static ring pressure absolutely. In lieu of this measurement, the user can estimate the actual static pressure of the flow and insert this value into the "Ps" column directly before the "Pt" column.

The "Sample Reduction Method3" sheet shows how to reduce the pressure data if only the differences between the ports are measured (i.e. P1-P6, P2-P3, P4-P5) using three differential transducers but the static ring pressure is NOT measured with an absolute sensor. The Method3 example assumes an incompressible reduction that is not suggested at speeds over Mach 0.2. The user must specify the local air density.

Reduction method #1 is demonstrated by using calibration data. The method to determine the yaw angle and the flow speed that is applied in the "Sample Reduction Method1" can be outlined as follows:

- Acquire the pressure data in any unit of pressure.
- Calculate Qbar C_α, and C_β.
- Use the appropriate curve fits to calculate α, β, C_t and C_s.
- Use the definitions of C_t and C_s (above) to calculate the total and static pressures (P_t and P_s, respectively).
- Knowledge of P_t and P_s can be used together with thermodynamic quantities to find the flow speed. Note that a compressible reduction is employed in this example spreadsheet.

Reduction method #2 is demonstrated by using calibration data. The method to determine the yaw angle and the flow speed that is applied in the "Sample Reduction Method2" can be outlined as follows:

- Acquire the pressure data in any unit of pressure.
- Calculate Qbar C_α, and C_β.
- Use the appropriate curve fits to calculate α, β, C_t and C_s.
- Use the definitions of C_t and C_s (above) to calculate the total and static pressures (P_t and P_s, respectively).
- Knowledge of P_t and P_s can be used together with thermodynamic quantities to find the flow speed. Note that a compressible reduction is employed in this example spreadsheet.

Reduction method #3 is demonstrated by using calibration data. The method to determine the yaw angle and the flow speed that is applied in the "Sample Reduction Method3" can be outlined as follows:

- Acquire the pressure data in any unit of pressure.
- Calculate Qbar and C_α and C_β.
- Use the appropriate curve fits to calculate α, β, C_q.
- Use the definitions of C_q (above), and the user specified density (ρ), to calculate the velocity.

$$|V| = \sqrt{\frac{2*Q}{\rho}}$$

5.0 Care and Cleaning of Multi-Hole Probes

Care and Handling

Your probe is packaged with caps over the exit tubes and the tip. These should remain on the probe at all times, if possible, until actual testing is to occur. Remove the exit tube caps one at a time as you replace them with your flexible tubing. **Keep the caps and packaging for later storage/shipping uses**. Any time the probe is not in use, the tubes and tip should be inspected and capped. It is much easier to keep a probe clean than it is to unclog a dirty probe. Proper probe care will go far towards avoiding probe repair.

Supplies and Equipment

To properly clean your probe you will need a syringe, needle, appropriate size flexible tubing to fit the stainless steel exit tubes, Isopropyl Alcohol (preferably reagent grade, but rubbing alcohol will do) a supply of compressed air (the air cans used for cleaning electronic equipment are particularly useful for injecting compressed air into the probes), and a filter/regulator with a quality filter, preferably providing filtration to 10 micron or smaller (the gas from the cans is already clean, so a filter would not be necessary). The filter and regulator can be purchased at your local industrial tool or welding supply store. You will need fittings, hose, and a nozzle or gun. Additional syringes, needles, or tubing can be ordered from Aeroprobe.

Cleaning the Ports

Probe cleaning should only be attempted when the response from the pressure transducers, or visual inspection indicates blockage of any ports. Use only isopropyl alcohol to clean the probe ports. Acetone may be used in extreme circumstances, but the probe should be cleaned immediately after exposure to acetone, as acetone leaves a residue that will clog the ports. Fill the syringe with clean alcohol, connect the needle, and insert an exit tube into the flexible tubing. Aim the probe tip at a trashcan or other receptacle, and inject the alcohol, emptying the syringe. Disconnect the needle from the syringe, and blow compressed air (at about 40 psi) into the needle housing. Let the air continue for a few seconds after the alcohol is cleared, to allow vapors to be evacuated. Be careful not to squirt alcohol where it doesn't belong! This includes clothes, furniture, open flames or hot surfaces, and especially your eyes. Be sure your work area has adequate ventilation so that there is no buildup of alcohol fumes.

6.0 References

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