Multi-hole Probes User Manual

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Standard Probes User Manual, Document No. 90001-02-UMN-02, Revision C, May 2015

Table of Contents

SECTION 1: Overview

System components

Aeroprobe Corporation multi-hole probes require five basic system components in order to complete a measurement of the three-dimensional flow velocity field. Aeroprobe provides all components of the system, however, these items are sold separately and this manual details the operation of the probe.

Multi-probe Measurement System Components:

1. The multi-hole probe
2. Aerodynamic calibration data
3. Pressure sensors
4. Data acquisition system
5. Pressure-to-velocity reduction software

Probe purchase contents

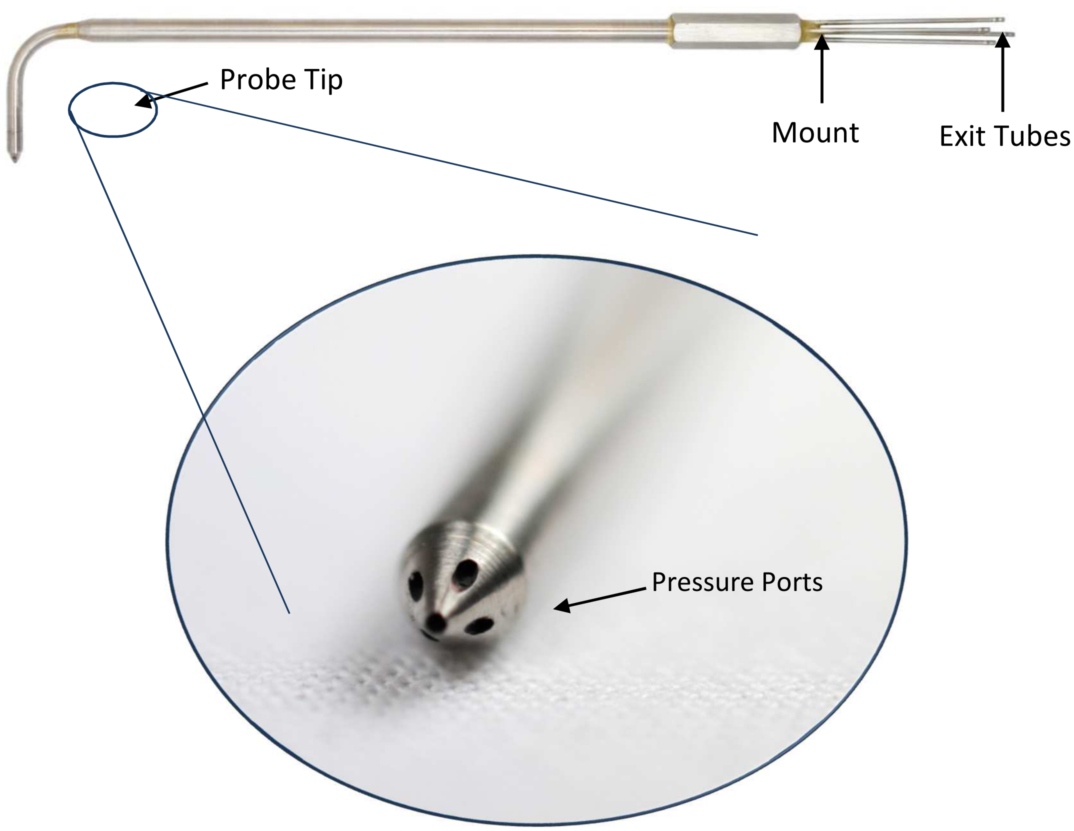
A probe purchase includes:

1) The 3-, 5-, 7- or 12-Hole probe (with protective tip cover).
2) A data flash drive with USB interface. The flash drive contains:
   a. The aerodynamic calibrations for the probes
   b. The probe manual (this document)
   c. Additional data/documentation files, as required for a particular probe
3) Ten (10) feet (3 meters) of flexible tubing per port (typically delivered in 50 ft rolls)
4) Storage case

WARNING: The probe is a highly sensitive and fragile device that can be easily damaged. Please use extreme caution when handling.

- ALWAYS PROTECT THE PROBE TIP AND PORTS. WHEN THE PROBE IS NOT IN USE, KEEP THE PROTECTIVE COVER ON THE PROBE, AND STORE IN THE PROBE CASE.
- DO NOT BEND THE PROBE SHAFTS, TIP OR EXIT TUBES.
- DO NOT EXPOSE THE PROBE TO EXCESSIVE VIBRATIONS.
- DO NOT DROP THE PROBE.
- DO NOT EXCEED THE OPERATING TEMPERATURE OF THE PROBE.
- DO NOT DISCARD YOUR DATA FLASH DRIVE.


Probe Case
Flexible Tubing
LOT NUMBER:
SAINT-GOBAIN
PERFORMANCE PLASTICS
Protective Cover
Multi-Hole Probe
Data USB Drive


Probe Tip
Mount
Exit Tubes
Pressure Ports

SECTION 2: Probe Maintenance

Inspection

To prepare the probe for use, remove the tip cover. Visually inspect all of the pressure ports on the tip of the probe and all of the exit tubes at the back of the probe. Make sure that they are clear of any debris or blockage.

Ensure all ports are clear by attaching a short piece of the provided flexible tubing to compressed air that is between 50 psi and 90 psi. The air should be free from oil and dirt to avoid clogging the probe. Air cans used for cleaning electronic equipment can be particularly useful for injecting compressed air into probes. Attach the other end of the flexible tubing to each exit tube one at a time and ensure air is exiting the respective port. The flow rates from each of the ports should be similar for all the ports.

Cleaning

New probes are cleaned prior to delivery, so cleaning a new probe is not a necessary step. However, frequent cleaning is recommended if the probe is heavily used or there is visible dirt build-up inside the ports or on the tip surface. Regular cleanings should involve the use of compressed air (oil and dirt free) between 50 and 90 psi to clear debris from the pressure ports. Use a short piece of the provided flexible tubing to connect the compressed air source to each exit tube and ensure air is exiting from the probe tip.

To remove heavy dirt build-up, the probe tip may be soaked in water with a small amount of a mild surfactant. Remove the probe from the liquid and use a soft nonabrasive cloth to wipe away the dirt from the tip. Use compressed air to remove all of the liquid from the ports.

If the probe develops a blockage that cannot be cleared by the above methods, use Nitinol wire to break up the debris. This type of wire is recommended because it is a flexible shape memory alloy wire that can easily be inserted and removed from the port. DO NOT use standard stainless steel wire because it could get lodged in the probe or break inside of the port.

For particularly difficult blockage, an alternative method to cleaning a blocked probe is to submerge the probe in an ultrasonic bath of water with a small amount of a mild surfactant. Aeroprobe recommends a bath time of 10-20 minutes followed by the use of the Nitinol wire as necessary, followed by flushing with water and clearing of all liquid using compressed air.

If there is a blockage present that cannot be removed with the methods above, the probe is not usable. Contact Aeroprobe’s customer support to discuss the situation. Do not attempt to remove a block with other methods, as this could alter the specifications of your probe and/or create further damage. Any attempts to remove a blockage or clean the probe that are not described in this section will void the warranty.

Leak checking

New probes are leak checked prior to delivery, so leak checking a new probe is not a necessary step. Leak checking is recommended if the probe has been previously used or there has been a possibility of damage.

Use a large container that can easily hold the probe. Fill the container up with water until the probe is completely submerged. Attach a short piece of the provided flexible tubing to compressed air that is between 30 psi and 90 psi. Attach the other end of the tubing to one of the exit tubes. The air will escape out of the corresponding pressure port on the tip. Gently cover that port with a finger so that no air can escape. Now, the port pressure line should be completely sealed with the compressed air trapped inside. Visually inspect the rest of the probe for the presence of air bubbles that would indicate a leak. Repeat the process for all remaining ports.

When the leak check is complete, use compressed air to remove any excess liquid from the inside and outside of the probe. If there is a leak present, the probe is not usable and needs to be repaired. Contact Aeroprobe customer support to discuss the situation. Do not attempt to repair a leak as this could alter the specifications of your probe and/or create further damage, and will void any warranty.

IMPORTANT: Remove all liquid from ports with compressed air. If any liquid is present the probe will not operate properly.

IMPORTANT: Do not physically alter the probe tip. Do not use common wire, sand paper, files or any abrasive cleaning tool.

IMPORTANT: Do not attempt to repair a leak. Contact Aeroprobe for further assistance.

SECTION 3: Probe Use

Pneumatic connections

This section contains a general description of how to make pneumatic connections to a standard probe. For standard multi-hole probes, the exit tubes are stainless steel tubulations with 0.040” OD. For custom designs please contact Aeroprobe.

The effectiveness of the probes is dependent on making an accurate pressure measurement. In order to acquire pneumatic pressures from the probe ports, it is necessary to make a leak-free connection from each probe port to a pressure sensor. This connection is most easily made with flexible plastic tubing.

The flexible tubing provided with each probe has the specifications provided in Appendix II: Flexible tubing specifications. Aeroprobe recommends this tubing for most low-pressure applications. This tubing can expand to seal on metal tubing of sizes 0.040” – 0.063” OD with tubulations. Other tubing may be used as desired or appropriate, but care should be taken to choose tubing that seals properly on the probe ports. For high pressure uses Aeroprobe recommends Scanivalve spring clamps.

The exit tubes are staggered at different lengths corresponding to a port numbering convention detailed in the figures below. The longest exit tube corresponds to port one, and the remaining ports are numbered and staggered sequentially, with the shortest tube corresponding to the highest-numbered port. The numbering convention (and thus the exit tube stagger) corresponds to a specific port orientation that was used to calibrate the probe, and is oriented with respect to a known reference surface labeled “R” on the probe. The same port connections must be employed each time when acquiring data or the probe calibrations will not apply and inaccurate data will result.

The first step in the process of connecting the probe is to attach flexible tubing to each exit tube. Trim the end of a piece of flexible tubing (trim about 3-5 mm of length). If the tubing is not trimmed a leak could form at this interface. It is particularly important to remember to trim the tubes if they have already been used previously. Holding the probe and flexible tubing so that the axis of the exit tubing is at about a 30° angle to the axis of the flexible tubing, gently press the flexible tubing over the edge of the exit tube. Once the flex tubing is over the end of the exit tube, gently rotate until the tube axes are parallel and press the flexible tubing down onto the exit tube until it passes over the bulge on the tube (~3-5 mm). The fit should be snug. In the same manner, attach the other end of the tubing to the pressure sensor being used. Repeat with remaining exit tubes.

Prior to using the probe in a test, it is recommended that you apply a known pressure to all of the tip ports, in situ, and checking the pressure level sensed by the transducer/data acquisition. In addition, a channelization procedure is recommended. During channelization, each port (one-by-one) is exposed to an increased/decreased pressure while the remainder of the ports are held at a constant, reference pressure (typically zero for differential sensors). When channelized, the pressure reading on the corresponding channel should show the increased/decreased pressure. If there is no change on the channelized port, or other ports also increase decrease ("follow") the tested port, this is an indication that there is a problem with the probe pneumatics, the data acquisition, or the probe itself. The combination of pressure/channelization tests will verify that all the pneumatic system components (probe, tubing and sensors) are free of blockages and leaks, and that the flexible tubing is connected correctly.

Mounting the probe

The probes are calibrated with respect to a specific coordinate system where the origin is located at the tip of the probe. The coordinate system is oriented with respect to the probe geometry and probe reference flat that is engraved with an R on the probe mount, as shown in the figures below. The data resulting from the pressure-to-velocity reduction will be with oriented with respect to the same coordinate system.

For ease of use, it is recommended that the probe be oriented so that the reference flat is "up", that is, the normal to the reference flat is vertically upwards. In some cases the probe cannot be mounted in a test while maintaining this orientation. In this case, it may be necessary to apply a coordinate transformation to the resulting data.

The velocity vector is defined with respect to the probe using the flow angles (α, β, θ, ϕ) and the velocity magnitude (|**V**|). The figures below each show the two coordinate systems Aeroprobe uses to describe the angle of the fluid flow relative to the probe. The first is a standard spherical coordinate system where the azimuthal angle (roll) is denoted by $\phi\,(0 \leq \phi < 2\pi)$ and the polar angle (cone) is denoted by $\theta\,(0 \leq \theta \leq \pi)$. The second coordinate system is a wind-axis system that is best suited for flight applications, where the incidence angles are typically low (< 20° with respect to the axis of the probe). In this second system, the angle of attack (α) is measured from the probe longitudinal axis to the projection of the wind direction onto the X_p-Z_p plane. The angle of sideslip (β) is measured from the projection of the wind direction onto the X_p-Z_p plane to the wind vector. The cone-roll coordinate system is used during calibration of Aeroprobe probes and is the basis of the data reduction algorithm (*AeroFlow*). The α–β coordinates are derived from the velocity components in post processing.

The relationship between the velocity components and the $\theta-\phi$ angles and α–β are given as follows where *u*, *v*, and *w* are the velocity components in the *x*, *y*, and *z* directions respectively.

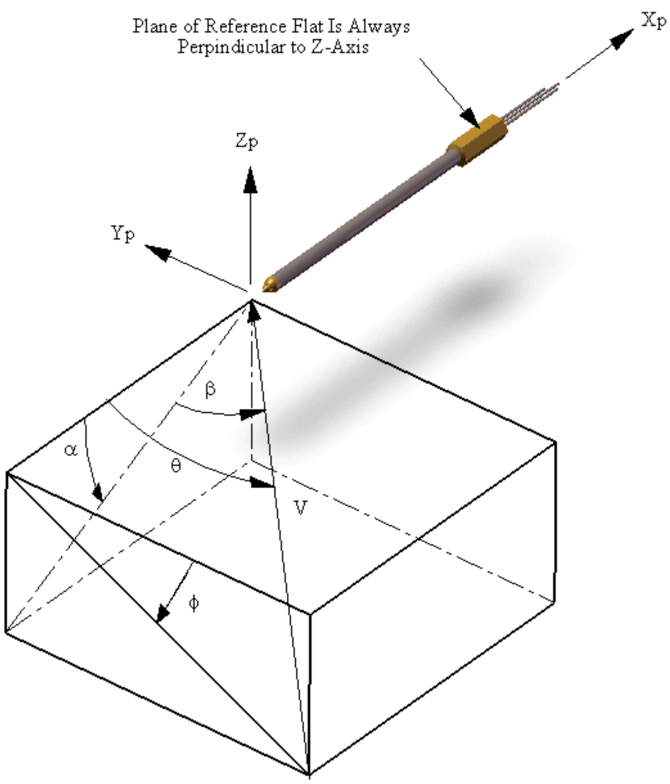
$$u = V\cos\theta$$
$$v = V\sin\theta\cos\phi$$
$$w = V\sin\theta\sin\phi$$

$$\alpha = \tan^{-1}\left(\frac{w}{u}\right) = \tan^{-1}(\tan\theta\sin\phi)$$

$$\beta = \sin^{-1}\left(\frac{v}{V}\right) = \sin^{-1}(\sin\theta\cos\phi)$$

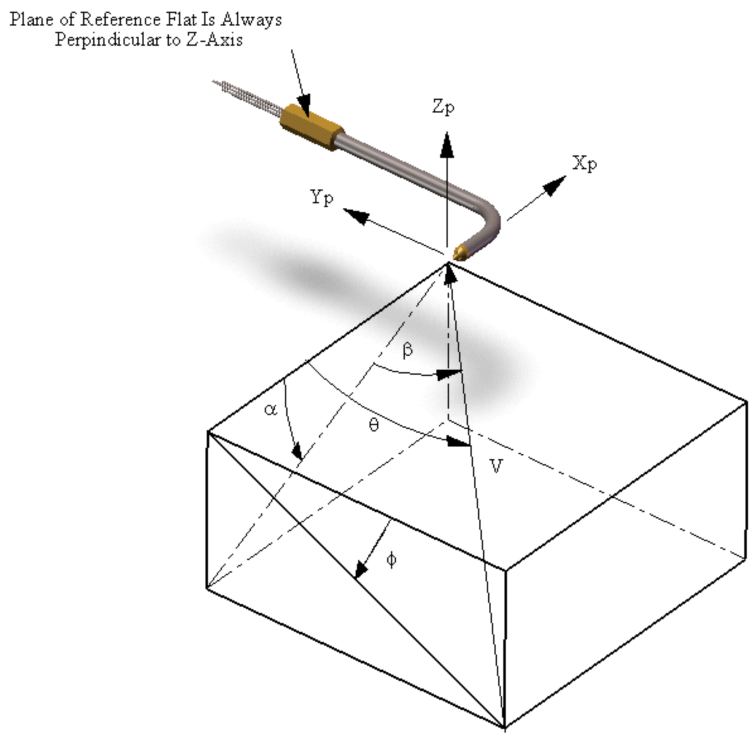
IMPORTANT: Only a single angle can be measured with 3-hole probes. The other angle is assumed to hold a value of zero.

IMPORTANT: When using 12-hole probes, α–β coordinates do not sufficiently describe the flow angles since α is poorly defined when both the *w*- and *u*- components of the velocity are near zero. This occurs when θ approaches 90° and ϕ approaches 0°. At these conditions, any noise present in the input pressure data will be significantly magnified when calculating the α angle. Therefore, Aeroprobe specifies using cone-roll coordinates exclusively in these conditions.



Local Coordinates for Straight Probe

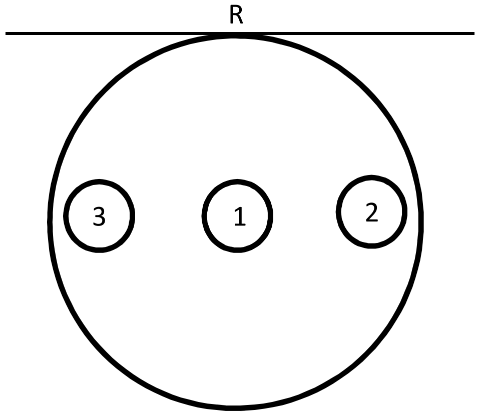
Local Coordinates for L-Shaped Probe



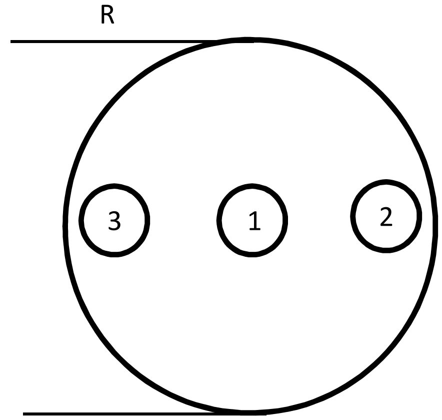
Port configurations

Aeroprobe Corporation standard multi-hole probes have three (3), five (5), seven (7), or twelve (12) ports machined into the probe tips, as shown in the figures below. The "R" indicates the location of the reference flat that is used to orient the probe during calibration and application. The nominal locations of the probe ports are shown. The relative arrangement of the ports will remain as indicated, but the actual locations of the ports can vary slightly. This slight variation does not impact the performance of the probe, as the probe calibrations account for any geometric differences.

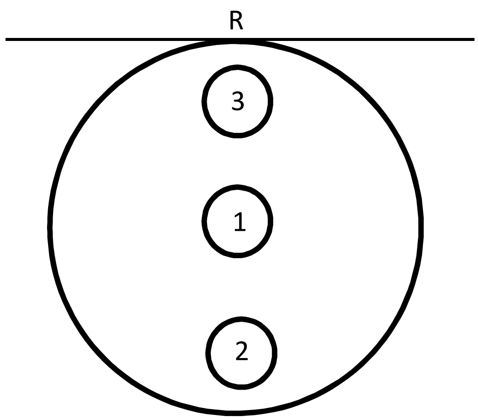
Standard Aeroprobe Port Configurations



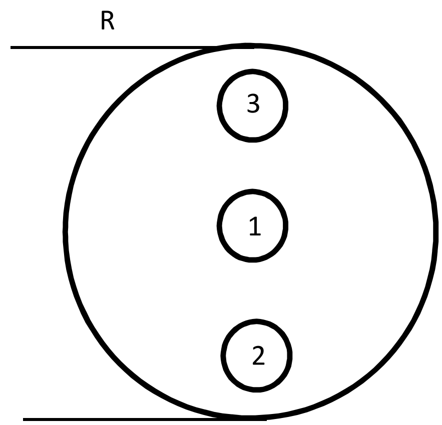
Straight 3-Hole Probe – Yaw Design



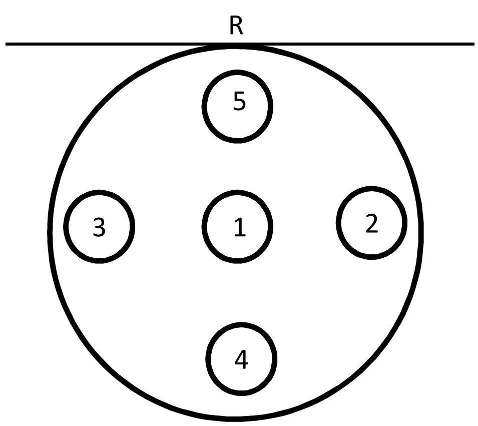
L-Shaped/Cobra 3-Hole Probe – Yaw Design



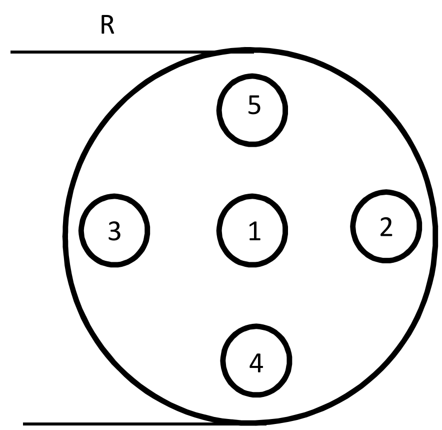
Straight 3-Hole Probe – Pitch Design



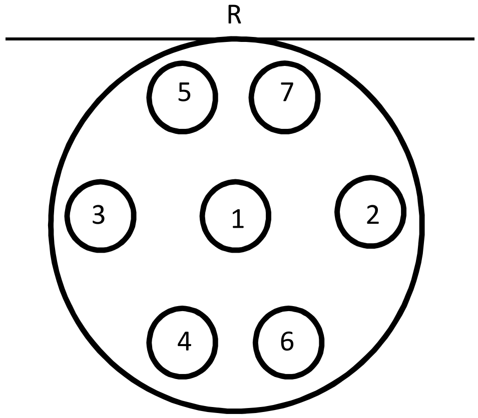
L-Shaped/Cobra 3-Hole Probe – Pitch Design



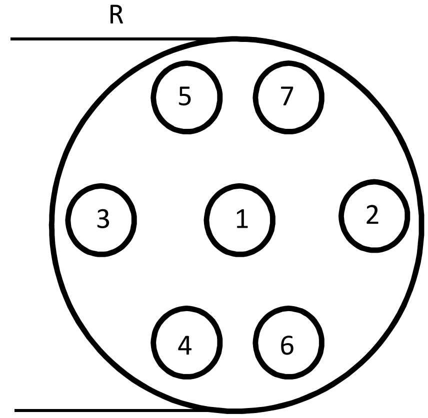
Straight 5-Hole Probe



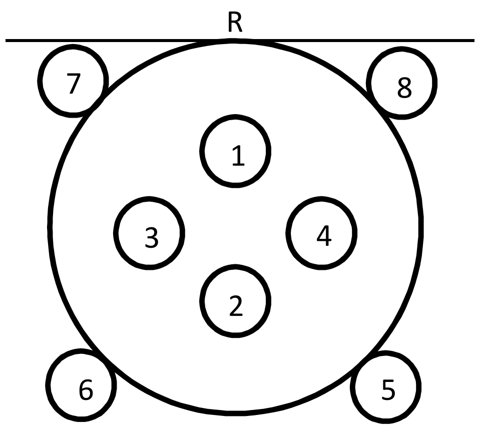
L-Shaped/Cobra 5-Hole Probe



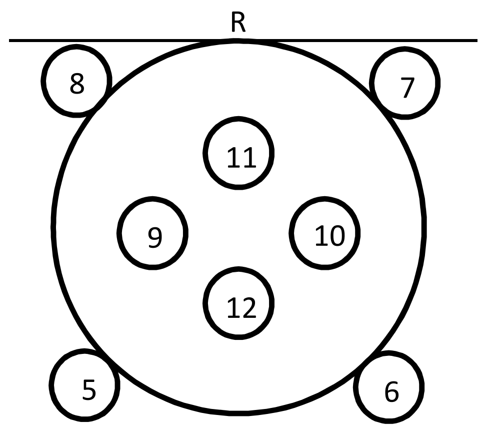
Straight 7-Hole Probe



L-Shaped/Cobra 7-Hole Probe



12-Hole Probe (Omniprobe)
Looking in positive x_p-Direction



12-Hole Probe (Omniprobe)
Looking in negative x_p-Direction

Probe calibrations

The aerodynamic calibration of the probe allows accurate measurements of the flow vector. At its most basic level, the calibration relates the probe port pressures to the two flow angles and the total and static pressure. Knowledge of the total and static pressure can be used together with a separate total temperature measurement to compute the flow speed. Because the flow around the probe depends on the nature of the flow over the probe, calibrations should span the Mach/Reynolds number range of the applications in which the probes will be used. Accurate use of the probe requires that the probe tip and overall geometry be in the same condition during measurement as during calibration. Any changes to the probe geometry can result in pressure measurement deviations that can adversely affect the result. Further, the probe should not be placed closer than 4 to 5 tip diameters to another body. Errors should be expected if measurements are made close to a solid wall or model. Boundary layer measurements therefore are not normally recommended.

The calibration file(s) supplied with the probe are the pressure maps that are used to convert pressure data acquired by the probe in an unknown flow into flow speed, flow angles and total and static pressure. These calculations are performed by Aeroprobe's *Aeroflow* software (sold separately). Please refer to the *AeroFlow* software manual for more information about how the calibration data is used.

Calibration files have a *.pcf extension, but can be opened by any text editor (including *Microsoft Excel*). The files are formatted in columns with a multi-line header. Please see Appendix I for a description of the calibration file format. The files are labeled with the probe serial number that is also engraved on the mount. Each file contains calibration pressure data as a function of flow angle for a single flow speed. If multiple calibration speeds were ordered for the probe, the Mach number is indicated at the end of the serial number in the file name. For example a file named 11036-1_M400.pcf is the calibration map for a probe with serial number 11036-1 calibrated at Mach = 0.400.

The pressures contained in the calibration files were measured with accurate pressure transducers with NIST-traceable calibrations. For accurate results, Aeroprobe recommends using pressure sensors with an accuracy of at least ±0.1% FS with an appropriate range for the particular application.

IMPORTANT: Be sure to attach the flexible tubing to the probe exit tubes according to the schematic in this document.

IMPORTANT: The coordinate system in which the probe data is calculated is defined relative to the probe. This may not be the same coordinate system as the test, and thus coordinate transformation may be required.

SECTION 5: Troubleshooting

Pressure readings

If a port is not reading the expected pressure, double-check all of the tubing and connections from the probe exit tubes to the pressure sensors. Make certain that the tubing was trimmed before being attached to the probe exit tubes. Make certain that the pneumatic lines are not twisted or kinked. If there are any in-line reducers make certain that the pneumatic tubing is trimmed and properly installed.

If problems remain after inspecting the tubing, then check each component of the probe pneumatics one at a time. First, disconnect the tubing from the probe and check for leaks/blocks as indicated in SECTION 2: Probe Maintenance. Next, disconnect the tubing from the sensors and blow compressed air through all of the lines. As with the probe, all lines should have consistent air flow. If the probe and the pneumatic tubing all have good air flow then check the sensors. The sensors can be checked by applying a known pressure to them that is within their pressure range.

IMPORTANT: Disconnect probe and tubing from the sensors before checking for blocks with compressed air. Failure to do so can cause damage to the sensors.

IMPORTANT: Do not exceed pressure limits.

Flow speed readings

If the probe is reading an unexpected speed (velocity magnitude), make sure that the ports are connected correctly. If ports are not connected consecutively to the pressure sensors, erroneous angles/speeds can result. It is easiest if the probe is connected using the same port arrangement that was used during the calibration. Port one (the longest exit tube) should be connected to sensor 1 etc. Also check that there are no leaks or blockages in the system.

Make certain that the speeds that are to be measured are within the calibration range of the probe and the pressure sensors. The error in the speed calculation will increase when trying to measure speeds outside of the range of the probe calibrations and will also increase when using only a small percentage of the pressure sensor range (< 10% as a general rule).

Angular readings

The angles that the *AeroFlow* software calculates depends on the port arrangement and the local coordinate system. If the angles appear to be the correct magnitude but in the opposite direction as expected, it is possible that the probe has been rotated or the pressure connections inverted. If the angles do not make any sense then it is likely that either the probe ports were not connected in the proper order or a port or line in the pneumatic system might be blocked or leaking. Also, check that there are no leaks or blockages in the system (see SECTION 2: Probe Maintenance)

Make sure that the expected flow angles (relative to the probe) are within the calibration range.

- 3-hole probes measure cone angles within a range of 60° (a roll angle of 0° is assumed).
- 5-hole probes measure cone angles within a range of 60°.
- 7-hole probes measure cone angles within a range of 70°.
- 12-hole probes (Omniprobes) measure cone angles within a range of 150°.

Angle measurements can also be affected if the probe is being used too close to a solid wall or model. This means that the probe should not be placed closer than 4-5 diameters to another body.

IMPORTANT: If there are other Aeroprobe products or software being used with the probe, please refer to the associated product manual for more troubleshooting tips.

Appendix I: Calibration file format

File Format for: *.pcf

FileType=PCF	Indicates the file type – Probe Calibration File
NHL=14	Number of header lines
Date=03/14/12	Date of calibration
Facility=APH	Facility calibration
Serial=Sample	Probe serial number
Customer=Sample	Name of customer
NP=7	Number of probe ports
Mach=0.200	Calibration Mach number
Calibration=1:1	Number of calibrations
CalPts=2401	Number of calibration points
TstPts=429	Number of test points
PortNumbering=AP Standard	Port arrangement – Always AP Standard
Units=Torr C m/s kg/m^3 deg mm	Units for pressures, temperature, velocity, density, angle and length

Theta [deg]	Phi [deg]	P1[1,2] [Torr]	P2 [Torr]	P3 [Torr]	P4 [Torr]	P5 [Torr]	…	P12 [Torr]	Pt[3] [Torr]	Po,Ps[4] [Abs,Torr]	To [C]
0.417	120.956	18.61	6.34	6.76	7.08	6.24		5.92	18.62	714.84	23.4
Calibration Angle	**Calibration Angle**	**Port 1 Pressure**	**Port 2 Pressure**	**Port 3 Pressure**	**Port 4 Pressure**	**Port 5 Pressure**	**…**	**Port 12 Pressure**	**Dynamic Pressure**	**Total Pressure**	**Total Temp**

Notes:

1) The port pressures and are measured differentially with respect to the local static pressure.
2) The number of ports pressure columns provided is dependent on the number of probe ports (3, 5, 7 or 12).
3) The differential total pressure is the difference between the total pressure and the static pressure.
4) Depending on the calibration facility, the absolute pressure measurement can be either the total (P_o) or static (P_s) pressure. This choice is made to minimize the measurement uncertainty. If the absolute static pressure is not given directly in the file, it can be calculated as $P_s = P_o - P_t$

Appendix II: Flexible tubing specifications

The flexible tubing delivered with the probe is used internally by Aeroprobe for most pneumatic connection purposes where multi-hole probes are concerned. This tubing may not be recommended for all applications, such as high-pressure or high-temperature.

The tubing has the following specifications:

Outer Diameter: 3/32” (2.38 mm)

Inner Diameter: 1/32” (0.794 mm) – will seal to 0.040” – 0.063” OD metal tubing with tubulations.

Wall Thickness: 1/32” (0.794 mm)

Minimum Bend Radius: 1/8” (3.28 mm)

Maximum Working Pressure at 73°F: 80 psi (551.6 kPa)

Vacuum Rating at 73°F: 14.7 psi (101.3 kPa)

Appendix III: Probe specifications

3-, 5-, and 7-hole probes

Measurement Accuracy

Flow angles[1,2]	± 1°
Velocity Magnitude[1,2]	<1% or 1m/s, (whichever is larger)
Thermodynamic Data[3]	Reference Pressure, Total Temperature
Flow Cone Angle of Receptivity	20° (3HP), 60° (5HP), 70° (7HP) NOTE: This is not directly related to the conical angle of the tip
Calibration Flow Speeds	5 m/s to Mach 2.0
Frequency Response	Standard[4]: <50 Hz Optional: Frequency Calibration Available
Media	Standard: Non-Reactive Gases, Water Optional: Other Media
Temperature Measurement	Optional: Thermocouple

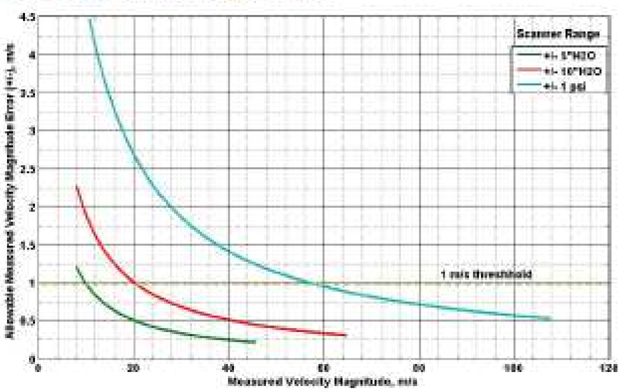
[1]*Based on Average of Test Point Data*
[2]*Utilizing 0.1% Accurate Pressure Sensors Properly Rated for Flow Speed*
[3]*For Most Accurate Compressible P-V Reduction. Additional Equipment Required*
[4]*Optimized for time-averaged flows*

Geometry and Construction

Probe Geometry	Straight, Cobra, L-Shaped, Drilled Elbow
Number of Holes	3, 5, 7
Tip Geometry[5]	Standard: 60° Conical Optional: Hemispherical
Tip Diameter	Standard: 3.18 mm Optional: 1.59 mm, 2.38 mm, 6.35 mm
Material	300 Series Stainless Steel Construction, Including Shafts and Internal Tubing
Pneumatic Connection	Exit Tubing of 1.02 mm (0.040") OD with Tubulation
Mounting	Standard: Hex Prism Optional: Rectangular Prism, Cylindrical with Flat
Probe Reference	Flat on Hex Mount
Flow Temp. Limits	Standard: 0 – 500°C

[5]*Indicates Full-Angle Measurements*

Velocity Magnitude Elaborated



The stated velocity accuracy for Aeroprobe's multihole probes is 1 m/s or 1% of the measured velocity, whichever is larger, assuming a properly ranged scanner. The graph below illustrates the effect of scanner range on velocity accuracy. The graph shows the allowable velocity error as a function of velocity for three different pressure scanner ranges, all with 0.5% full-scale span error. The calculated error assumes that the pressure measured by the scanner is the dynamic pressure and no system or reduction error is accounted for.

When designing a multihole probe test it is important to consider the effect of pressure measurement error at the desired flow velocity. For example, the user should not expect accuracies of less than 1/ms using the +/- 1 psi scanner with 0.5% FSS error for a measurements below approximately 60 m/s.

12-hole probes (Omniprobes)

Measurement Accuracy

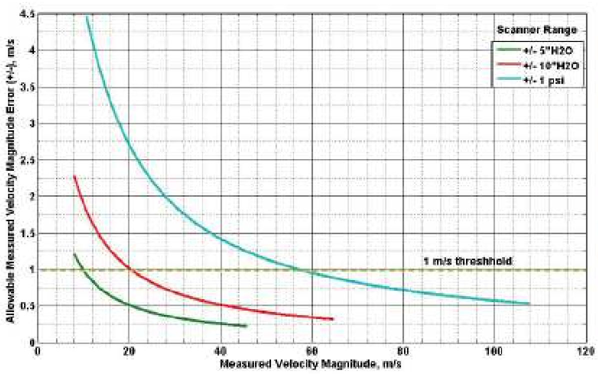
Velocity Magnitude[1,2]	3%
Flow Angle of Receptivity	Cone Angle: 150°
Flow Angles	± 1.5
Calibration Flow Speeds	5 m/s to Mach 1
Frequency Reponse	<50 Hz, Frequency Calibration Available Upon Request
Media	Non-Reactive Gases (Stainless); Other Media Possible – Contact Aeroprobe

[1] *Based on Average of Test Point Data*
[2] *Utilizing 0.1% Accurate Pressure Sensors Properly Rated for Flow Speed*

Geometry and Construction

Probe Geometry	Straight, L-Shaped
Number of Holes	12
Tip Geometry	Spherical
Tip Diameter	Standard: 9.53 mm Optional: 6.35 mm
Material	303, 304 Stainless Construction, Including Shafts and Internal Tubing
Pneumatic Connection	Exit Tubing of 1.02 mm (0.040") OD with Tubulation
Mounting	Hex Prism (9.53 mm Standard Flat-to-Flat) Optional: Rectangular Prism, Cylindrical with Flat
Probe Angle Reference	Straight: Flat on Hex Mount
Temperature Rating	Standard: 0 – 500°C

Velocity Magnitude Elaborated



The stated velocity accuracy for Aeroprobe's omniprobes is 1 m/s or 3% of the measured velocity, whichever is larger, assuming a properly ranged scanner. The graph below illustrates the effect of scanner range on velocity accuracy. The graph shows the allowable velocity error as a function of velocity for three different pressure scanner ranges, all with 0.5% full-scale span error. The calculated error assumes that the pressure measured by the scanner is the dynamic pressure and no system or reduction error is accounted for.

When designing a omniprobe test it is important to consider the effect of pressure measurement error at the desired flow velocity. For example, the user should not expect accuracies of less than 1/ms using the +/- 1 psi scanner with 0.5% FSS error for a measurements below approximately 60 m/s.

Appendix IV: Technical drawings for select probes

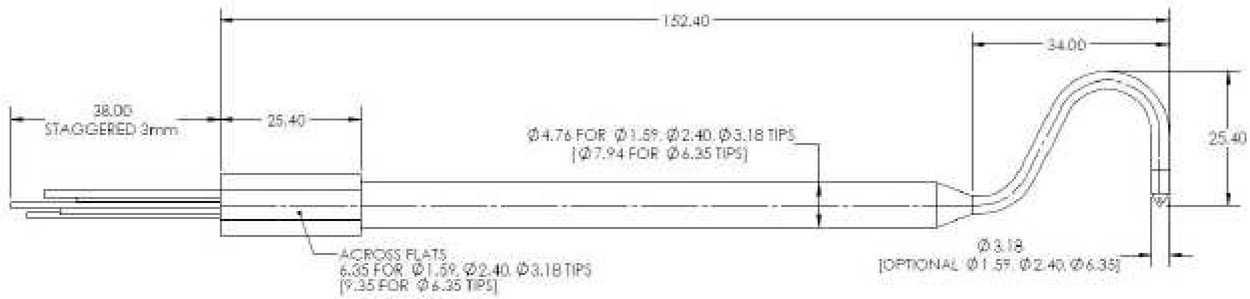
3-, 5-, and 7-hole probes

Straight

Model Number: P-C03C03S-SX-S-152

Cobra

Model Number: P-C03C03C-SX-S-152-025-034

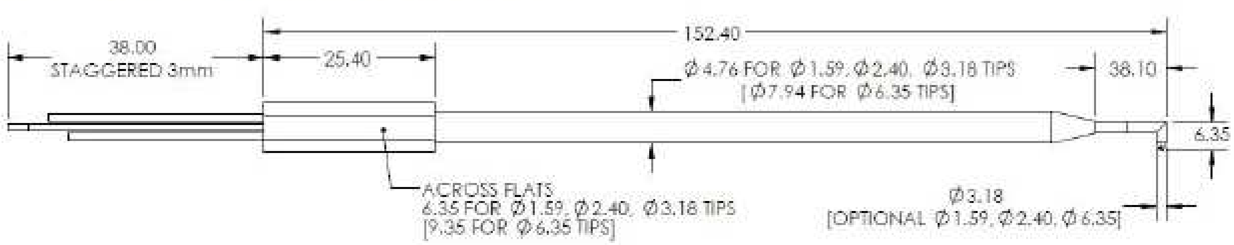


L-Shaped

Model Number: P-C03C03L-SX-S-152-025

Drilled Elbow

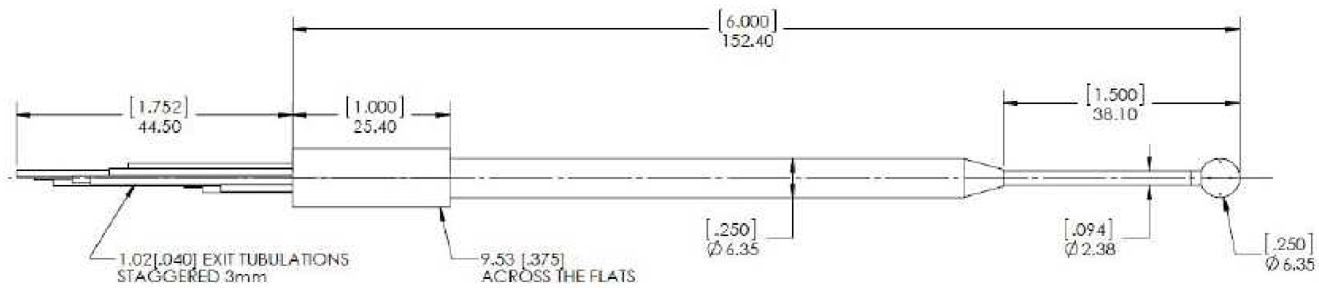
Model Number: P-C03C03D-SX-S-152-006



12-hole probes (Omniprobes)

Straight

Model Number: P-C12H06S-SX-S-152



L-Shaped

Model Number: P-C12H09L-SX-S-152