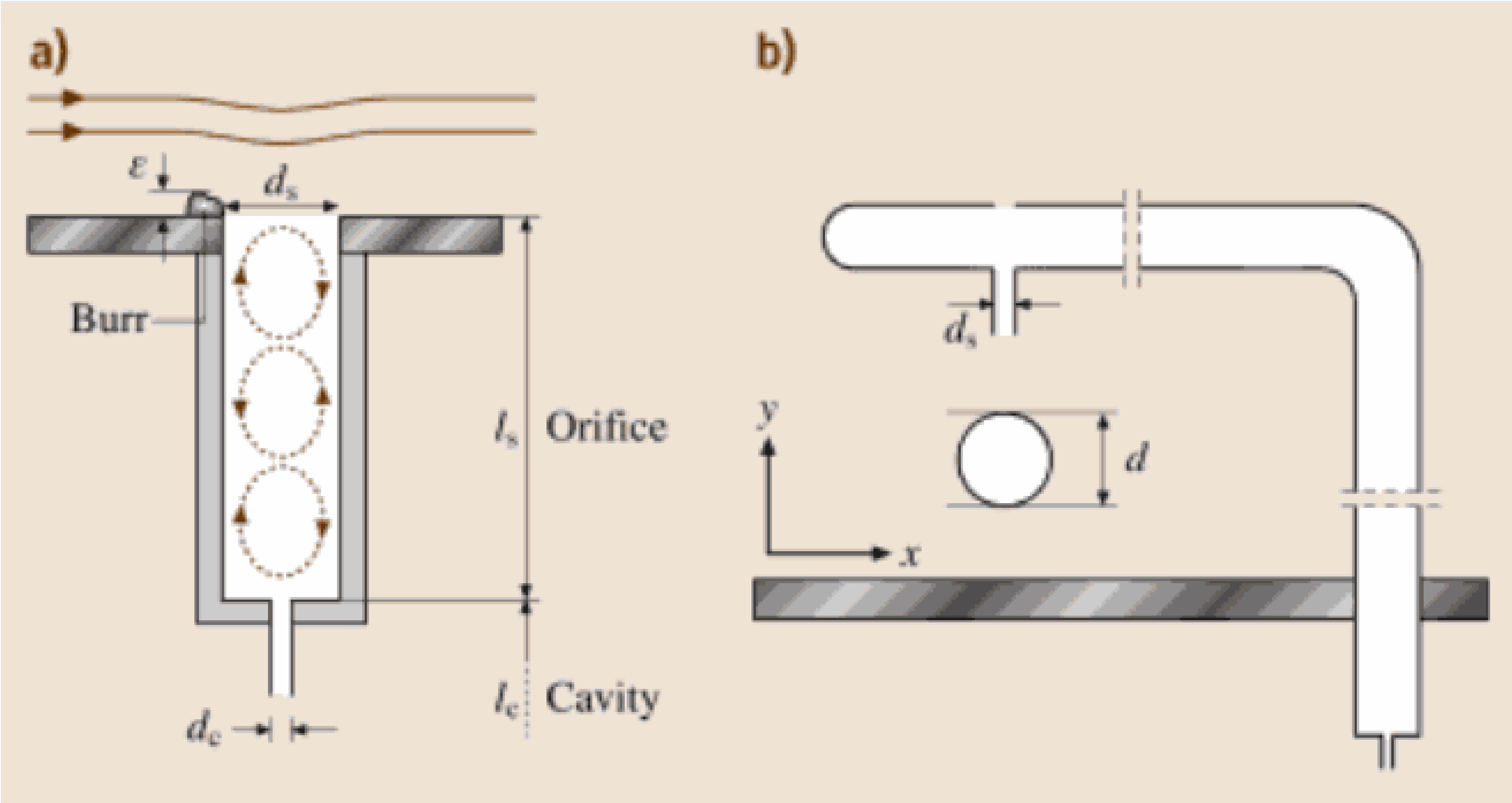
Summary and additional notes for Static pressure measurements:



Determination of static pressure a) Wall tapping b) static tube

Error in pressure is function of:

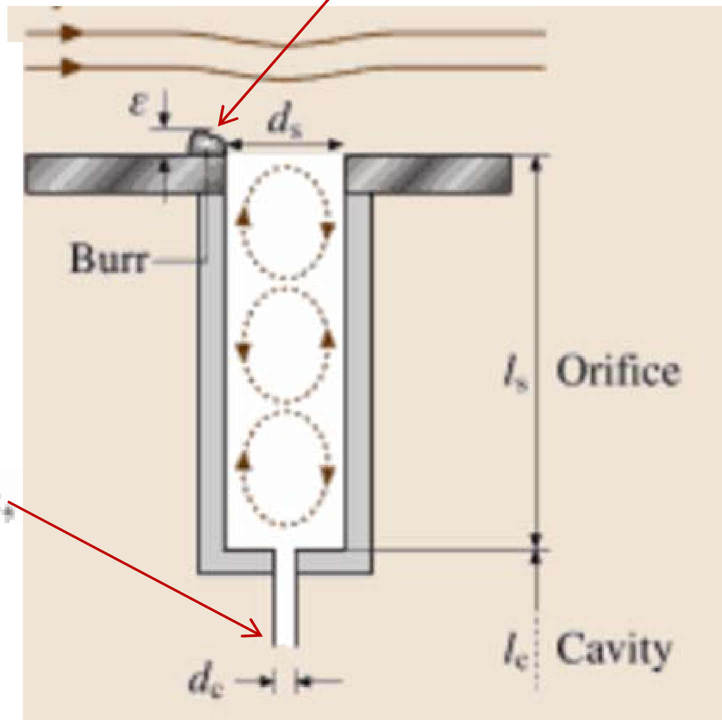
$$\Pi = \frac{\Delta p}{\tau_w}$$
$$= f\left(\frac{d_s u_\tau}{\nu}, \frac{d_s}{D}, M, \frac{l_s}{d_s}, \frac{d_c}{d_s}, \frac{\epsilon}{d_s}\right)$$

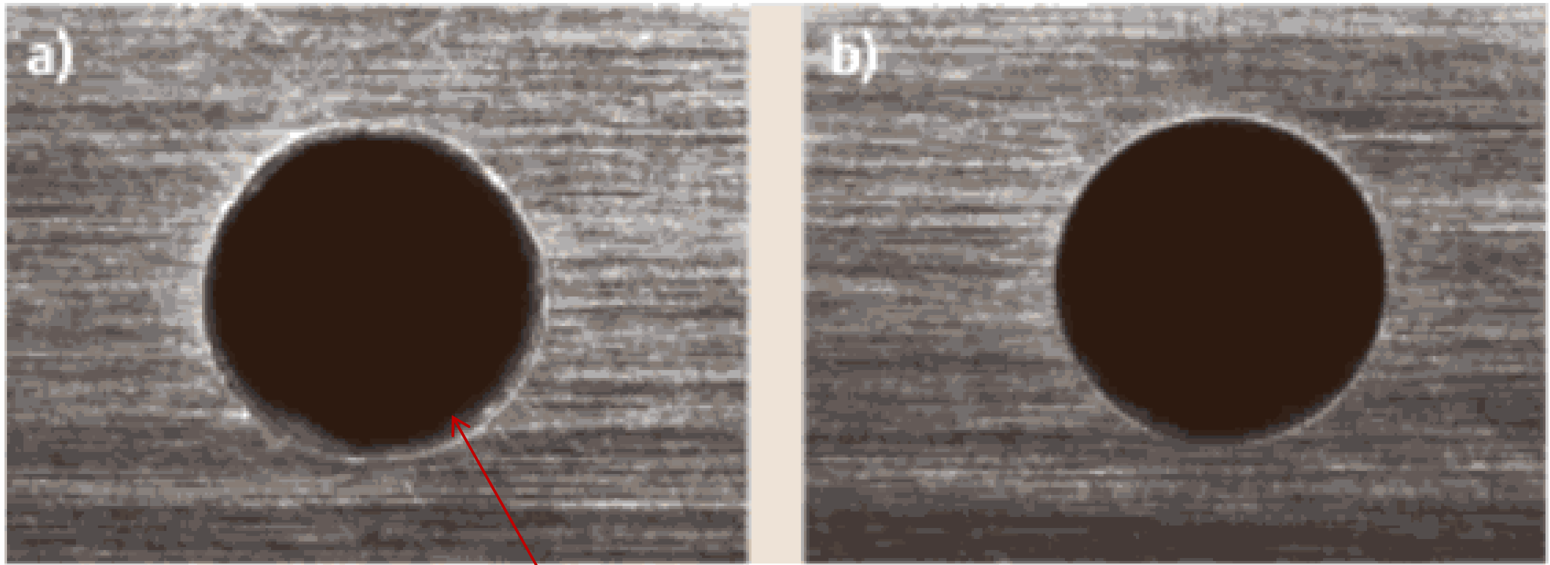
Error in pressure is function of:

$$\Pi = \frac{\Delta p}{\tau_w} = f\left(\frac{d_s u_\tau}{\nu}, \frac{d_s}{D}, M, \frac{l_s}{d_s}, \frac{d_c}{d_s}, \frac{\epsilon}{d_s}\right)$$

And it is also function of laminar or tubulent condition of the wall-bounded flow.
Here,

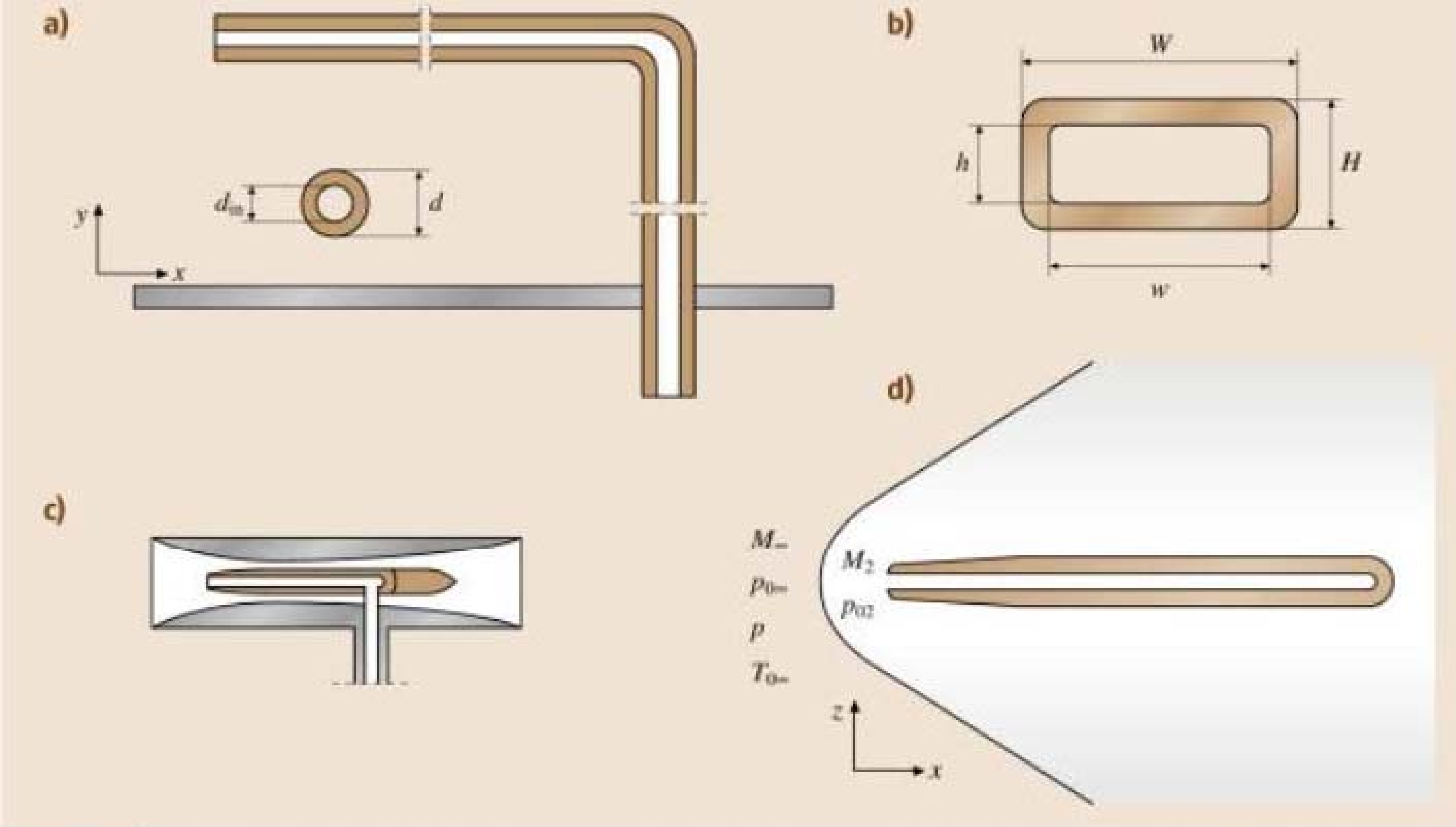
d_s is the tapping (orifice) diameter,
$u_\tau = \sqrt{\tau_w/\rho}$ is the friction velocity,
D is the flow lengthscale, (e.g. In a pipe flow, D is the diameter of pipe)
M is the Mach number
l_s is the depth of the orifice,
d_c is the diameter of the cavity behind the orifice,
ϵ is the root-mean-square height of burrs on the edge of the tapping orifice,
ρ is the fluid density
ν is the kinematic viscosity





Magnified images of wall tapping with $d_s = 2.381$ mm. **(a)** Rejected due to burring ($\epsilon/d_s = 0.63 \times 10^{-3}$) and **(b)** Accepted (After *McKeon* and *Smits* [4.13])

Total pressure measurement summary:



Probes for the measurement of total pressure (a) blunt-nosed cylindrical Pitot probe; (b) flattened Pitot prob
(c) Kiel probe; and from shock relationships: (d) Pitot probe in supersonic flow with known freestream static pressure p
or reservoir pressure $p_{0\infty}$

Flow Direction Measurements

Flow Direction Measurements

To describe a flow-field, both the flow direction and velocity magnitude are needed.

The flow direction measurements also allow a better alignment of the probe to the flow direction as required for accurate static pressure measurements.

Variations of the velocity component in the plane perpendicular to the probe stem are measured by the **yaw angle**. Variations of the velocity direction in the plane perpendicular to it are measured by the **pitch angle**.

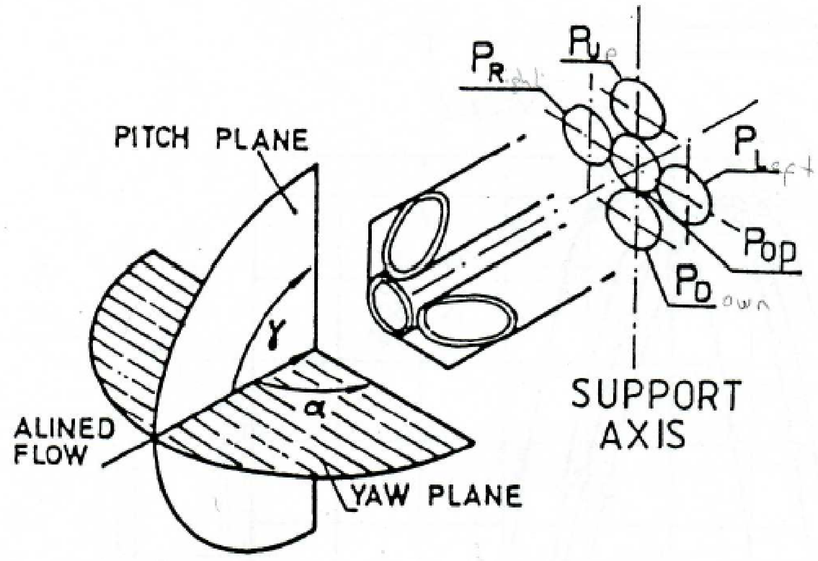


Fig. 3.1 - Definition of pitch and yaw angle

Yaw Angle Measurements

The simplest geometry of a directional probe is a slanted tube.
It consists of a total head probe with its nose cut at an angle A.

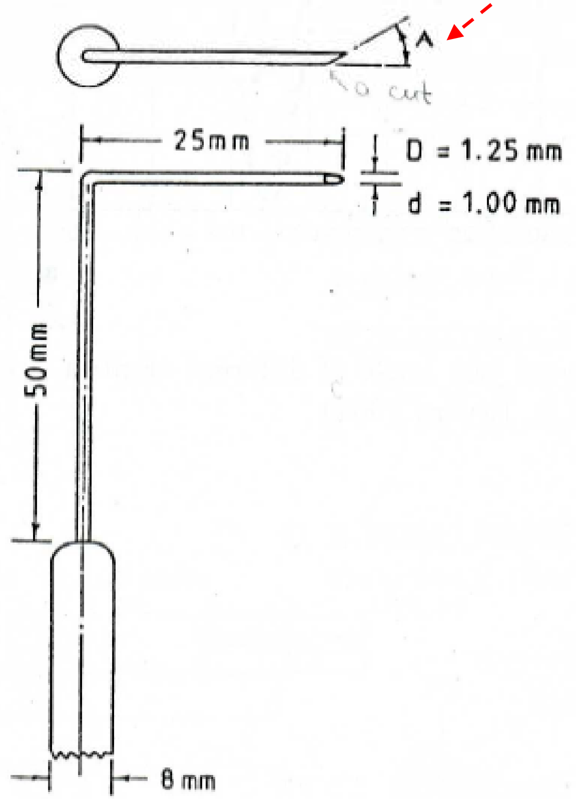
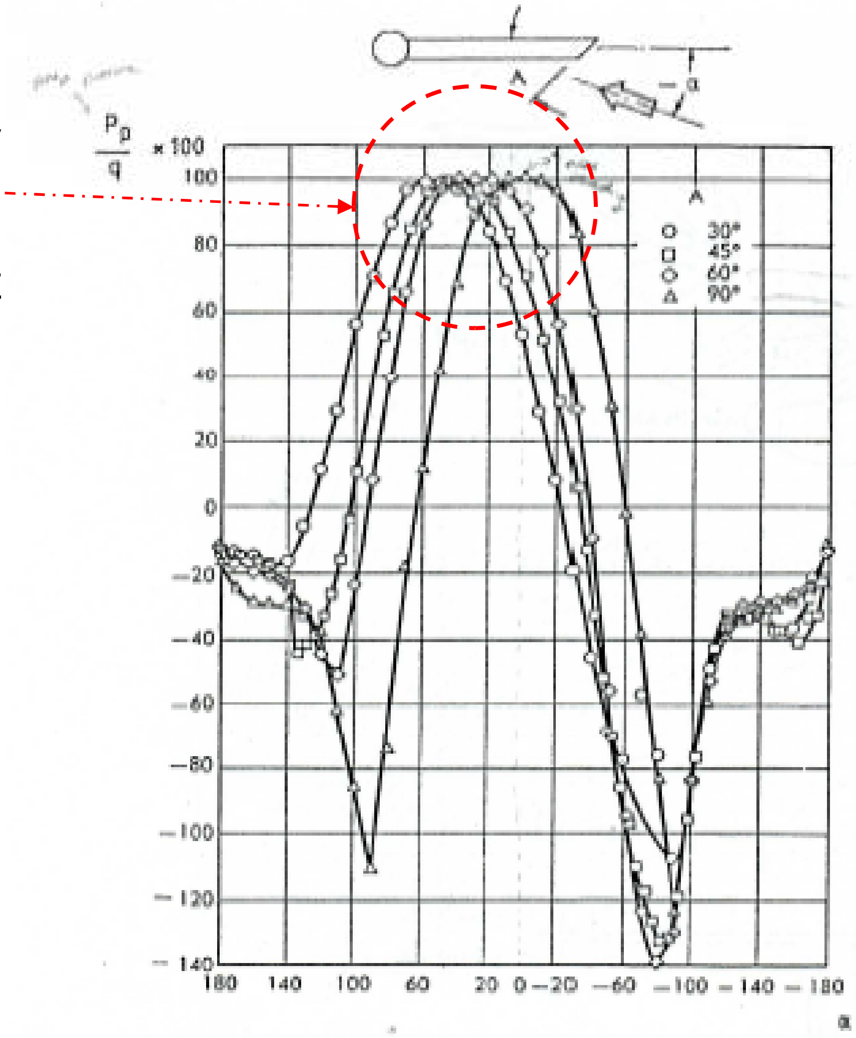


Fig. 3.2 - Slanted tube geometry for yaw angle measurements
(J.R. Erwin, 1964)

Yaw Angle Measurements

Rotating the probe around the stem axis allows the flow angle to be defined by seeking the maximum pressure reading.

The response of the slanted tube to inlet flow angle allows the determination of the yaw angle within ±5° only.



One pressure measurement is therefore not sufficient to provide accurate directional information.

Yaw Angle Measurements

The large pressure gradients observed at negative yaw (α) angles can be used for an accurate definition of the flow direction by measuring the pressure difference between two symmetric slanted tubes (ex: A=30° and A=-30°)

Different probe geometries based on this principle:

Conrad's "Cobra" probe is the most widely used.

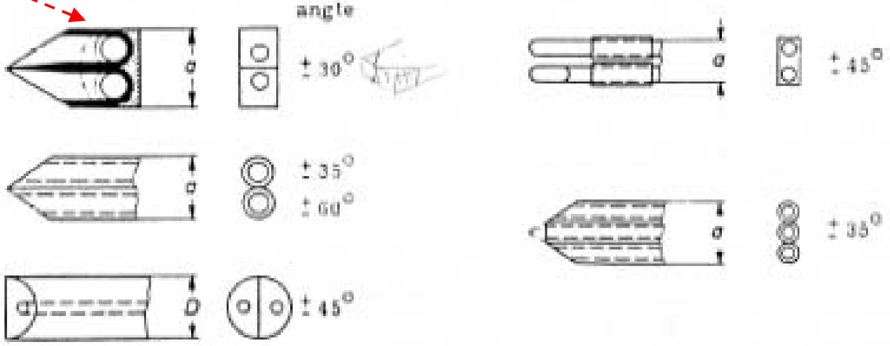
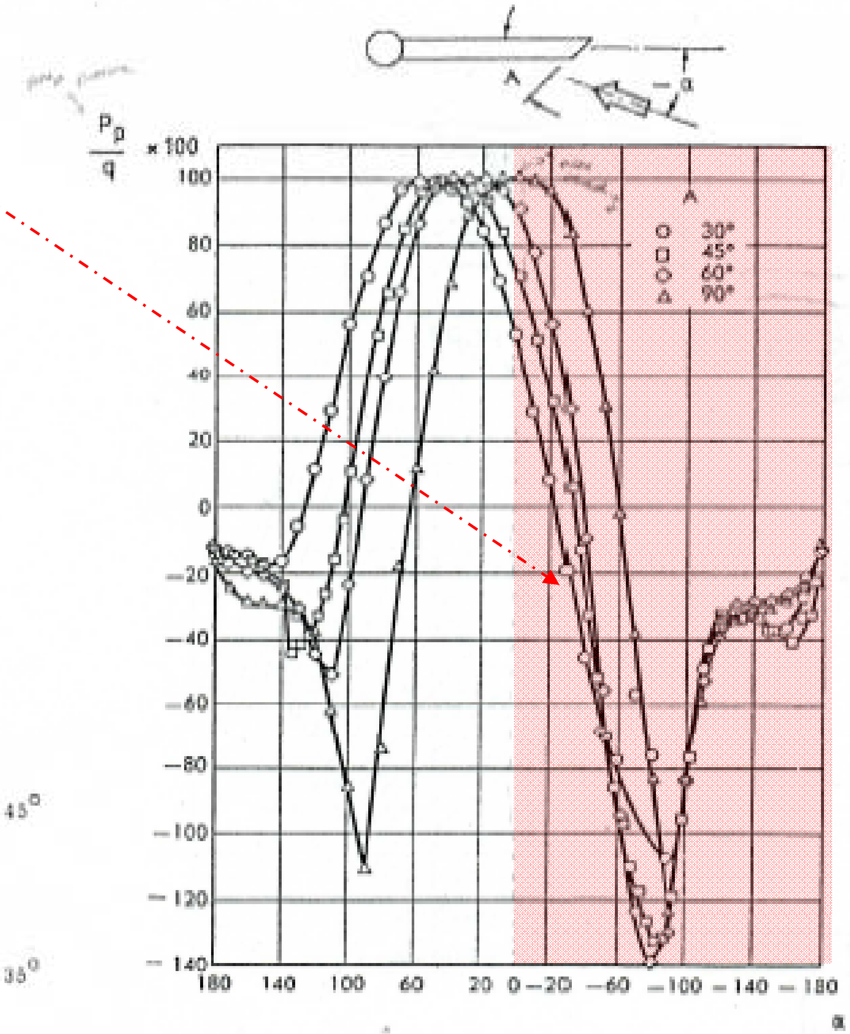
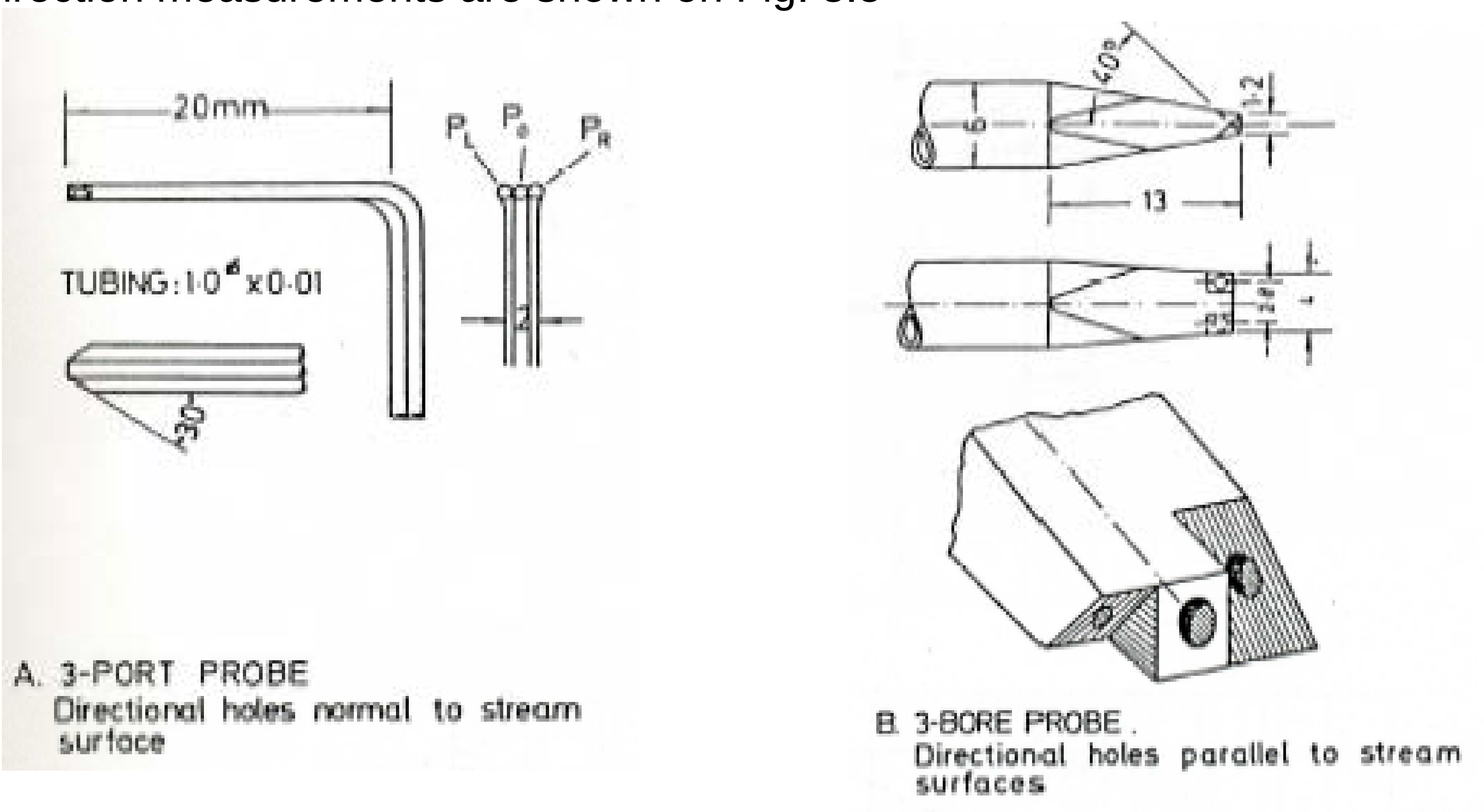


Fig. 3.4 - Two dimensional flow directional probes
(W. Wuest, 1967)



Yaw Angle Measurements

Typical examples of probes which combine total, static-pressure and direction measurements are shown on Fig. 3.5



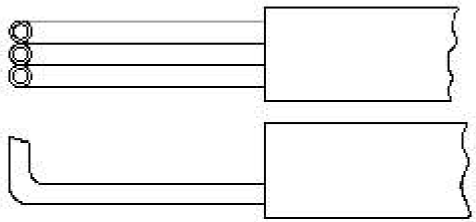
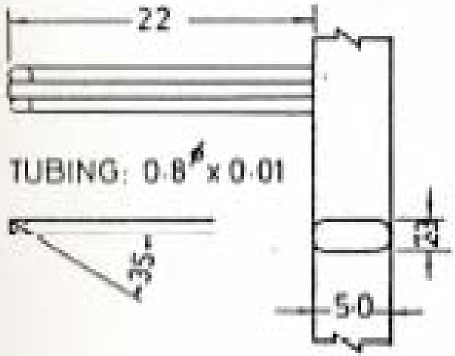


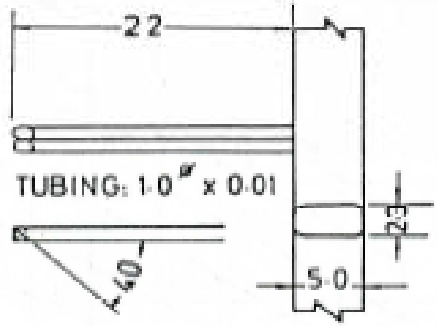
Fig. 3.5 - Various types of two dimensional probes
(C.H. Sieverding, 1975)

Yaw Angle Measurements

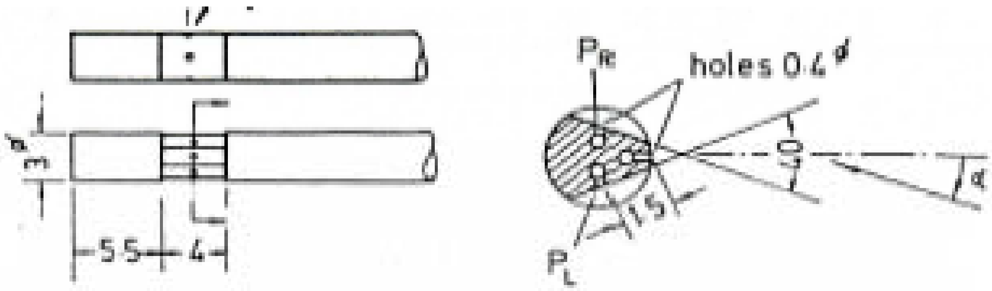
Typical examples of probes which combine total, static-pressure and direction measurements are shown on Fig. 3.5



C. 3-PORT PROBE
Directional holes parallel to stream surfaces



D. 2-PORT PROBE
Directional holes parallel to stream surfaces

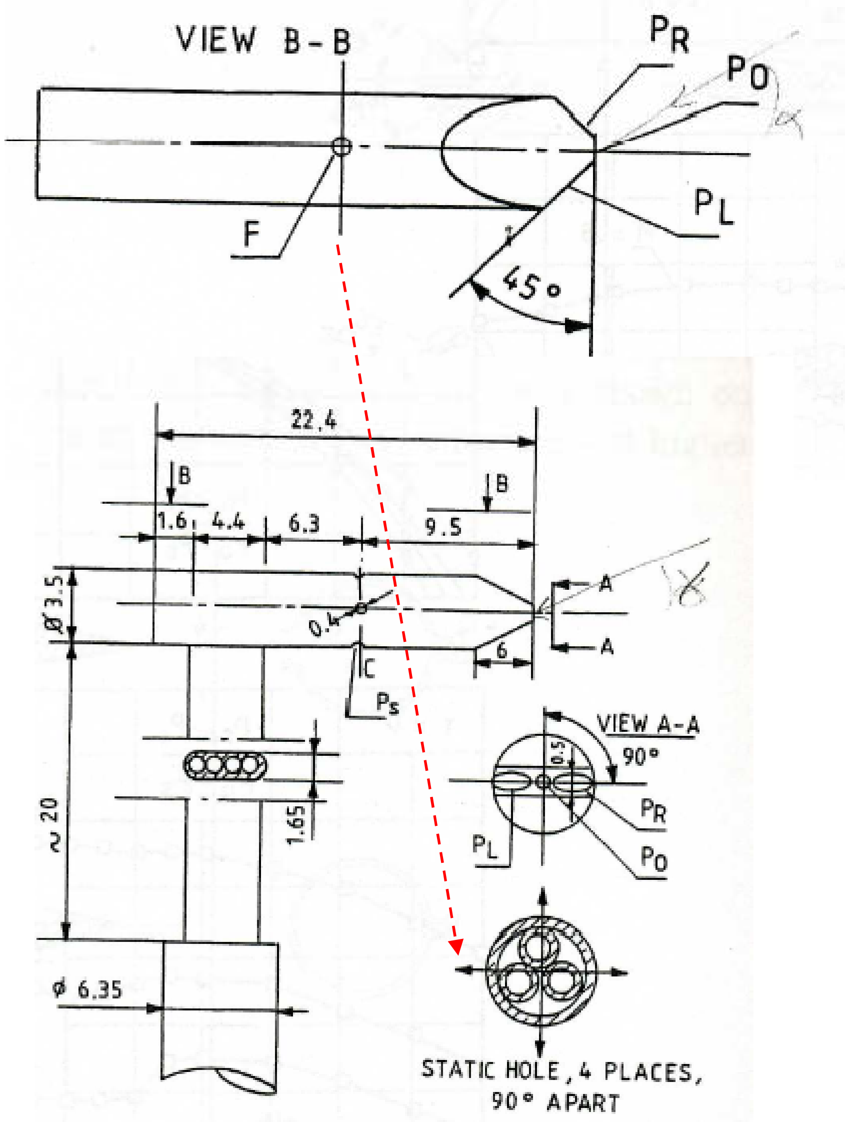


E. CYLINDRICAL PROBE
Directional holes normal to stream surface

Yaw Angle Measurements

There are two ways in which a pressure sensitive direction probe can be used.

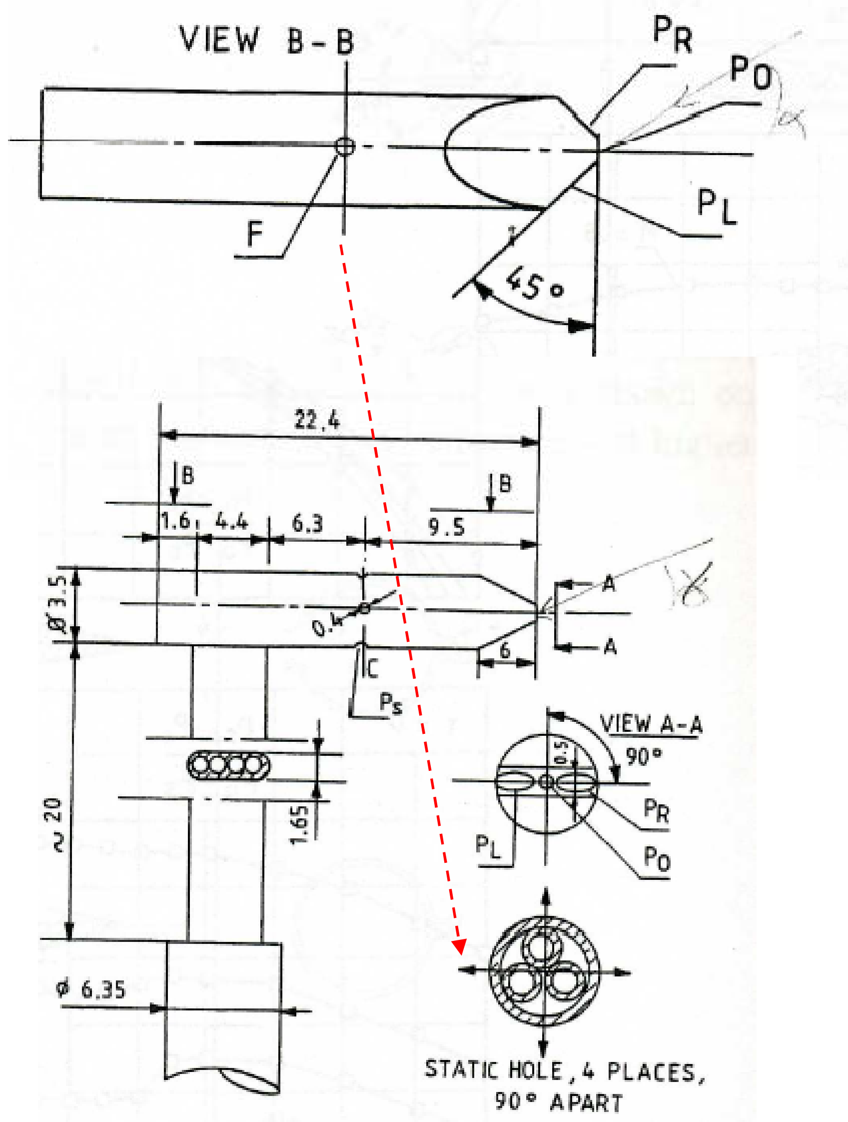
The simpler and more direct one is the method in which the probe is rotated to balance the pressure difference between the two orifices. The flow angle is then just the rotation angle of the probe.



NACA short prism probe

Yaw Angle Measurements

In the alternative approach, the probe is in a fixed position facing the flow and the flow direction is defined from the measured pressure difference by means of a calibration curve.



Yaw Angle Measurements

A typical calibration curve of a NACA short prism probe is shown on Fig. 3.6

The pressure difference P_L-P_R, varies linearly with the yaw angle.

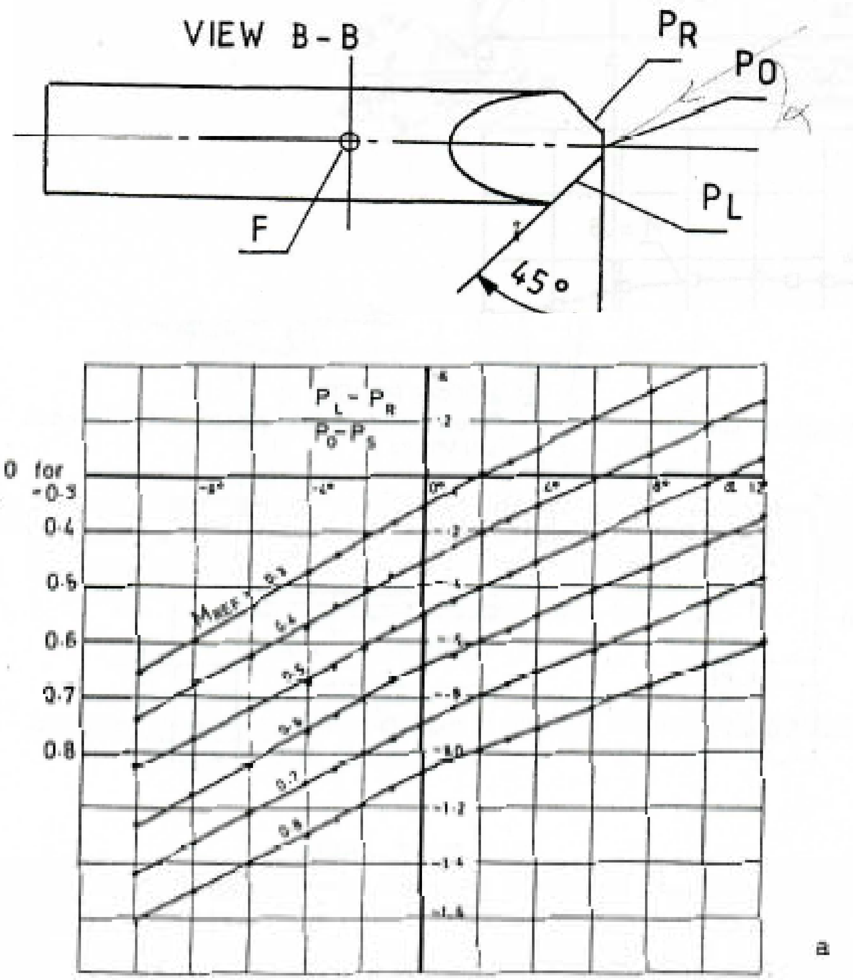
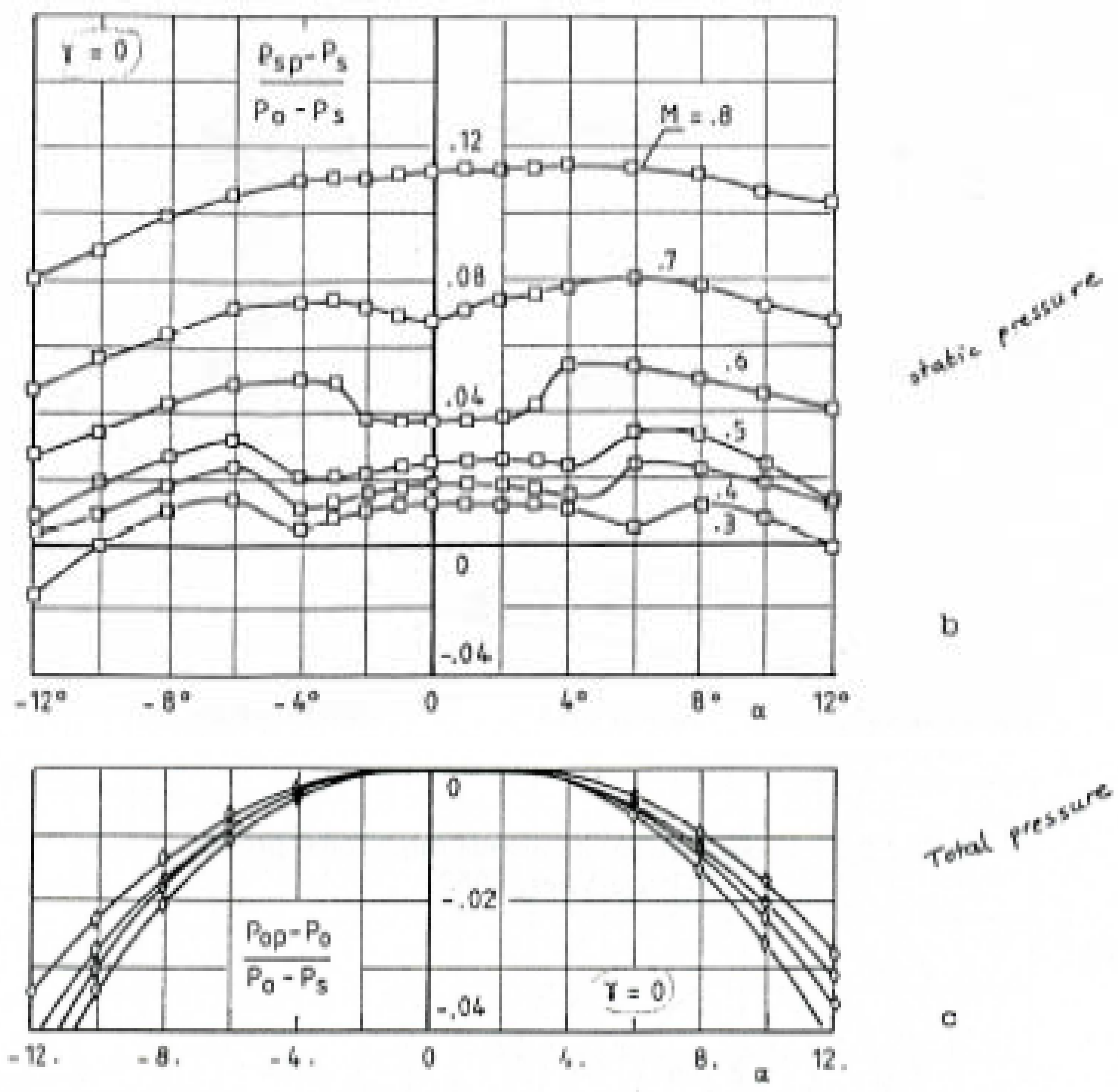


Fig. 3.6 - NACA probe and calibration curves
(F.A.E. Breugelmans, 1964; J. Erwin, 1964)

Yaw Angle Measurements

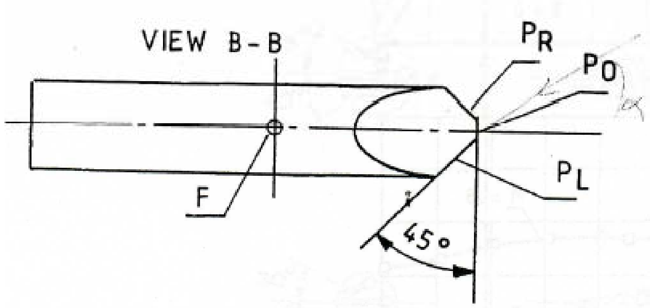
The variation of measured static pressure and total pressure with yaw angle:

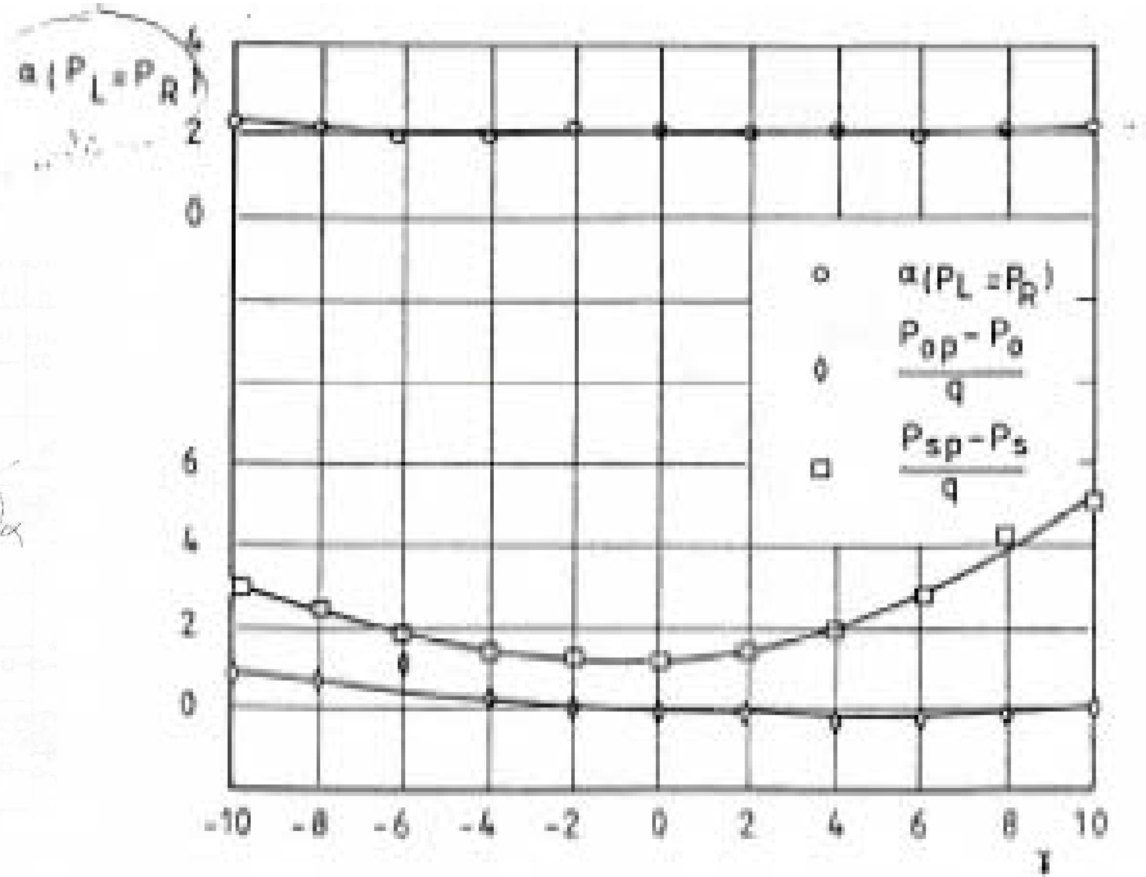


Yaw angle

Yaw Angle Measurements

A typical dependence on pitch angle of zero yaw angle, static and total pressure:





Pitch angle

Yaw Angle Measurements

Other directional probes are: cylinder probes, aerofoils and bent tube (finger probes)

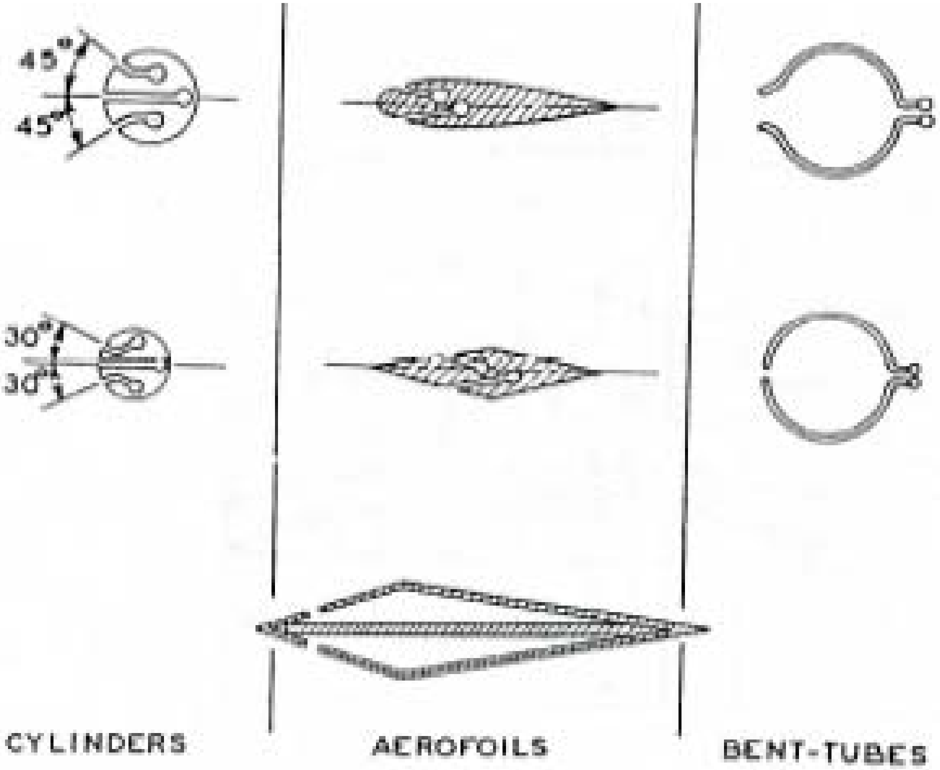


Fig. 3.7 - Cross section of various directional probes (O. De Vries, 1958)

Yaw Angle Measurements

A typical calibration curve of a cylindrical probe:

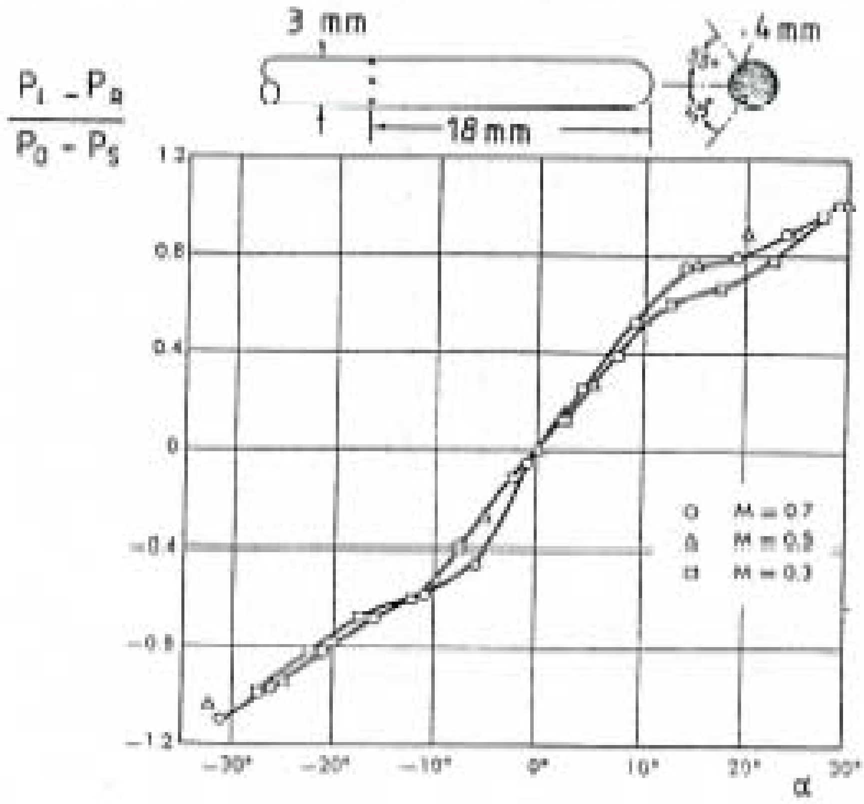


Fig. 3.8 - Variation of cylindrical probe pressure difference with yaw angle (J.E. Erwin, 1964)

Three dimensional flow direction probes

Adding a pair of symmetrically slanted tubes in the plane perpendicular to the yaw plane, allows the simultaneous definition of pitch and yaw angle.

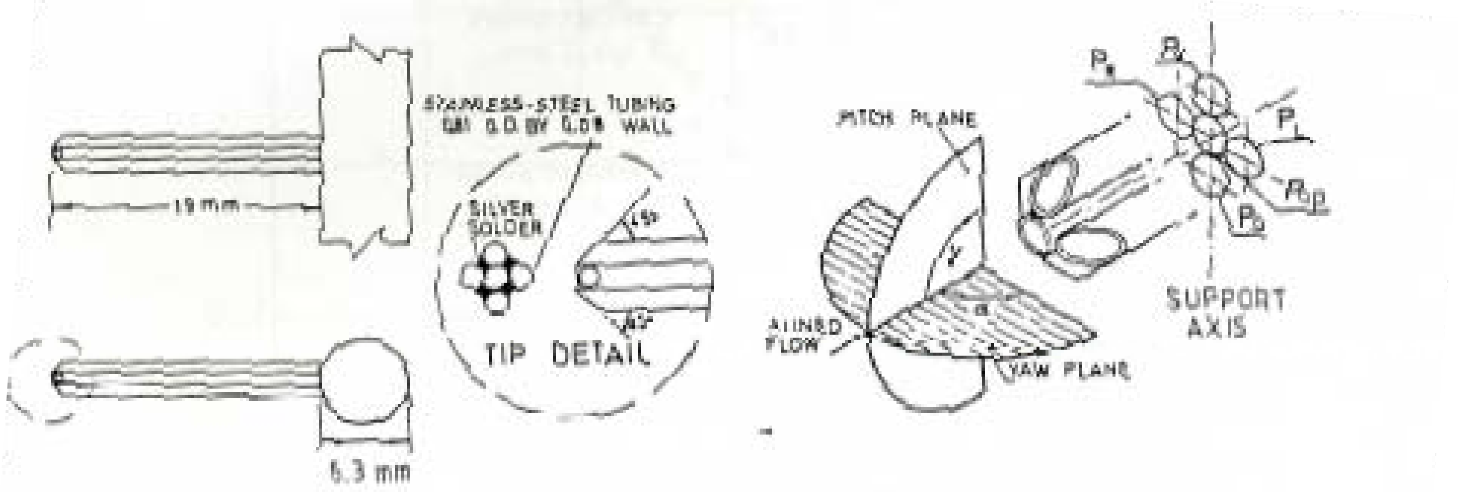
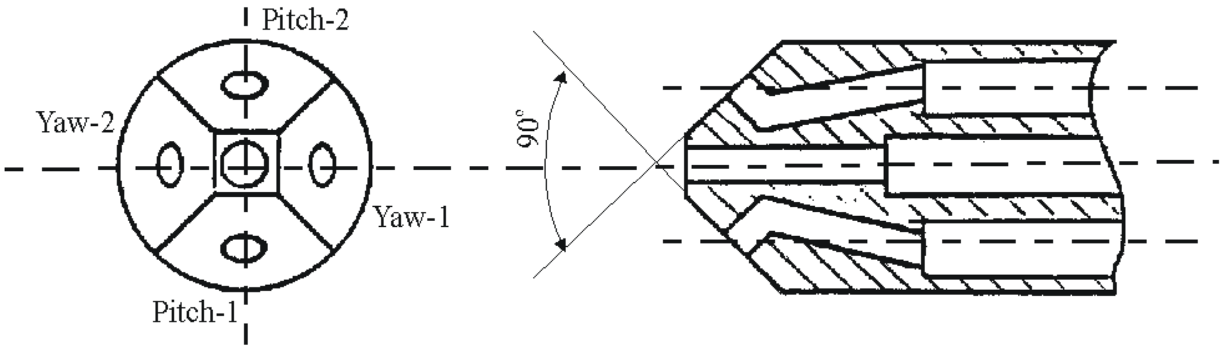
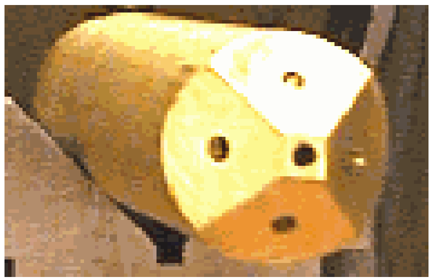


Fig. 3.9 - Three dimensional flow direction probe

Three dimensional flow direction probes





Three dimensional flow direction probes

The calibration is more complex as it requires a symmetric variation of the yaw angle at different pitch angles.

The calibration curves allow the calculation of pitch and yaw angle, static and total pressure, as a function of

P_{op} , P_L, P_R, P_U, P_D

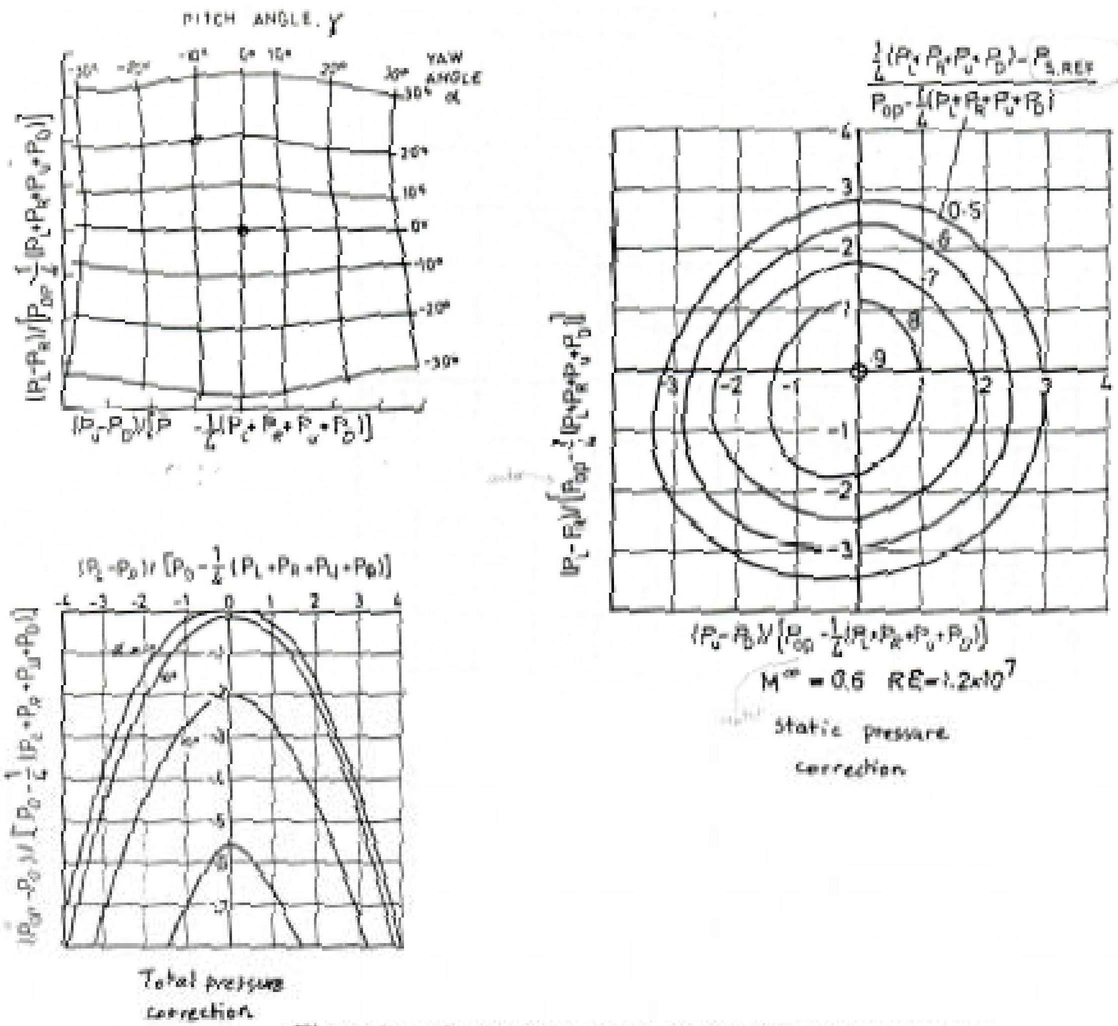


Fig. 3.10 - Calibration charts for 3D flow direction probe (J.T. Dudziniski & L.N. Krause, 1969)

Three dimensional flow direction probes

Other probe geometries:

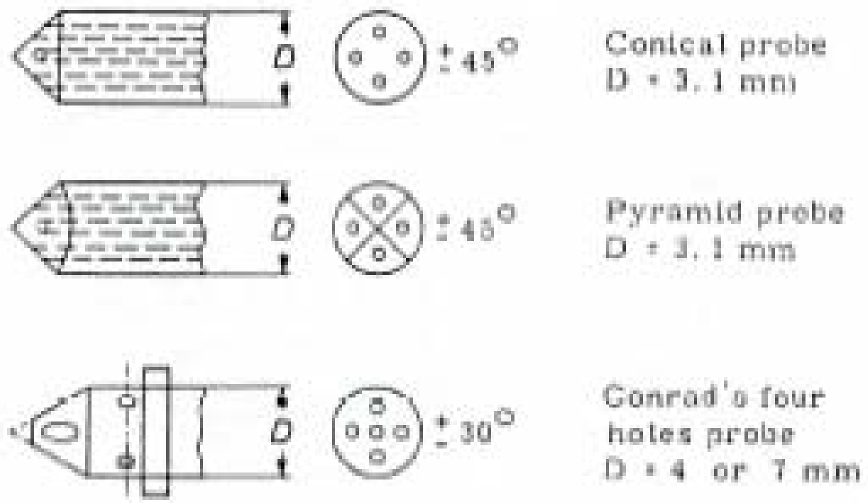
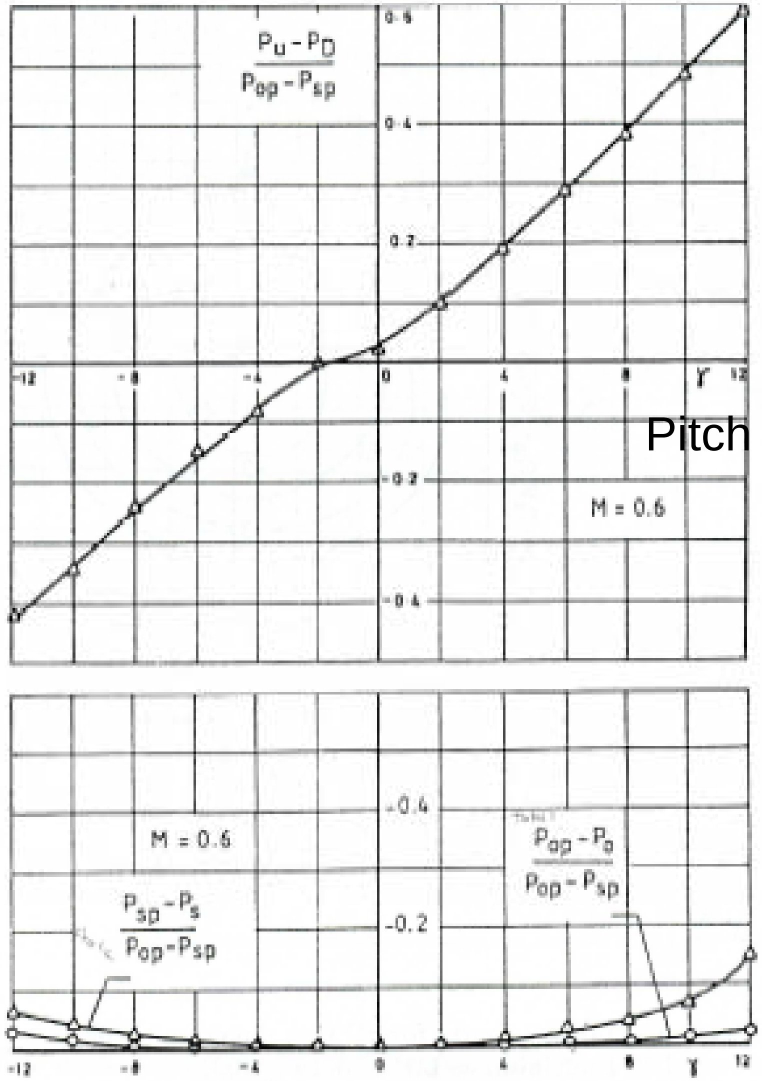


Fig. 3.11 - Three dimensional flow direction probes
(W. Wuest, 1967)

•Conrad's four holes probe has four holes for directional measurements and total and static pressure holes for velocity measurements.
•The collar downstream of the static pressure holes is adjusted in such away to maintain the measured static pressure close to the true value over a wide range of Mach numbers.

Three dimensional flow direction probes

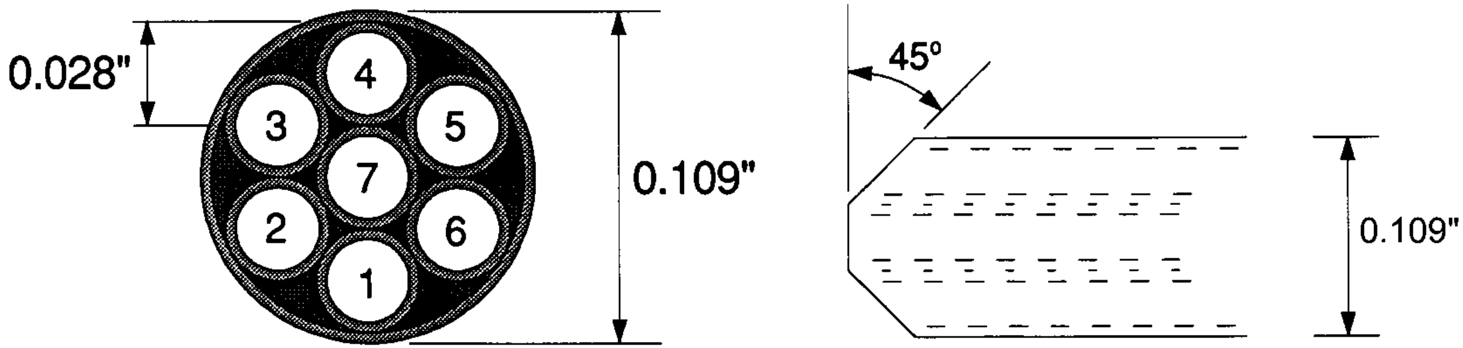
Adjusting the probe during the measurements to zero yaw angle allows a simpler calibration in function of the pitch only.



Pitch angle

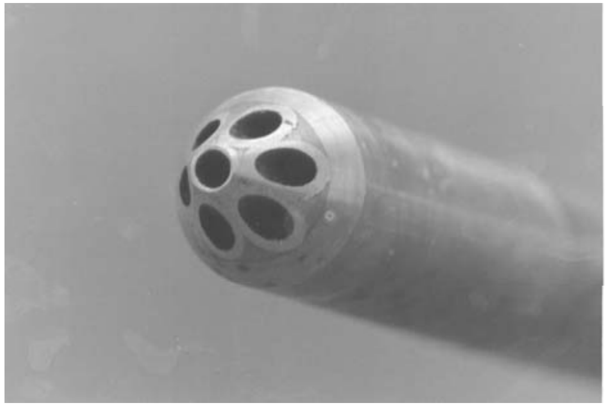
Fig. 3.12 - Calibration curves of Conrad's four hole probe (K. Bammert et al., 1973)

7 hole Probe

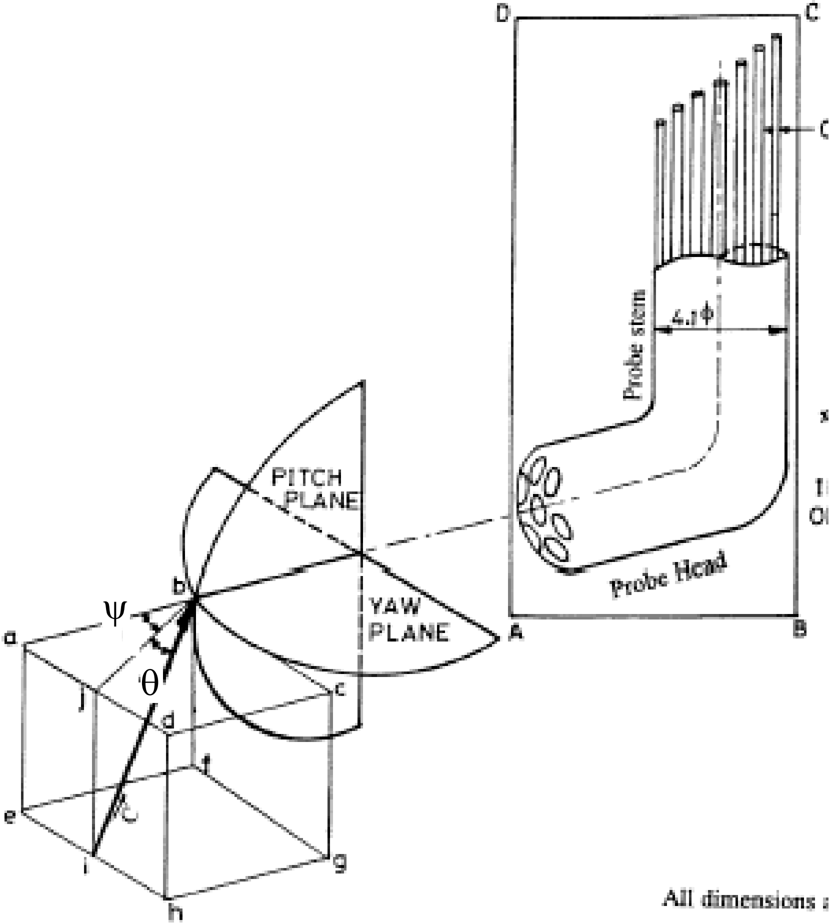


Measures

- total pressure
- static pressure
- 3 velocity components



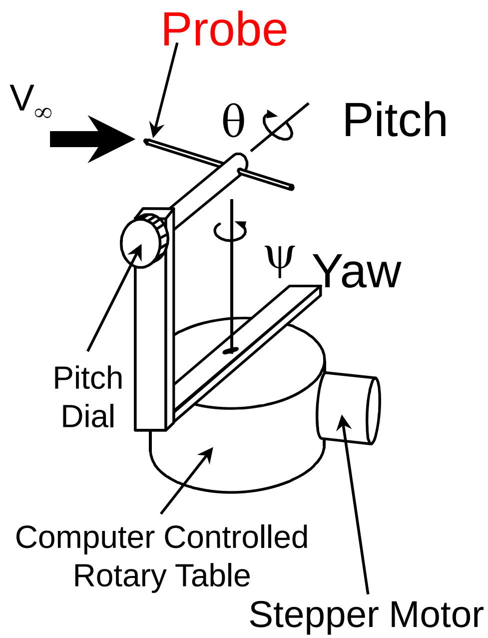
Seven-Hole Pressure Probe Coordinate System is Defined By Pitch and Yaw Angles



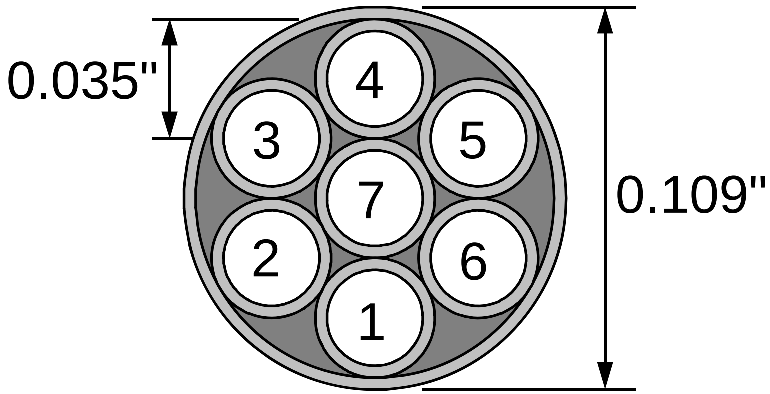
$$u = \left|\vec{V}\right| \cdot \cos\theta \cdot \cos\psi$$

$$v = \left|\vec{V}\right| \cdot \sin\theta$$

$$w = \left|\vec{V}\right| \cdot \cos\theta \cdot \sin\psi$$



Velocity Invariant, Non-Dimensional Seven-Hole Probe Pressure Coefficients



$$C_{P_A} = \frac{P_4 - P_1}{P_7 - \overline{P}}$$

$$C_{P_B} = \frac{P_3 - P_6}{P_7 - \overline{P}}$$

$$C_{P_C} = \frac{P_2 - P_5}{P_7 - \overline{P}}$$

$$\overline{P} = \frac{1}{6}\sum_{i=1}^{6} P_i$$

Flow Angle Coefficients:

$$C_{P_\alpha} = C_{P_A} + \frac{C_{P_B} - C_{P_C}}{2} \qquad \text{Pitch}$$

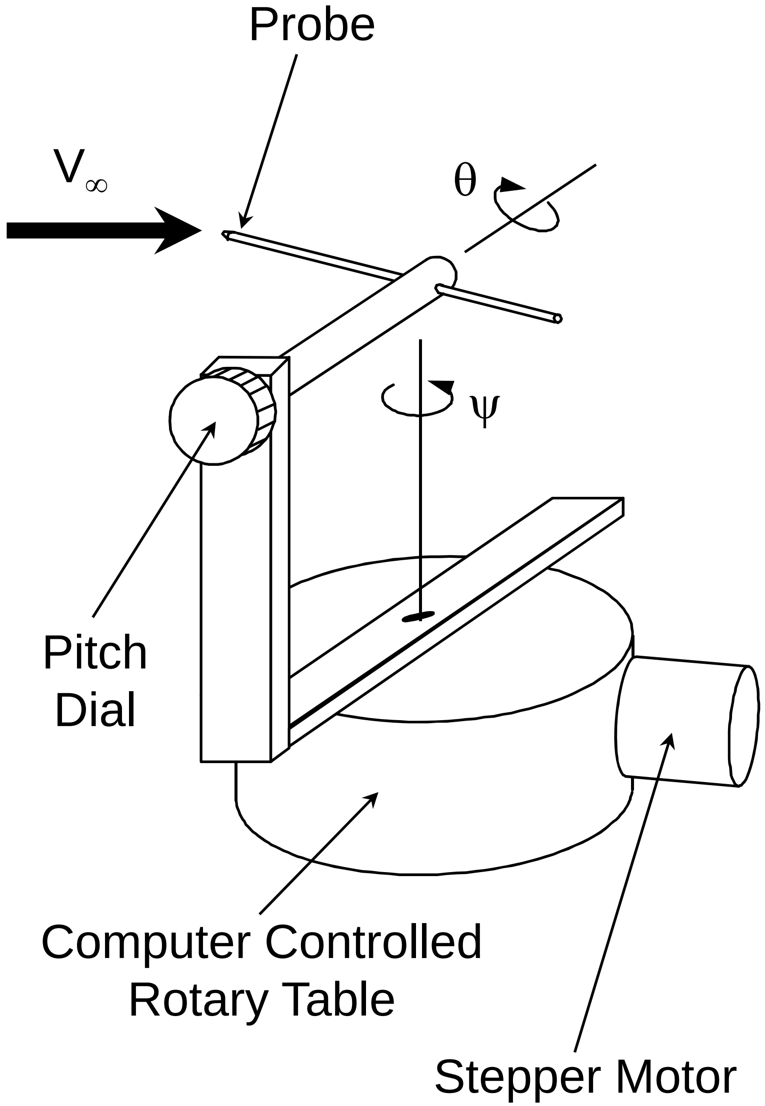
$$C_{P_\beta} = \frac{1}{\sqrt{3}}\left(C_{P_B} + C_{P_C}\right) \qquad \text{Yaw}$$

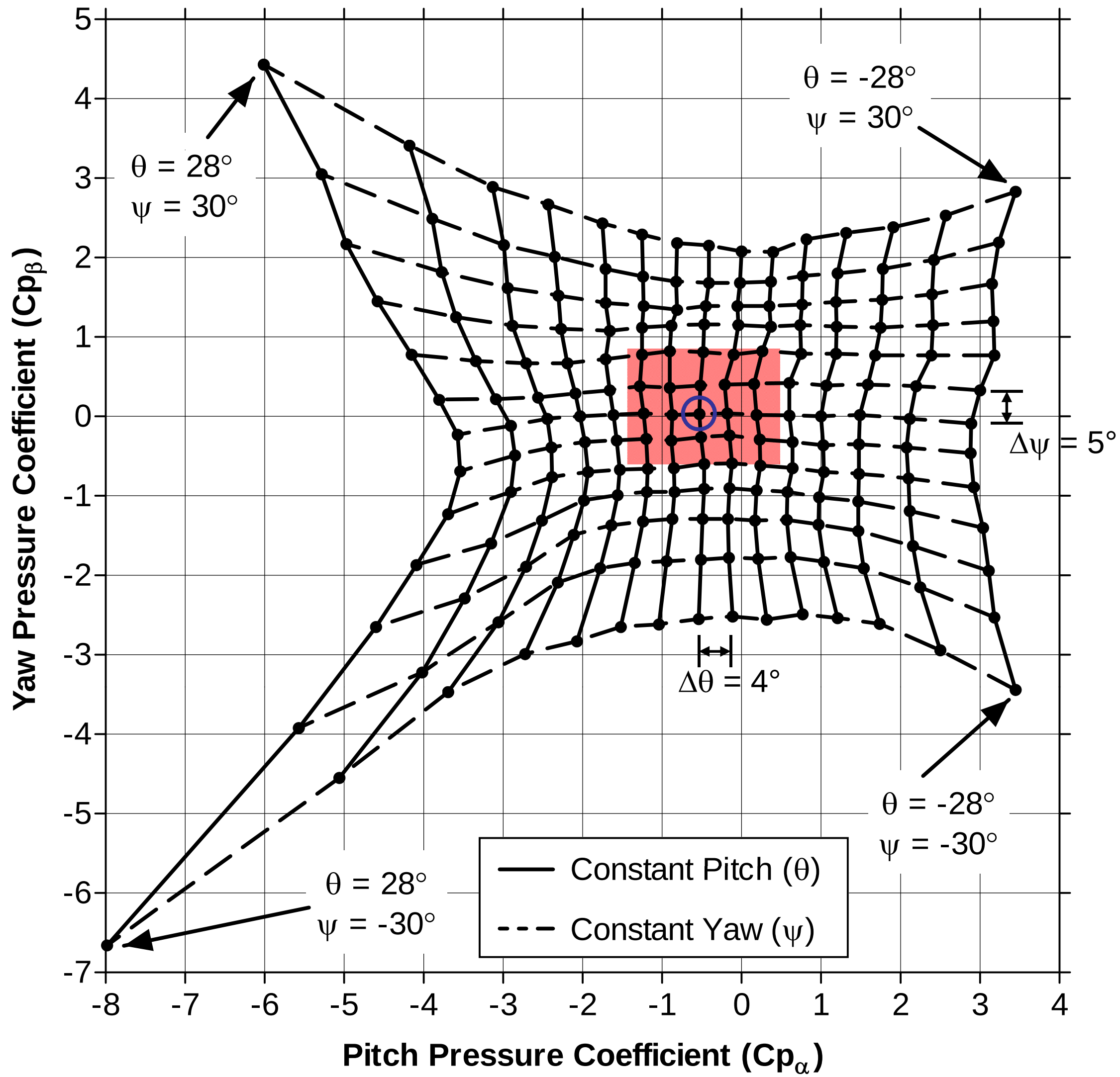
Total and Static Pressure Coefficients:

$$C_{P_{Total}} = \frac{P_7 - P_{Total}}{P_7 - \overline{P}} \qquad C_{P_{Static}} = \frac{\overline{P} - P_{Static}}{P_7 - \overline{P}}$$

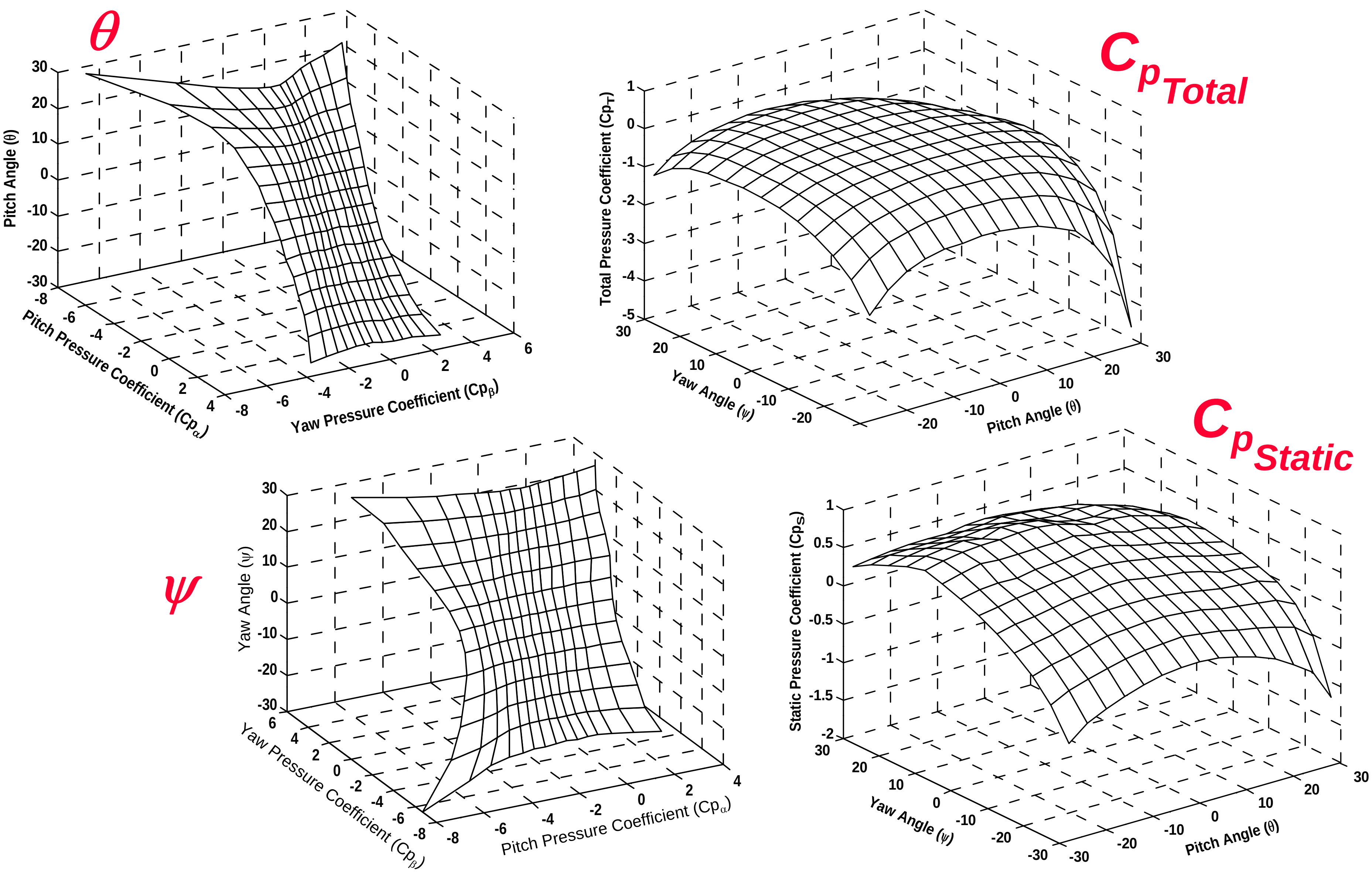
$$\left|\vec{V}\right| = \sqrt{\left(\frac{2}{\rho}\right)\left(P_7 - \overline{P}\right)\left(1 + C_{P_{Static}} - C_{P_{Total}}\right)}$$

Seven-Hole Probe Angular Sensitivity Must be Calibrated in a Uniform Flow Field





Seven-Hole Pressure Probe Calibration Data



Computation of Flow Direction, Flow Velocity, total pressure, static pressure from Seven-Hole Pressure Probe

Measure Probe Pressures
$(P_1, P_2, P_3, P_4, P_5, P_6, P_7)$

Compute:

$$C_{P\alpha} = f(P_i)_{i=1,7}$$
$$C_{P\beta} = f(P_i)_{i=1,7}$$
$$\overline{P} = \mathrm{mean}\left(P_i\right)_{i=1,7}$$

Interpolate on probe calibration data to find flow angles:

$$\theta = f(C_{P\alpha}\ ,\ C_{P\beta})$$
$$\psi = f(C_{P\alpha}\ ,\ C_{P\beta})$$

Interpolate on probe calibration data to find total and static pressure coefficients:

$$C_{P_{total}} = f(\theta\ ,\ \psi)$$
$$C_{P_{static}} = f(\theta\ ,\ \psi)$$

Compute total and static pressure:

$$P_{Total} = P_7 - \left(P_7 - \overline{P}\right) C_{P_{total}}$$
$$P_{Static} = \overline{P} - \left(P_7 - \overline{P}\right) C_{P_{static}}$$

Compute magnitude of flow velocity:

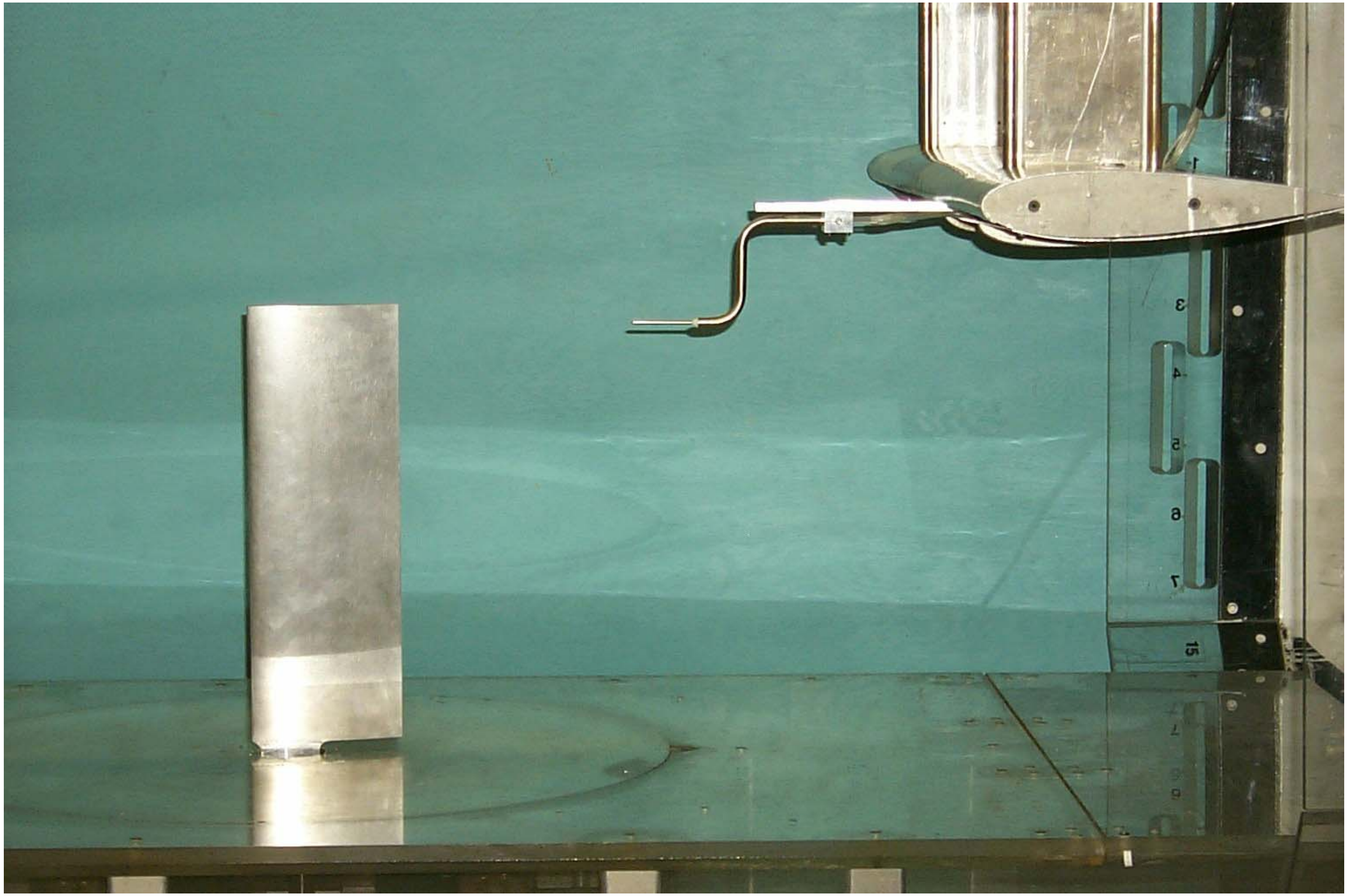
$$\left|\vec{V}\right| = \sqrt{\left(\frac{2}{\rho}\right)\left(P_7 - \overline{P}\right)\left(1 + C_{P_{Static}} - C_{P_{Total}}\right)}$$

Compute velocity components:

$$u = \left|\vec{V}\right| \cos(\Theta)\cos(\Psi)$$
$$v = \left|\vec{V}\right| \sin(\Theta)$$
$$w = \left|\vec{V}\right| \cos(\Theta)\sin(\Psi)$$

Example Experiment

Measuring the tip vortex behind a NACA 2412 wing section in the low-speed wind tunnel



Mach Number Influence

A properly designed and constructed directional probe should not be affected by changes in Reynolds or Mach number, as long as the flow is symmetrical about the probe axis.

The accuracy of a directional probe will not be impaired, even not in supersonic flows, if the probe is parallel with the flow, because this will give a symmetric shock pattern.

However, a fixed probe at non-zero incidence may be seriously in error, because the shock on one side may be very different from its counterpart, which will affect the measurement.

The static pressure measurement however is very sensitive to Mach number and yaw angle.

Mach Number Influence

Mach number and geometry of the probe head have an influence on angular sensitivity: $S=P_L-P_R/(P_0-P_s)$

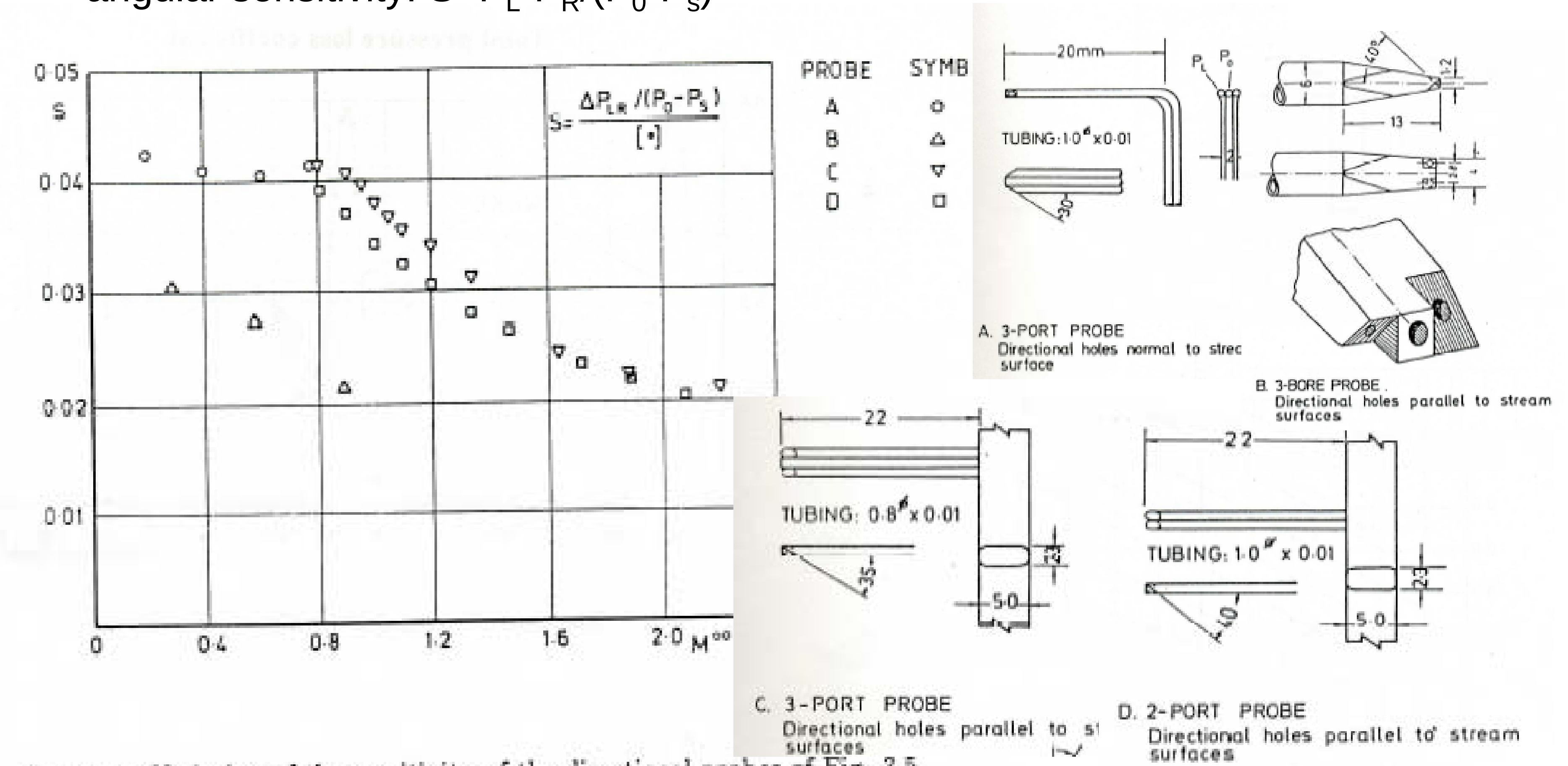


Fig. 3.13 - Variation of the sensitivity of the directional probes of Fig. 3.5, as a function of Mach number (C.H. Sieverding, 1975)

Velocity and pressure gradients

The finite distance between the slanted tube orifices prevents an accurate measurement of the flow direction in flows with a velocity gradient.

The flow angle distribution shown on Fig. 3.14 is measured in the wake behind a compressor blade, by means of a NACA short prism directional probe.

The measured sinusoidal variation of the flow angle in the wake is uniquely due to the probe size.

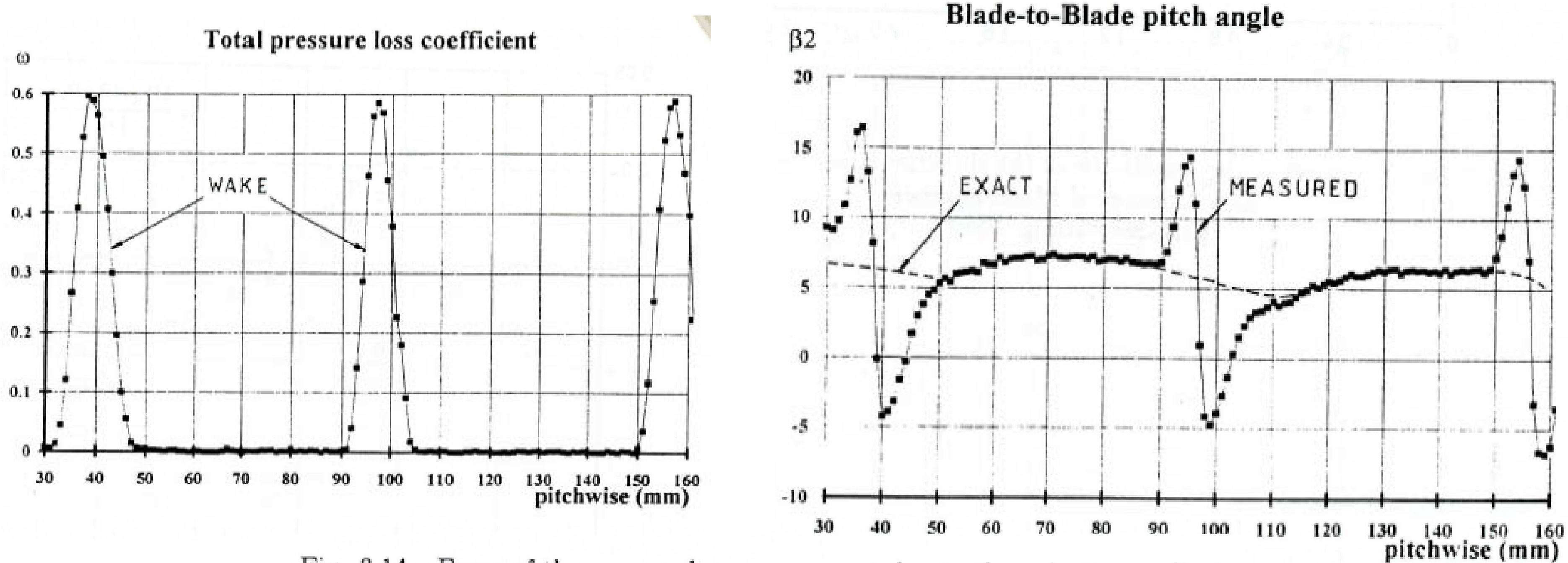


Fig. 3.14 - Error of the yaw angle measurement due to the velocity gradient generated by the wake of a compressor blade

Velocity and pressure gradients

Large velocity gradients occurring in transonic flows where expansion waves, shocks and wakes are interfering require special probes to assure accurate measurements.

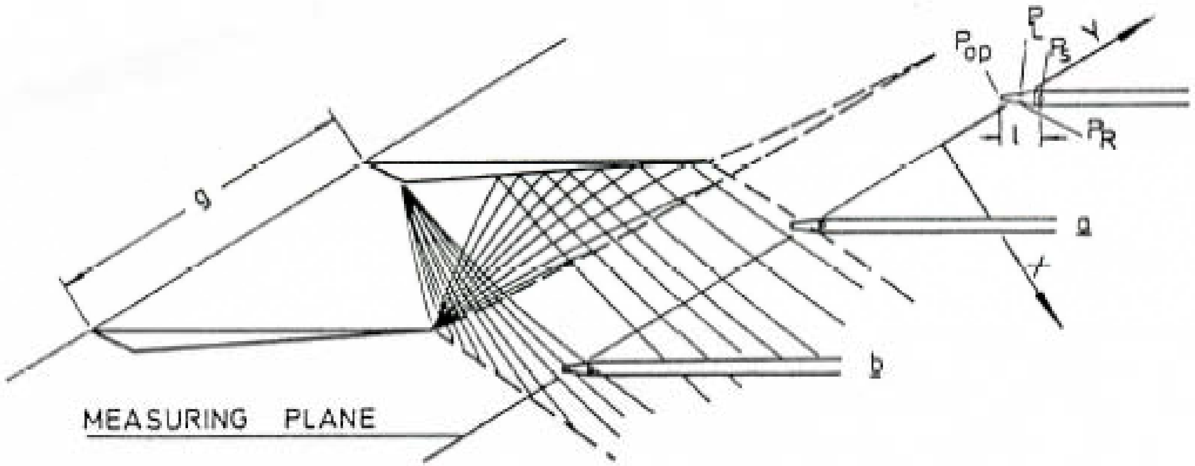


Fig. 3.15 - Shock and expansion wave interference with probes
(C.H. Sieverding, 1975)

Velocity and pressure gradients

The requirement of measuring total pressure, static pressure and the differential pressure for flow angle, simultaneously in one point, is not feasible and has to be replaced by:

A. Measurement of all values along a line perpendicular to a two dimensional flow-field by means of separate sensing elements <u>(neptune and needle probe)</u>

B. Use of very compact probes, having all sensing elements, or at least the total and static pressure holes, close together <u>(wedge and truncated cone probe)</u>

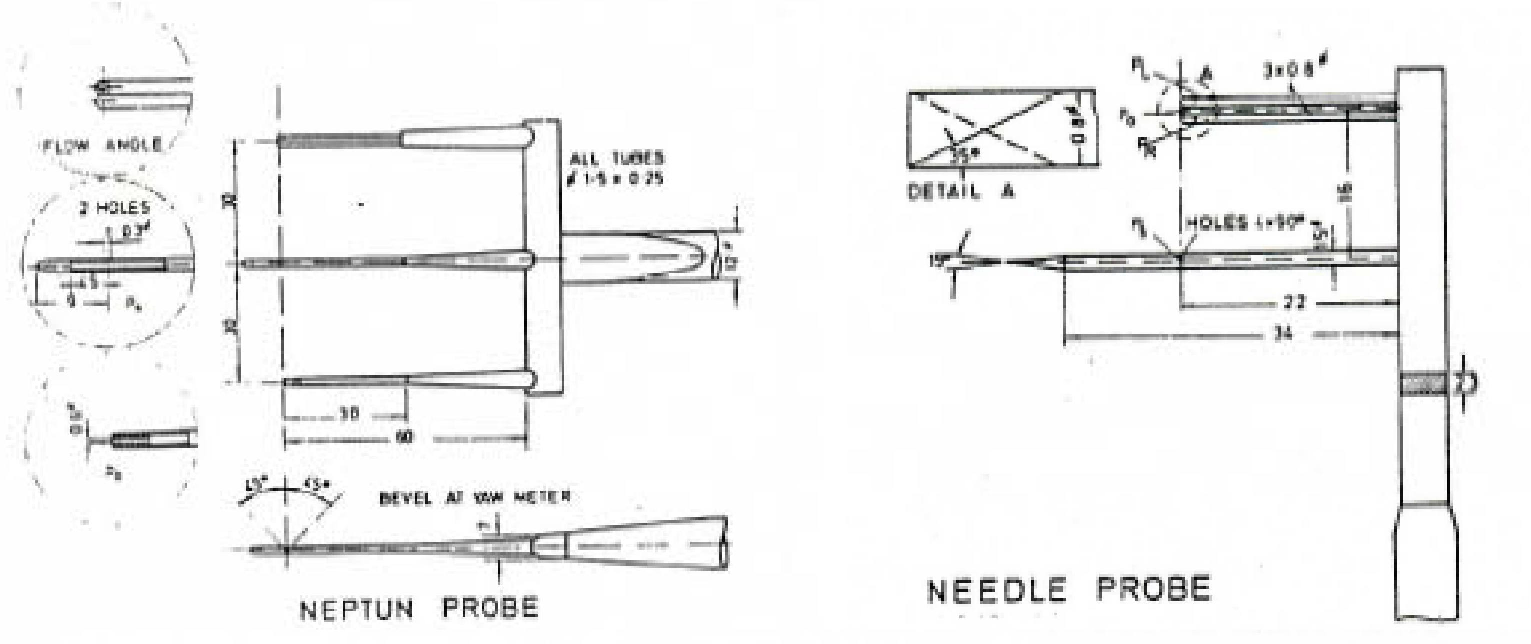


Fig. 3.16 - Probes designed for non uniform supersonic flows
(C.H. Sieverding, 1975)

Velocity and pressure gradients

<u>wedge and truncated cone probe</u>

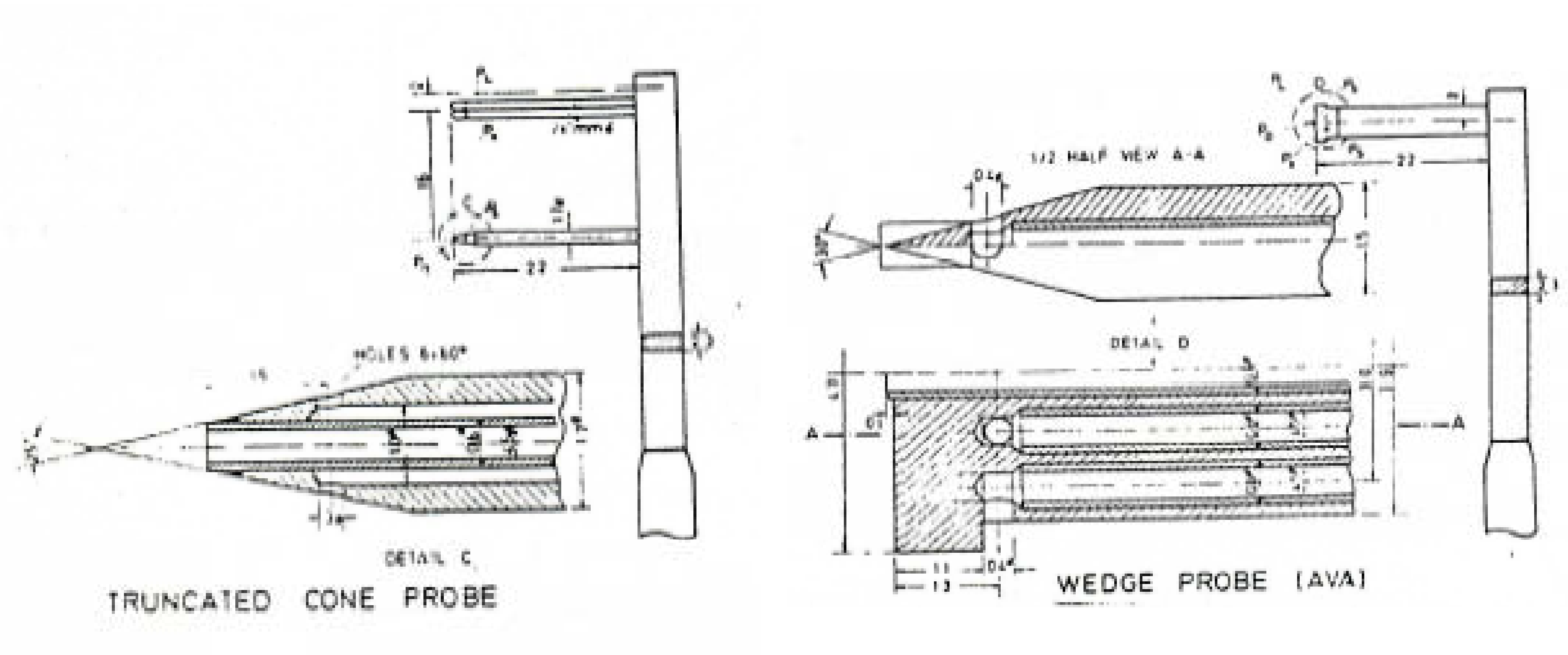
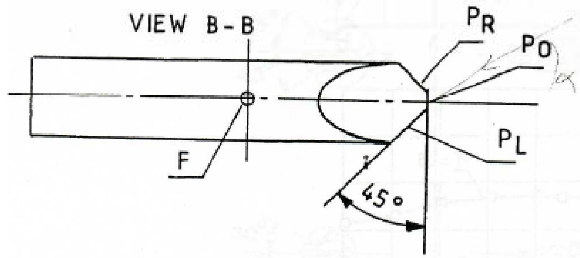


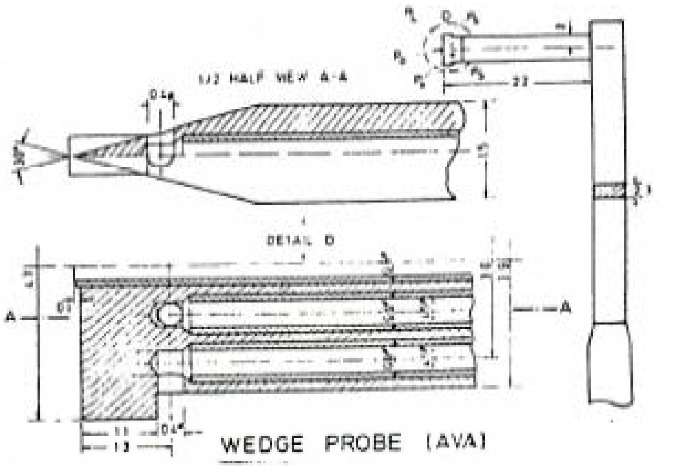
Fig. 3.16 - Probes designed for non uniform supersonic flows
(C.H. Sieverding, 1975)

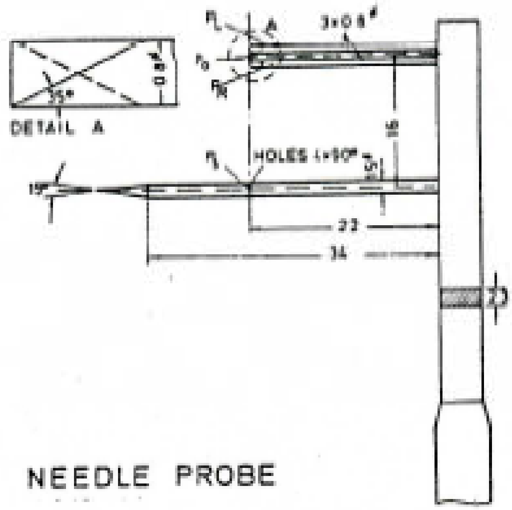
Velocity and pressure gradients

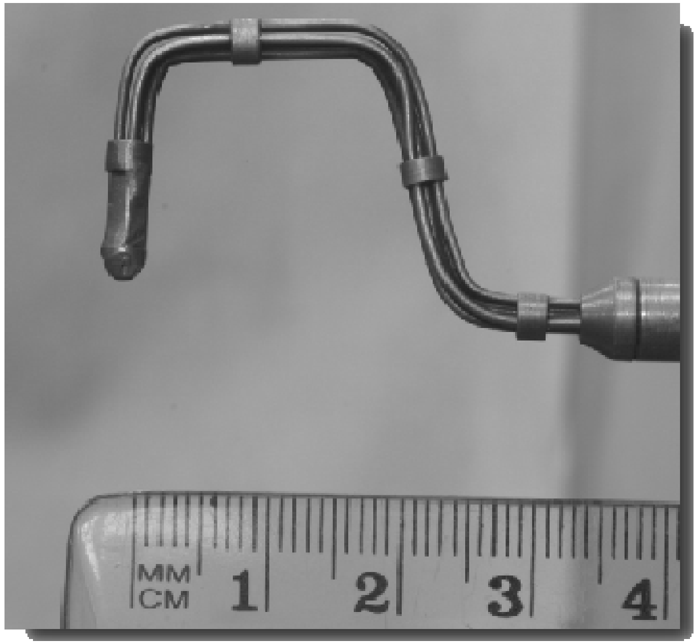
•NACA short prism probes have to be excluded for transonic flow measurements because of the long distance between the total and static pressure orifices.



•AVA wedge probe and VKI needle probe is used to measure the transonic flow downstream of turbine cascades.







•A paper on calibration of 5 hole probes:
Reichert BA and Wendt BJ (1994) A New Algorithm for Five-Hole Probe Calibration, Data Reduction, and Uncertainty Analysis. NASA Technical Memorandum 106458

http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19950005965_1995105965.pdf

•You can find an example code in the following website for the calibration of 5 hole Probe:

http://www.nongnu.org/fivehole/download.html

Diagram showing local pressures and velocities in vicinity of fuselage like body