PRESSURE PROBES FOR TURBULENCE MEASUREMENT

J.D. Hooper

Turbulent Flow Instrumentation Pty Ltd
1 Blackbutt Place, Engadine NSW 2233

Abstract: An improved version of the four-hole directional pressure probe or Cobra probe is described, in which the frequency response has been extended to 1.5 kHz. The probe measures all three orthogonal mean and turbulent velocity components at a point in the flow field. The probe also resolves the local mean and turbulent components of static pressure, allowing moments between the fluctuating velocity components and pressure to be determined.

1. Probe Design

Multi-hole pressure probes have been used to measure the mean velocity components in turbulent single phase flows for many years, particularly in regard to swirling flows where the mean flow direction is unknown (1-7). The pressure probes are generally calibrated in steady flows of low turbulence intensity, and for a limited range of yaw and pitch angles, ratios of the differential pressure readings given by the probe head taps can be formed which determine the angle of an unknown velocity vector relative to the probe axis. The work of Perry (4) showed that a three hole probe could determine the mean total and dynamic pressure and flow yaw angle for a limited range of Reynolds numbers. This concept was extended by Shepherd (5) to a four hole or Cobra pressure probe which allowed the pitch angle to be determined at the same time. The local fluid mean static pressure was given implicitly the calibration method adopted by both these papers, as the difference of the resolved total and dynamic pressure.

Hooper and Musgrove (6,7) adopted the Cobra probe geometry developed by Shepherd (5) after they had extensively tested both it and the more conventional five hole conical and hemispherical head pressure probes. It was found that the Cobra probe showed little Reynolds number sensitivity in the velocity range of 16 to 110 m/s (6), in comparison to the five hole conical and hemispherical probes.

The design of the Cobra probe is shown by figure 1, for a probe with a pressure tap hole of 0.5 mm diameter. Geometrically similar probe heads with pressure tap holes in the range of 0.5 to 3.0 mm have been constructed and calibrated, showing the same steady state response for an equivalent Reynolds number.

The placement of the pressure transducers on the probe head undoubtably provides the best frequency response. Ainsworth and Oldfield (8) have used surface mounted pressure transducers on a probe head with a similar geometry to the Cobra probe. However, to the authors knowledge, it is not currently possible to obtain pressure transducers with a sensor diameter of 0.5 mm, and probes with surface mounted transducers are considerably larger than the Cobra probe of figure 1.

2. Probe Steady State Calibration and Frequency Response

The steady state calibration of the probe follows the method given by Hooper and Musgrove (6). A numerical study (De Guzmann et al (9)) of the faceted head of the probe showed the very high pressure gradients across the head. The extension of the Cobra probe to the measurement of both mean and turbulent flow structure is dependent on the frequency response of the pressure measurement system, and a small physical scale for the probe head in relation to the flow structures it is to resolve. The propagation of a dynamic pressure field through a long tubing system, to a fixed volume pressure transducer, has been studied in order to monitor the dynamic response of wind tunnel models, and more recently in the field of wind engineering. The work of Berg and Tijderman (10) gives both a detailed theoretical analysis and experimental verification of the predicted phase and amplitude response for a multi-segment tubing system. The pressure transfer function is defined as:

$$H(f) = G_{ac}(f) \, / \, G_{aa}(f) \qquad (1)$$

The power spectrum $G_{aa}(f)$ is derived by Fourier transform of the time record of the pressure signal at the probe head pressure tap $P_a(t)$, and the cross spectra $G_{ac}(f)$ by the Fourier transform of this pressure and $P_c(t)$, the response in the pressure transducer volume. Various methods of compensating for the distortion introduced in the probe head tap pressure by the transmission path have been developed, with Holmes and Lewis (11) using a small length of fine diameter tubing known as a restrictor in the pressure line. However, the frequency response can be corrected for the amplitude and phase distortion by dividing the pressure signals by the inverse of the known transfer function, the method adopted..
The technique developed for correcting the distortion of the pressure transmission path for the Cobra pressure probe has been independently proposed by Smith (13), in a pressure probe used to study atmospheric turbulence. This probe is of a considerably larger size with a head 25 mm in diameter, and uses purpose built pressure transducers to measure velocities of a few m/s. The upper frequency resolved by that probe was 200 Hz.

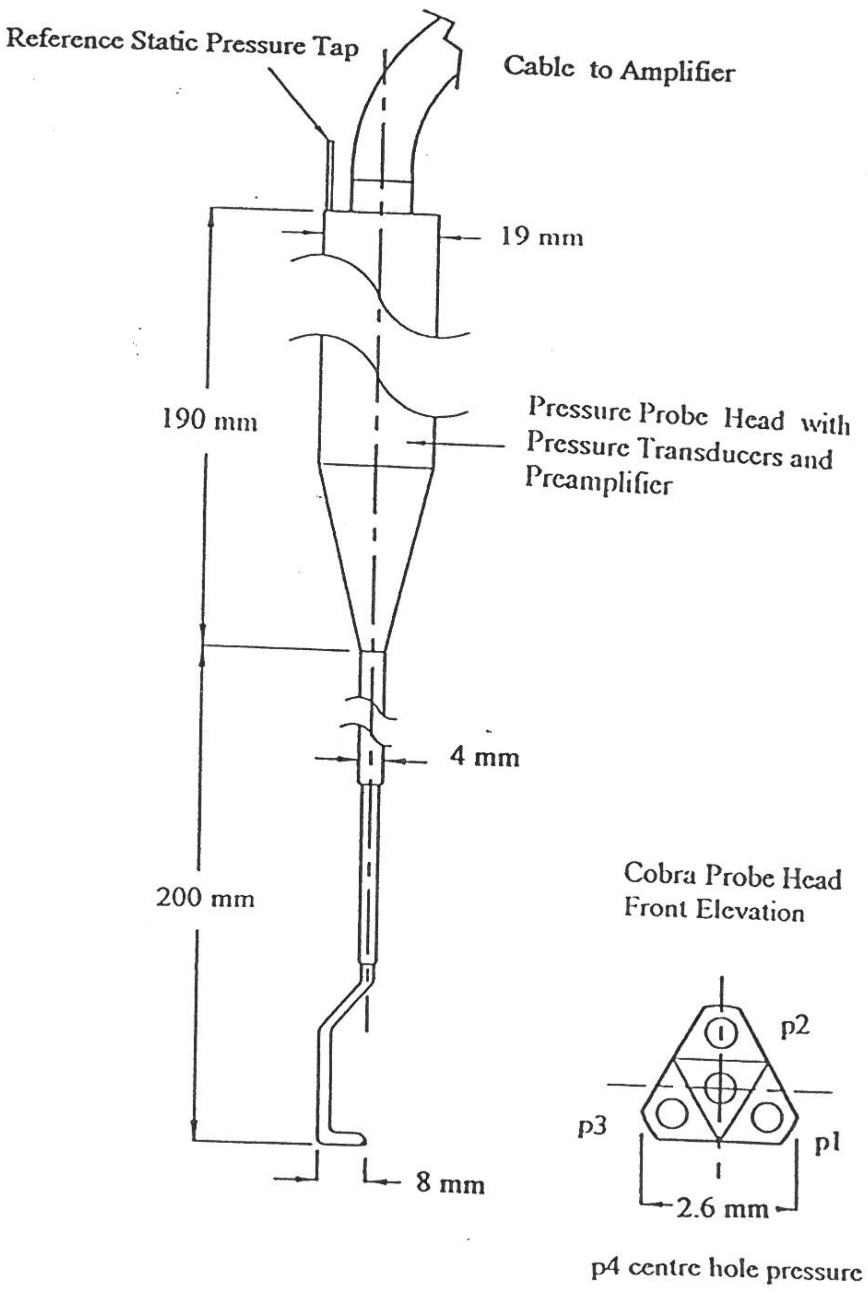
3. Experimental Results in Developed Pipe Flow.
The Reynolds stress distribution and correlation between the dynamic static pressure and the axial turbulent velocity component are given by figures 2(a) to (d) for developed single phase turbulent pipe flow. This calibration flow has been extensively used to test hot-wire anemometer techniques (see for example Hooper (14)), and is a flow in which the r-z component of the Reynolds stresses may be calculated from the axial pressure gradient. The data presented is in good agreement with hot-wire data.

4. Conclusion
The four hole Cobra pressure probe has been shown to be able to measure all components of the Reynolds stresses in developed turbulent pipe flow, for both the 0.5 mm and 1.0 mm tap diameter probes. Developed pipe flow may be regarded as a calibration flow, and the agreement of the data presented with results generated by hot wire anemometers, laser Doppler velocimetry and other optical flow measurement systems substantiates the techniques developed to extend the frequency response of the probe

References

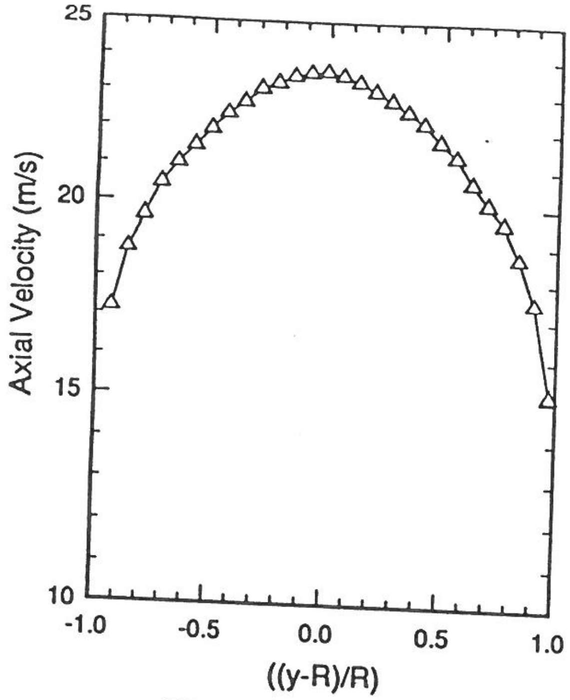
(1) Lee, J.C. and Ash, J.E., Trans. ASME 78, p 603, 1956
(2) Bryer, D.W. and Pankhurst, R.C. "Pressure Probe Methods for Determining Wind Speed and Direction", HMSO (London), 1971
(3) Judd, M.A. J. Phys. E., Sci. Instruments 8, p 115, 1975
(4) Perry, J.H. "Calibration and Comparison of Cobra Probe and Hot Wire Anemometer for Flow Measurements in Turbomachinery" CSIRO Tech. Report No TR 1, Highett, Victoria 1974
(5) Shepherd, I.C., Trans. ASME, J. Fluids Engng., 103, p 509, 1981
(6) Hooper, J.D. and Musgrove, A.R., Proc. 4th Int. Symp. on Transport Phenomenon in Heat and Mass Transfer, University of NSW, p 1364, 1991
(7) Musgrove, A.R. and Hooper, J.D., Proc. 3rd World Conf. Exp. Heat. Tfr., Fluid Mech. and Thermodynamics, V1, p 172, Hawaii 1993
(8) Ainsworth, R. and Oldfield, M.L.G., University of Oxford, Dept. of Engineering Science, Private Communication, 1993

(9) De Guzman, M.M., Fletcher, C.A.J. and Hooper, J.D., Int. J. Num. Methods in Heat and Fluid Flow, 4, p 425, 1994
(10) Berg, H. and Tijderman, H., "Theoretical and Experimental Results for the Dynamic Response of Pressure Measuring Systems", Nat. Aero. and Aeronautical Research Institute Report NLR-T.R.F. 238, 1965
(11) Holmes, J.D. and Lewis, R.E., J. Wind. Engng, and Indust. Aerodynamics, 25, p 249, 1987
(12) Irwin, H.P.A.H., Cooper, K.R. and Girard, R., J Wind Engng. and Indust. Aerodynamics, 5, p 93, 1979
(13) Smith, S.E. "An Instrument for Measuring Turbulence During Wind Erosion", Ph.D. Thesis, Murdoch University, 1994
(14) Hooper, J.D. "Fully Developed Turbulent Flow through a Rod Cluster", Ph.D. Thesis, University of NSW, 1980

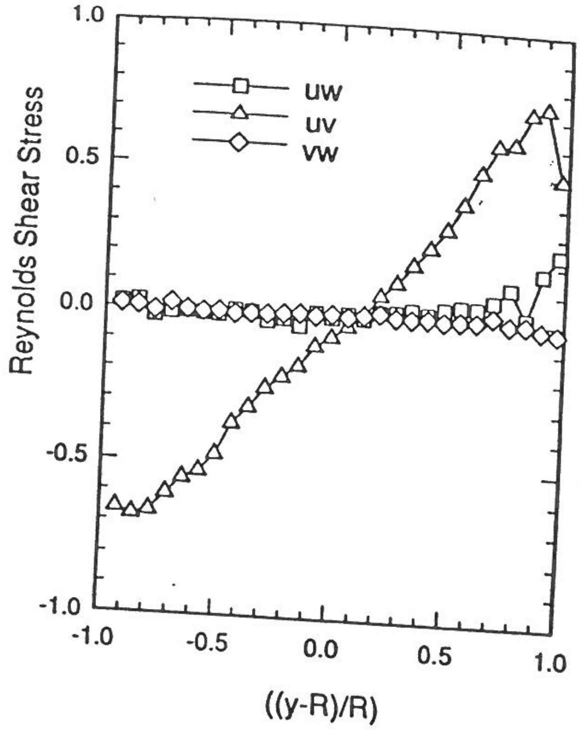


The four hole faceted head Cobra pressure probe. Tap diameter 0.5 mm.

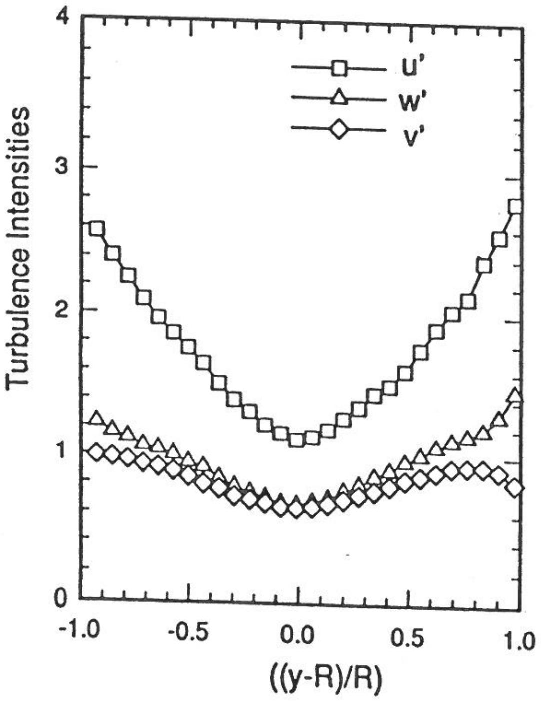
Figure 1.



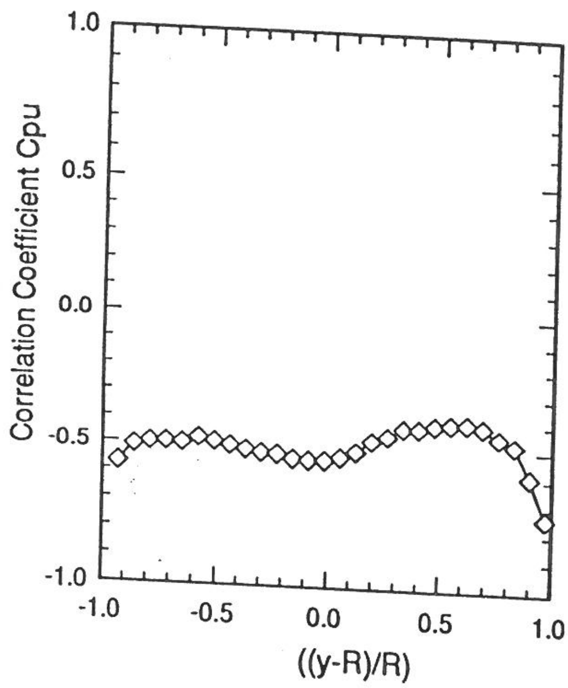
Mean Velocity Distribution, 142 mm i.d. pipe.
Flow development length 127 diameters.
Figure 2 (a).



Turbulence Intensities at pipe exit.
Figure 2 (b).



Correlation Cpu at pipe exit.
Figure 2 (d).



Reynolds stresses at pipe exit.
Figure 2 (c).