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PRESSURE PROBE MEASUREMENTS OF REYNOLDS STRESSES AND STATIC PRESSURE FLUCTUATIONS IN DEVELOPED PIPE FLOW

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Abstract

Multi-hole pressure probes have been extensively used to measure the magnitude of the mean velocity vector and flow direction in turbulent single phase flows. By extending the frequency response of the pressure measurement system to at least 1.5 kHz, it has been shown to be possible to resolve simultaneously all components of the mean velocity and Reynolds stresses at a point in the flow. An additional parameter measured is the mean and turbulent components of the local static pressure, allowing moments between the fluctuating pressure and velocity to be measured. This capacity, not available with the laser Doppler or hot wire anemometer, may lead to new insights in turbulence modelling. Results for developed single phase turbulent pipe flow are given, including the mean axial velocity profile, all components of the Reynolds stresses and the correlation between the axial turbulent velocity component and the static pressure fluctuations. The technique used to obtain the given frequency response is discussed.

1. Introduction

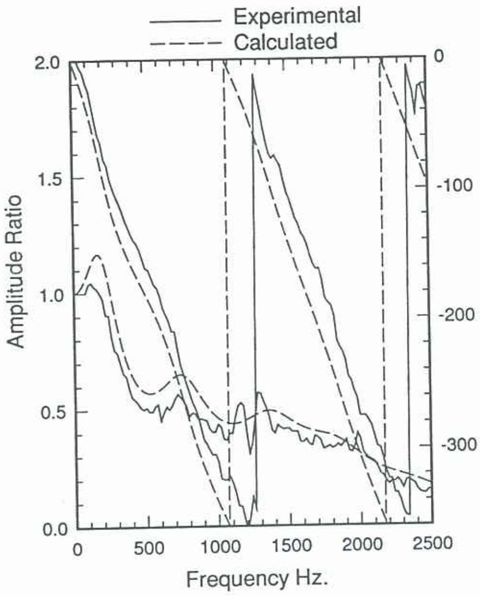
Multi-hole pressure probes have been used for many years to measure the mean velocity components in turbulent single phase flows, particularly in regard to swirling flow where the direction of the mean velocity is not known (Everett et al. (1983), Lee and Ash (1956), Bryer and Pankhurst (1971), Hooper and Musgrove (1991), and Shepherd (1981)). The work of Shepherd extended the value of such probes by showing that it was possible to determine the local mean static pressure level in the fluid, by appealing to four calibration surfaces to determine the local total pressure, dynamic pressure, and yaw and pitch angle. The limitation was that only the mean flow parameters were measured, leaving the determination of the turbulent velocity components to hot wire or more recently laser Doppler anemometry.

The strengths and associated problems of both these turbulent velocity measurement methods are more fully discussed by Musgrove and Hooper (1993). However, it is sufficient to allude to the fragile nature of the hot wire sensor, and to the problem of using it in high turbulence intensity flow where the signal decomposition into the associated orthogonal velocity components is extremely difficult, to show the principal limitations of the method. Laser Doppler anemometry is less restrictive and may be used in extremely high turbulence intensity flows, although problems of satisfactory flow seeding, the need for optical access, and the high capital cost of the equipment limit the method to mainly laboratory use.

The extension of pressure probe techniques to measure the mean and local turbulent flow structure is above all dependent on the ability to measure the pressure field, at the tap locations on the probe tip, sufficiently rapidly to determine the energy containing and part of the inertial range of the spectrum of the turbulent velocity components. The Taylor model of a frozen turbulent structure advected past the probe tip may be used as an optimisation criteria for the probe. In this, the spatial resolution of the probe is balanced with the temporal response. This criteria shows that for a probe head dimension of approximately 3.0 mm, a frequency response to 1.5 kHz is sufficient for flow velocities up to 50 m/s. The limit of the spatial resolution of the probe is assumed to be for structures of the order of ten times the head dimension or greater.

2. Frequency Response of Pressure Probe

The optimum frequency response of a pressure probe can be obtained by mounting the solid state pressure transducers directly on the probe head, which is the method adopted by Ainsworth and Oldfield (1993). Limitations of this technique at present include the relatively large scale of the normally solid state piezo resistive pressure transducer, the fragile nature of the transducer which if surface mounted is exposed to mechanical damage, and the normally low pressure to voltage sensitivity of such transducers. By mounting the pressure transducer remote from the probe head, but tuning the connecting pressure lines and transducer volume to achieve the maximum frequency response, it is possible to obtain a distorted but fast frequency response. The method of Holmes and Lewis (1987) in mechanically tuning the combined pressure transducer volume and connecting tubes to achieve a flat frequency response to approximately 400 Hz is replaced by accepting the non-linear amplitude and phase response shown in figure 1.



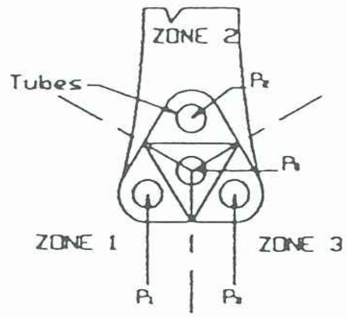
Calculated and Experimental Transfer Function

Figure 1.

Linearisation is then performed by transforming the time record of the probe pressure signals to the frequency domain, dividing each ensemble or record by the experimentally determined probe tip to pressure transducer transfer function of figure 1, and then transforming the corrected signals back into the time domain.

3. Cobra Probe

The design of the Cobra four hole pressure probe, based on a three sided prism with the top apex removed is due to Shepherd (1981), who generalised the design of the three hole yaw probe by the addition of a pitch sensitive pressure tap. The probe head is shown by figure 2., and the probe is normally constructed with a "J" shaped stem so that it may be rotated in yaw by up to 360 degrees without altering the measurement point. The probe has been extensively tested by the authors to a Mach number of 0.8, and the calibration surfaces have been shown to be remarkably independent of Reynolds number for the incompressible flow region. The separation angles of the flow from the plane surfaces at the probe tip are primarily set by the angle of the flow vector to the surface, and the influence of the free stream turbulence intensity and surface roughness effects are apparently minimised. The probe used to generate the reported pipe flow results had a tap hole diameter of 0.5 mm, a head width of 2.6 mm and 200 mm of pressure tubing separating the pressure transducers from the probe tip. This geometry results in the transfer function given by figure 1. An active, six pole, low pass filter was used to filter the amplified pressure transducer signals, and this filter was set to a 3 dB roll-off point at 1.5 kHz to avoid signal aliasing. Ensembles of data each 4096 time steps in length were recorded at a digitisation frequency of 5.0 kHz by a four channel sample and hold A/D board mounted in a host 486 level PC computer. All signal processing, including the Fast Fourier transform used to remove the distortion of the transmission of pressure signals from the probe head to the pressure transducers, was performed by this computer. The method of relating the four linearised pressure signals at each time step and on each face of the probe to the required velocity information, namely total pressure, static pressure and flow yaw and pitch angles is described by Hooper and Musgrove (1991).



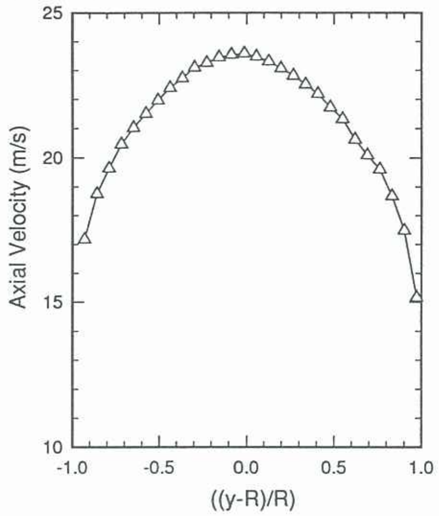
Cobra Probe Head Geometry

Figure 2

4. Experimental Results

The earlier papers of Hooper and Musgrove (1991,1993) reported the response of the probe in highly swirled pipe flow and in a turbulent, highly swirled free jet. The turbulence intensities in both flows was high, and indeed the higher frequency pressure probe was developed to measure flow in these geometries. However, the Reynolds stress distribution in these flows has not been measured by an independent technique, and a calibration flow is needed to test the probe response and calculation methods. The flow selected was developed single phase turbulent pipe flow in a pipe of 140 mm internal diameter and 18.0 m long, and powered by a 22 kW variable speed centrifugal blower. For this geometry, the Reynolds shear stress involving the cross product of the axial u and radial v turbulent velocity components can be directly related to the wall shear stress (Hooper (1981)), and the normalised axial, radial and tangential turbulence intensities (normalised by the wall friction velocity) conform to a well known distribution which is similar in the wall region to turbulent boundary layers. The axial velocity profile, measured 10 mm downstream of the pipe exit, is shown by figure 3.

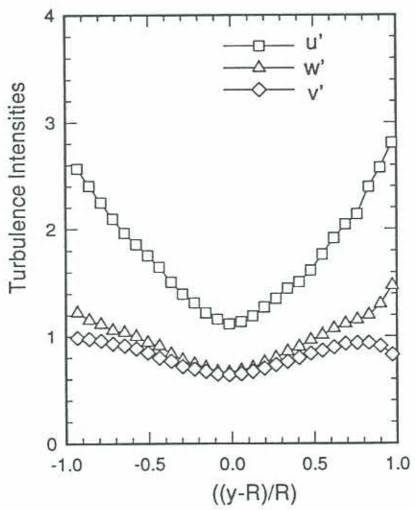
The mean velocity distribution is reasonably symmetric about the pipe centre line. The Reynolds number of the flow is 196000 with a flow development length of 128 pipe diameters, and so the flow may be assumed to be fully developed.



Mean Axial Velocity Profile.

Figure 3

The turbulence intensities u', v' and w' which are the square root of the normal components of the Reynolds stresses divided by the wall shear stress, are shown by figure 4.

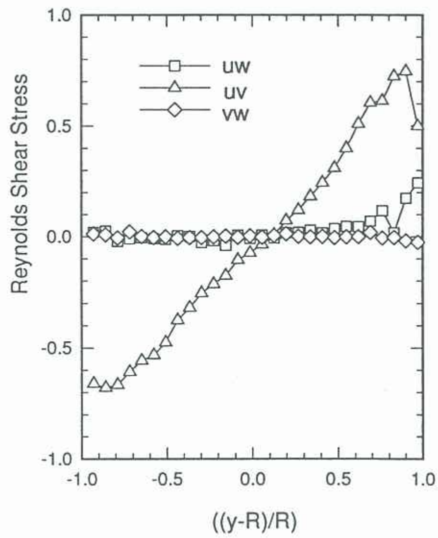


Turbulence Intensities u', v' and w'

Figure 4

The axial turbulence intensity u' is similar to the expected distribution, rising to a maximum level of approximately 2.5 in the wall region with a minium of 1.1 in the centre of the pipe. The value at the pipe centre line may be high, as hot wire data for developed pipe flow show a value of 0.8 for this region (Hooper (1981)).The distribution of the radial turbulence intensity v' is again in general agreement with data measured by hot wire anemometry (Hooper (1981)), but the absolute magnitude is lower. The hot wire results show a value of v' of 0.8 in the centre of the pipe against the pressure probe result of 0.7. Additionally, there is a lack of symmetry in the distribution with respect to the pipe center line. The probe head width of 2.6 mm is not greatly larger than a typical hot wire anemometer sensor, but the flow interference effect is clearly greater than a hot wire probe. The v' turbulence intensity data indicates that the pressure probe is unable to resolve the velocity components near to the pipe wall. The tangential turbulence intensity w' is again similar to the hot wire data, but of reduced magnitude.

The Reynolds shear stress components normalised by the pipe wall shear stress are show by figure 5. The non-zero component $-\rho\overline{uv}/\tau_w$ is close to the expected linear distribution which asymptotes to + or - the wall shear stress at the pipe wall, for dimensionless distances from the pipe centre line of less than 0.9. It is apparent from Figure 5, however, that the pressure probe cannot satisfactorily resolve these components in the wall region of the pipe.

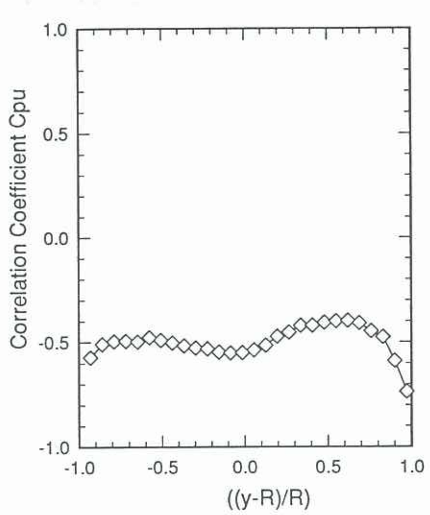


Normalised Reynolds Shear Stresses

Figure 5

The components $-\rho\overline{uw}/\tau_w$, $-\rho\overline{vw}/\tau_w$ are shown by the Navier Stokes momentum equations to be zero for developed pipe flow, and again this distribution is shown by figure 5 for dimensionless distances to the pipe centre line of less than 0.9. Ten data records were averaged at each radial pipe location to generate the data shown by the above figures, giving a total time record length slightly in excess of eight seconds. The PC computer required approximately three minutes to record and process the data at each point.

Both the time averaged and dynamic component of the local fluid static pressure is available in the data given by the Cobra pressure probe. This is a result of the use of two calibration surfaces giving the local total and dynamic pressures (Hooper and Musgrove (1991), Shepherd (1981)). This feature of the probe and calibration system has been tested and used in swirling annular pipe flow to measure the radial distribution of the mean static pressure field. The pressure probe gave results consistent with the static pressure shown by wall pressure taps at the inner and outer surface of the annulus. In the exit plane of the pipe and for the symmetric non-swirled turbulent pipe flow of this study, the mean static pressure field, to the resolution possible with the probe, is zero. However, the dynamic component of the static pressure field for this study was found to be significantly correlated with one turbulent velocity component.



Correlation C_{pu}

Figure 6

The correlation between the axial turbulent velocity component and the turbulent static pressure field is shown by figure 6. The radial variation of this correlation coefficient is reasonably symmetric with respect to the pipe centre line, if the pipe wall regions (or dimensionless centre line distances greater than 0.9) are excluded. The turbulent static pressure field was not found to be significantly correlated with the radial and tangential turbulent velocity components in this flow geometry.

5 Conclusion

The four hole Cobra pressure probe has been shown to be able to measure all components of the Reynolds stresses in a calibration turbulent flow, provided that the use of the probe is limited to the core region of the flow and away from the high shear gradients near to the duct walls. The additional capability of the probe, namely to resolve the local mean and turbulent static pressure, allows for the first time moments between the turbulent velocity components and static pressure to be measured.

REFERENCES

Ainsworth R. and Oldfield, M.L.G., 1993 "Private Communication", Dept. of Eng. Sci., U. of Oxford.

Bryer, D.W. and Pankhurst, R.C. 1971. "Pressure Probe Methods for Determining Wind Speed and Flow Direction" HMSO (London)

Everett, K.N., Gerner, A.A. and Durston, D.A., 1983 AIAA Journal, , 21, p992

Holmes, J.D and Lewis, R.E., 1987 J. Wind Engng. and Ind. Aerodynamics, 5, p93

Hooper, J.D and Musgrove, A.R. deL., 1991 Proc. 4th Int. Symp. on Transport Phenomenon in Heat and Mass Transfer, U. of N.S.W., p1364

Hooper, J.D., 1981 "Fully Developed Turbulent Flow through a Rod Cluster" PhD Thesis, U. of N.S.W.

Lee, J.C. and Ash, J.E., 1956 Trans ASME, 78, p603

Musgrove, A.R. deL and Hooper, J.D., 1993 Proc. 3rd World Conf. on Exp. Heat Tfr., Fluid Mech. and Thermodynamics, V.1, p172

Shepherd, I.C., 1981 Trans ASME, J. Fluids Eng., 103 p590

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