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USE OF A HOT-WIRE ANEMOMETER TO EXAMINE THE PRESSURE SIGNAL OF A HIGH-FREQUENCY PRESSURE PROBE

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ABSTRACT

The determination of both the fluctuating total and static pressures away from a wall in a turbulent flow field is difficult. In order to test the methodology adopted by the Cobra pressure probe to do this, the centre-hole fluctuating pressure signal of the four-hole pressure probe was used to measure the axial turbulent velocity component in a free jet, using a small signal approximation. This time dependent velocity was compared to the turbulent axial velocity component measured by a hot-wire anemometer, also located on the axis of the jet but 10mm upstream of the Cobra probe head. Reasonable agreement was demonstrated between the two time dependent signals of the axial turbulent velocity.

INTRODUCTION

Linearisation of a fluctuating pressure signal transmitted through a tubing system corrects for the amplitude and phase changes experienced by the different frequency components of the original pressure signal. The Cobra probe (Hooper and Musgrove, 1997) relies on linearisation of the pressure signals through each of its tubes, that link the probe head to the transducers, to provide a reconstruction of the dynamic velocity and pressure fields measured at the head. Through the use of calibration surfaces, the pressure data are converted to a time history of the instantaneous velocity vector, relative pitch angle, relative yaw angle and local static pressure.

The Cobra probe pressure signals are linearised using the inverse Fourier transform method proposed by Irwin *et al.* (1979). This method involves the Fourier transformation of the pressure signal into the frequency domain, division by a complex transfer function followed by Fourier transformation back into the time domain. The linearised pressure data are then used in the calibration surfaces. The transfer function of the pressure tubing, relating the dynamic pressure at the probe head to that at the pressure transducers, is thus important in obtaining the linearised dynamic pressure signals. The required transfer function can be obtained either theoretically or experimentally. Both methods have been used and a comparison is provided in this paper.

The aim of this experiment was to take simultaneous measurements in a turbulent flow field with a hot-wire anemometer and the Cobra probe so that fluctuating velocity signal and spectral comparisons could be made. The Cobra probe pressure tubing transfer function, determined using a small signal analysis and the hot wire velocity signal, was also to be compared with transfer functions determined theoretically and experimentally using other methods.

EXPERIMENTAL METHOD

A 1.0kW centrifugal blower provided medium turbulence intensity, single-phase airflow which was fed through a turbulence-reducing grid followed by an 8:1 contraction. The jet exit was a round, 40mm diameter pipe. Tests were conducted at a mean velocity of 25m/s with an axial turbulence intensity of 5% at the measurement location.

A single-wire hot-wire anemometer was placed normal to the mean flow, 90mm downstream of the jet exit. The hot wire was 25mm in total length with a 2mm long, 5μm diameter Tungsten active section. The 25mm wire length was used to diminish the effects of flow disturbance from the hot-wire probe forks on the flow to the Cobra probe. The hot-wire was calibrated with the Cobra probe in place to diminish the errors resulting from the influence of the Cobra probe on the flow to the hot-wire. The non-linearised output from the hot-wire bridge circuit was used for all measurements. Data were recorded with a Sony 16-bit digital instrumentation recorder (which incorporates 8^{th}-order anti-alias filters) on digital audio tape (DAT) at 12kHz.

The head of the Cobra probe was placed 10mm directly downstream of the active section of the hot-wire (100mm from the jet exit). The maximum external dimension of the probe head is 2.6mm. The probe head was aligned with the flow such that the pressures at the three outer holes were all balanced. This indicated that the mean pitch and yaw angles were zero and that the centre hole was aligned with the mean flow. Each of the four pressure tubes joining the head of the Cobra probe to the transducers were 270mm in length and had an internal diameter of 0.5mm. The transducer volumes were all $5mm^3$. These dimensions were used in determining the theoretical transfer function of the tubing. The bridge output from the Cobra probe centre-hole transducer was low-pass filtered (with a -3dB point at 2kHz) and recorded simultaneously with the hot-wire data on DAT.

SMALL SIGNAL ANALYSIS OF COBRA PROBE PRESSURE SIGNAL AND COMPARISON WITH HOT-WIRE VELOCITY SIGNAL

As velocity and pressure are related by a square law, it is not normally possible to directly compare a hot-wire velocity signal with a dynamic pressure signal using linear signal identification methods. However, by using a small signal analysis of the pressure signal and making some approximations, a linear relationship between the velocity signal and dynamic pressure signal can be formed. In forming the linear relationship, it is assumed that the mean flow is in the axial direction, that the mean static pressure in the jet is equal to atmospheric static pressure and that the static pressure fluctuations are much smaller in magnitude than the total pressure fluctuations. With these approximations and assumptions, it can be shown that the time dependent pressure signal is related to the velocity signal by Equation 1, where: p(t) is the pressure fluctuation time series; ρ is the air density; u(t) is the axial component velocity fluctuation time series; and U is the mean velocity in the axial direction.

$$p(t) \approx \rho U u(t) \tag{1}$$

Equation 1 may be rearranged to solve for the time dependent velocity using a fluctuating pressure signal (Equation 2).

$$u(t) \approx \frac{p(t)}{\rho U} \tag{2}$$

For these tests, the mean velocity was taken as the mean velocity from the hot wire.

A section of a plot of the fluctuating velocity signal from the Cobra probe (determined using the small signal analysis of the non-linearised pressure signal) is shown with the fluctuating velocity signal from the hot wire in Figure 1. For clarity, only a very short time period is shown but the trends continue for the complete time record. It should be noted that the Cobra probe velocity signal has been time shifted. This corrects for the time lag due to the flow moving from the hot-wire to the Cobra probe head and for the transmission of pressure waves through the Cobra probe tubing system to the probe transducers.

Figure 1 shows that the velocity signal from the Cobra probe generally followed that from the hot wire but the higher frequency components were attenuated. Spectral analysis confirms this with the Cobra probe frequency spectrum showing a sharp roll-off starting at 200Hz while the hot-wire spectrum does not roll off until 350Hz. Figure 2 shows a comparison of the velocity signal power spectra from the hot wire and the Cobra probe. The sharp roll-off in the hot-wire power spectrum indicates that the flow was not fully developed and did not contain broad-band turbulence.

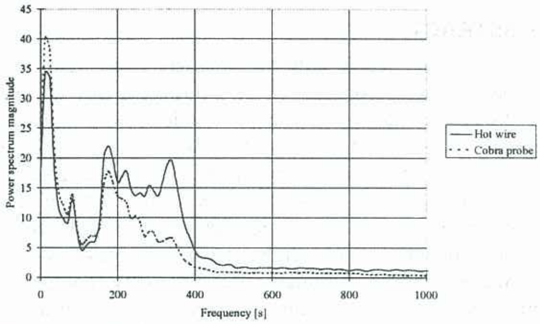

Figure 2 : Comparison of power spectra

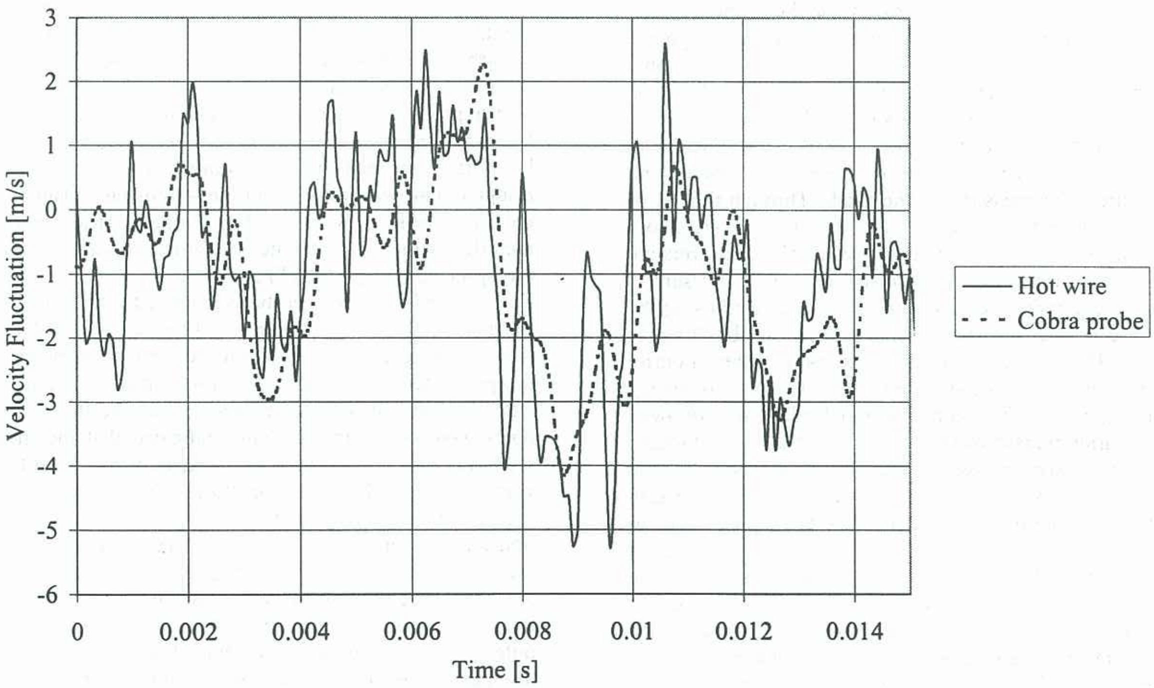

Figure 1 : Comparison of hot-wire and non-linearised Cobra probe fluctuating velocity signals

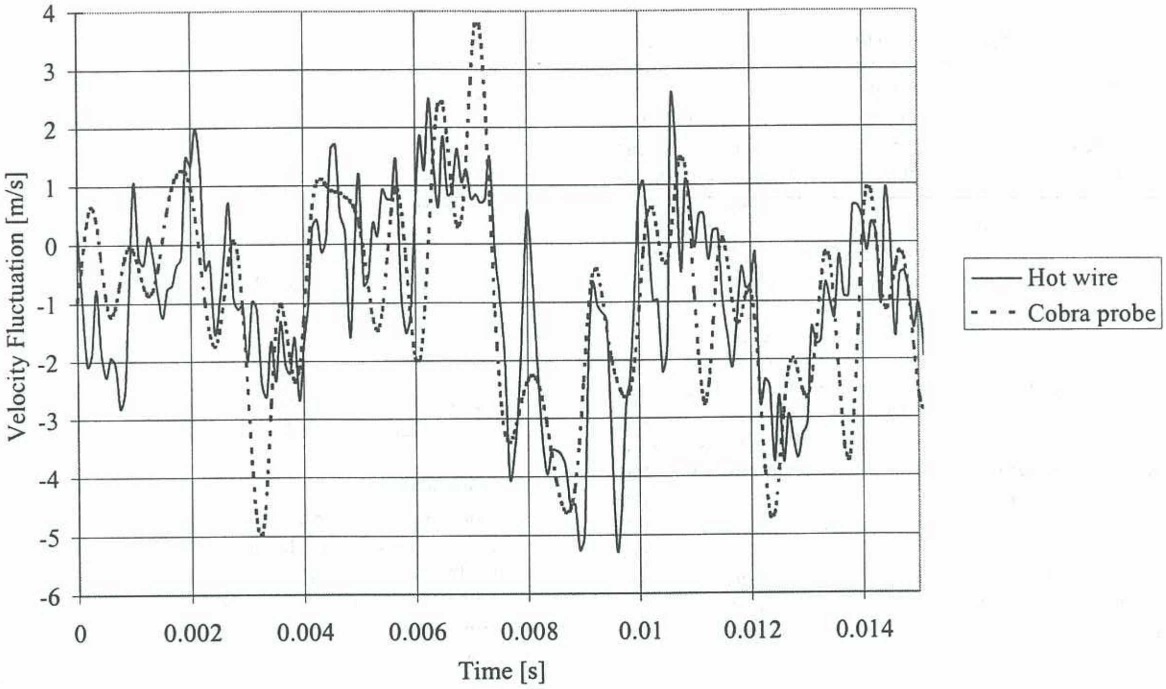

Figure 3 : Comparison of hot-wire and linearised Cobra probe fluctuating velocity signals

Using an experimental transfer function generated with a white noise source (refer to the following section) the Cobra probe pressure signal was linearised and used in the small signal analysis to produce a linearised velocity signal. The same time sequence as shown in Figure 1 is shown in Figure 3, with the linearised Cobra probe velocity signal in place of the non-linearised signal.

Clearly, the higher frequency components of the velocity signal have been enhanced and the signal tends to better trace the higher-frequency components of the hot-wire signal than the non-linearised signal does. It is observed from Figure 3 that the lower frequency components of the signal correlate reasonably well. It is also noted that the higher frequency peaks evident in the time signal, which do not correlate as well as the low frequency components, occur with periods approximately equal to the time required for the flow to translate from the hot wire to Cobra probe head. This indicates that the turbulent flow structure has modified in this 10mm spatial translation and influenced the results. The degree of flow structure modification in the spatial translation from the hot wire to the Cobra probe head could be determined by repeating the experiment with a second hot-wire anemometer in place of the Cobra probe. Additionally, the non-axial components are shifting the fluid packets as seen by the hot wire away from the Cobra probe head, which also influences the time dependent velocity signal.

Comparison of transfer functions

Using the small signal analysis, it was possible to directly compare the transfer function between the hot-wire and Cobra probe signals to the Cobra probe pressure tube transfer functions computed theoretically and from other experimental data.

The Cobra probe pressure tube transfer function was calculated theoretically using the theory of Berg and Tijderman (1965), as utilised by Holmes and Lewis (1987), and is shown in Figure 4. The experimental transfer function was determined by placing the Cobra probe head in a duct with an amplified speaker at one end and open at the other. A B&K SPL meter was placed next to the probe head (within one quarter-wavelength of the highest frequency) and used as the reference. The speaker was fed white noise and simultaneous measurements taken from the probe and microphone were used to calculate the transfer function. The experimental white noise transfer function is shown in Figure 4.

The transfer function between the hot wire and Cobra probe was determined using the small signal analysis of the Cobra probe centre-hole pressure signal and the hot-wire velocity signal. As detailed in the previous section, a small signal analysis of the Cobra probe pressure signal can provide a fluctuating velocity signal to be used in linear signal analysis. The experimental hot-wire transfer function is also shown in Figure 4.

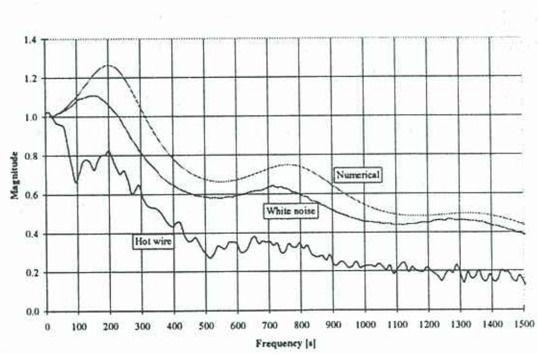

Figure 4 : Comparison of tube transfer functions

A comparison of the Cobra probe pressure tube transfer functions from the different methods shows considerable variation. The experimental white noise transfer function is of consistently lower magnitude than the theoretical transfer function but this is believed due to the geometry of the pressure tubing. A sharp right-angle bend near the probe head and another relatively small-radius bend near the transducers produce more attenuation of the signal than is predicted using the theory of Berg and Tijderman (1965), which holds for straight tubing or tubing with large bend radii. The detailed geometry of the tubing was not accounted for in the theoretical calculation of the transfer function.

The transfer function estimated from the hot wire and Cobra probe centre hole pressure signal (labelled 'Hot wire' in Figure 2) is of a consistently lower magnitude than the other estimates. The most likely cause of this discrepancy is that the static pressure fluctuations are of a significant magnitude. Thus, the assumption that the fluctuating component of the static pressure signal was negligible may not be tenable, invalidating Equation 2. A power spectrum of the static pressure signal determined from the Cobra probe calibration surfaces, using all four pressure signals from the probe, shows the static pressure fluctuations to be significant in parts of the spectrum (Figure 5).

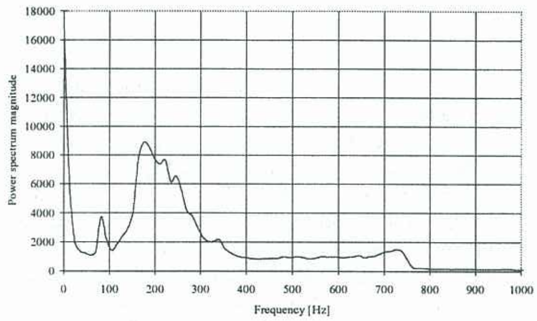

Figure 5 : Static pressure power spectrum

__Signal Coherence__

A plot of the coherence between the small signal analysis of the Cobra probe centre-hole pressure signal and the hot-wire velocity signal is shown in Figure 6. It is observed that the coherence dips to just 0.4 at 100Hz (which corresponds to an unexpected dip in the transfer function generated with the hot-wire data) and that the coherence is less than 0.3 above 480Hz. These regions of low coherence correspond to regions of low signal power (refer to the power spectra shown in Figure 2) and suggest the signal perturbations are too small to be accurately measured with the set up used. Repeating the test with a more developed flow may lead to increased coherence over a wider range. Also, as discussed in the previous sections, the turbulent flow structure changes between the hot wire and Cobra probe head, thus reducing the level of signal coherence, particularly at higher frequencies.

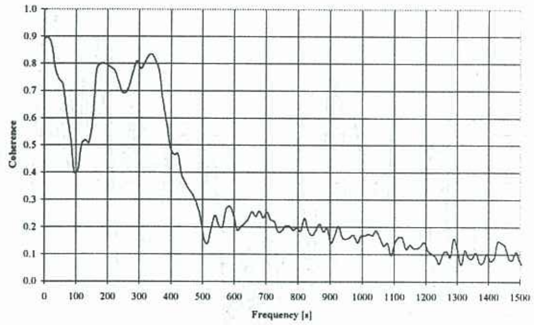

Figure 6 : Coherence between hot-wire and Cobra probe velocity signals

CONCLUSION

A hot-wire anemometer was used to compare the frequency response of the Cobra probe tubing system with theoretical and experimental data previously obtained. A small signal analysis of the Cobra probe pressure signal provided a fluctuating velocity signal to compare with the hot-wire velocity signal.

Spectral analyses of the velocity signals showed that the higher frequency components of the Cobra probe signal were being attenuated more than those of the theoretical and white noise tests. It was found that some frequency components of the fluctuating static pressure were large enough in magnitude to cause errors due to the assumption in the small signal analysis that the static pressure fluctuations are much smaller in magnitude than the total pressure fluctuations.

Reasonable correlation was found between the hot-wire and Cobra probe time dependent signals of the axial turbulent velocity.

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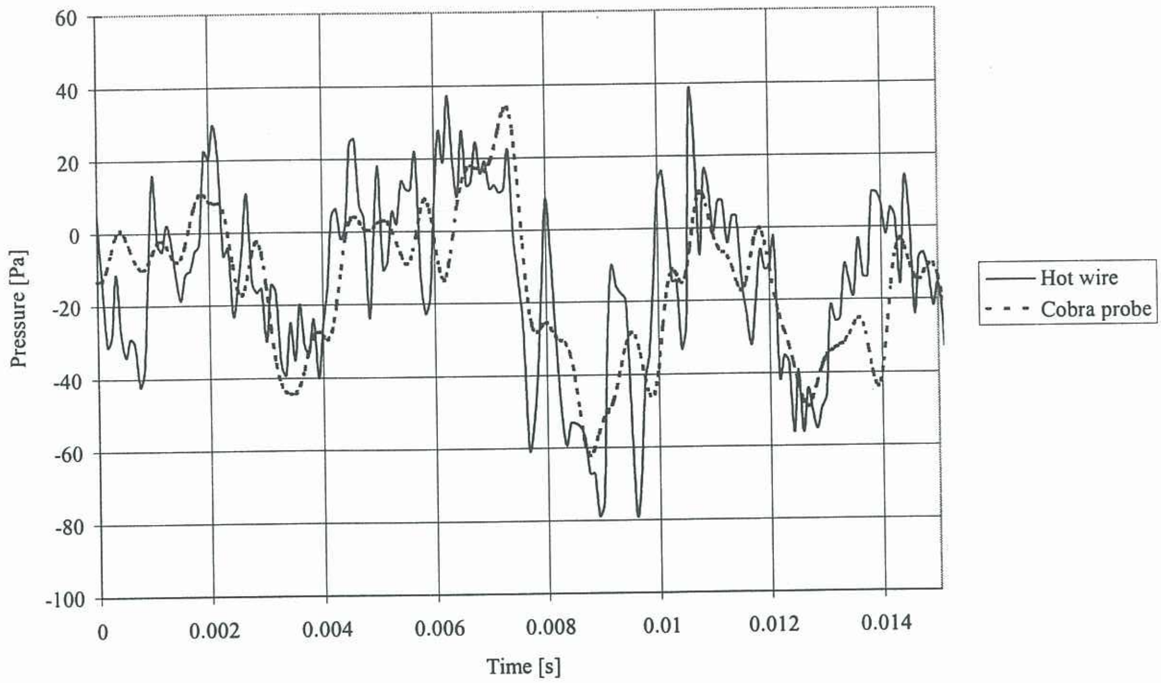

Figure 5 : Comparison of hot-wire and non-linearised Cobra probe fluctuating pressure signals

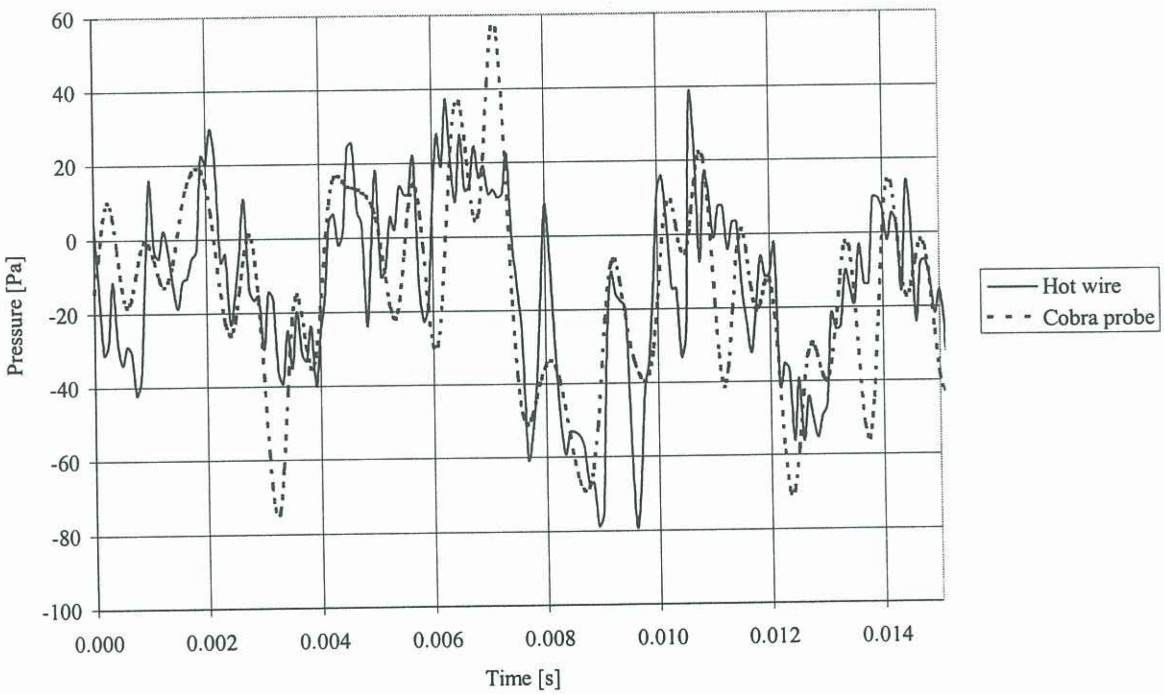

Figure 6 : Comparison of hot-wire and linearised Cobra probe fluctuating pressure signals