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CALIBRATION AND USE OF A HOT-WIRE PROBE FOR HIGHLY TURBULENT AND REVERSING FLOWS

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Summary

The calibration and use of a shielded dual-sensor hot-wire probe, originally developed at McGill University for velocity measurement in highly turbulent and reversing flows, is described. The new probe permits measurements to be made in flow conditions which are not amenable to conventional hot-wire techniques. Two conventional hot-wire anemometers are used to drive the probe and a simple electronic circuit is required to decode the signals and produce a continuous voltage analogue of the velocity component in one dimension.

1. Introduction

In the study of building aerodynamics at model scale, whether for wind loading or environmental studies, one major problem has always been the measurement of flow velocity in those regions of highly turbulent and reversing flows close to the building models. Conventional single-sensor hot-wire probes are of little use in flows having turbulence intensities higher than 20%, owing to the directional ambiguities caused by their two-dimensional response in the plane normal to the sensor wire. Several solutions to this problem have been developed which vary in their suitability for this application. A solution was sought for use in the new Boundary Layer Wind Tunnel at BRE [1] which would preferably be compatible with conventional hot-wire anemometry equipment. Three methods were immediately ruled out because of expense and the following particular reasons: the laser anemometer, although it has great potential, because it is still clumsy to traverse and it requires special optics to resolve the directional ambiguity and a clear line-of-sight; the tri-axial hot-wire array, because it requires continuous tracking of the instantaneous velocity vector to resolve the directional ambiguity; and the tri-axial split-film array, because it requires the decoding of six output signals. Three other methods were seriously considered: the reverse-flow

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sensing hot-wire probe of Downing [2], which was a single-sensor hot-wire with temperature sensors to detect the thermal wake of the hot-wire and hence the flow direction; the pulsed-wire probe of Bradbury and Castro [3] which measured the time-of-flight of a tracer of heated air to a temperature sensor; and the shielded dual-sensor hot-wire probe of Guenkel, Patel and Weber [4], which will be described later. Downing's probe had a major disadvantage in that, while able to resolve flow reversals, it was unable to cope with large lateral components of velocity. The pulsed-wire probe of Bradbury and Castro was a true one-dimensional velocity sensor. However, it did require specialised electronics to drive it and was essentially a digital instrument since it sampled the flow at intervals. The McGill probe of Guenkel *et al.* was also

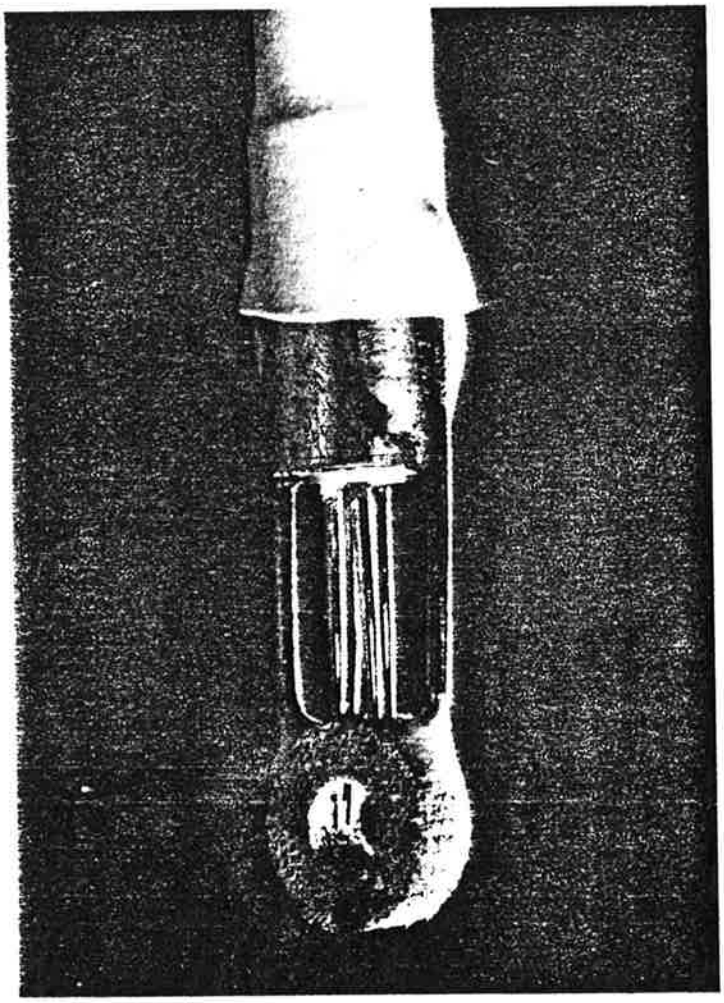


Fig.1. BRE version of McGill probe.

a true one-dimensional velocity sensor, but for our particular application it had two advantages over the pulsed-wire probe. The first was that it produced a continuous voltage analogue of the one-dimensional velocity component which could be analysed by either analogue or digital means. The second was that it required two standard hot-wire anemometers to drive it, with only a small amount of additional electronics to decode the signals. It was therefore decided to build a duplicate of the McGill probe and decoder, to calibrate it, and, if possible, to improve its performance for use in the Boundary Layer Wind Tunnel at BRE.

2. Probe and decoder

The probe, shown in Fig.1, consists of a disc-shaped shield placed over a DISA 55P71 dual parallel sensor hot-wire probe and secured by "heat-shrink" sleeving. The shape of the shield had been selected to produce a one-dimensional flow field through the hole at its centre with a velocity proportional to the velocity vector along the axis of the hole. The proportions of the original McGill probe were determined by interpolation between two extremes and, although Guenkel *et al.* [4] showed that the directional response was close to the required cosine form, it was felt that a better fit might be obtained. To this end, the BRE version was made deliberately too thick and was progressively filed down between calibrations until the best response had been obtained. This operation was performed in four stages, requiring the removal and replacement of the shield on each occasion, without once breaking the sensor wires of the probe. The final dimensions of the shield are given in Fig.2.

Having obtained the required directional response, the sign ambiguity, *i.e.* forward or backward, was removed using the effect of the thermal wake of

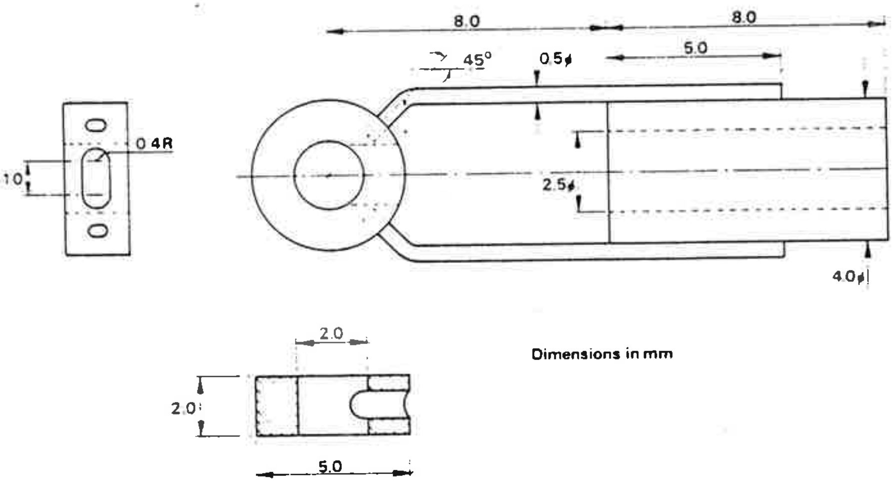


Fig.2. Dimensions of the shield.

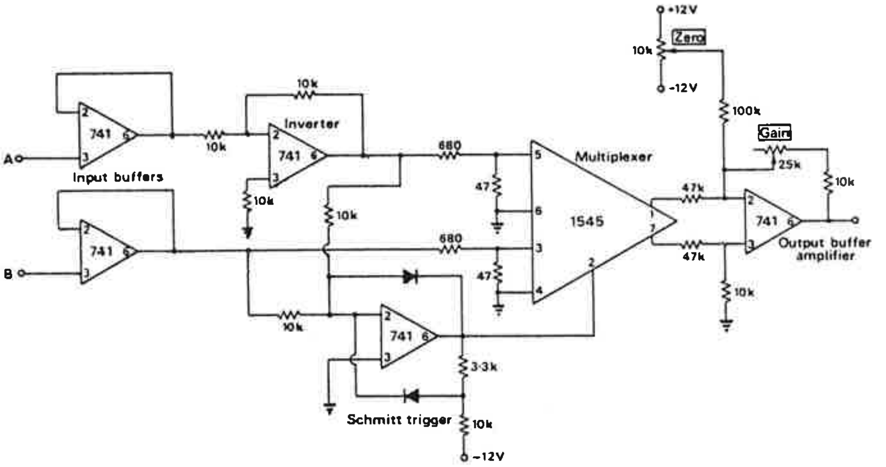


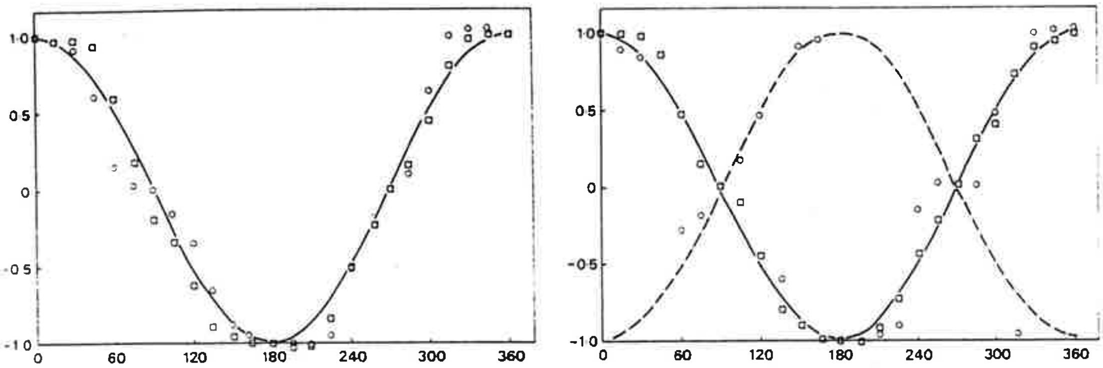
Fig.3. BRE version of the McGill decoder.

the upstream sensor on the downstream one. The dual-sensor probe was driven by a pair of DISA K series linearised constant-temperature anemometers and the instantaneous velocity and direction information contained in the two output signals was decoded by means of the electronic switching circuit shown diagrammatically in Fig.3. The sign of the backward sensor signal was inverted. The magnitudes of the two signals were continuously compared by a Schmitt trigger which was used to gate a multiplexer. The larger (upstream sensor) signal was allowed to pass as the output signal by the multiplexer while the smaller (downstream sensor) signal was blocked. A buffer output stage provided gain and zero shift controls. The BRE version of the decoder was designed to be compatible with the output range of the DISA K anemometers and operates over a 2V range with common signal ground and a nominal bandwidth of d.c. to 100 kHz.

3. Calibration of the probe

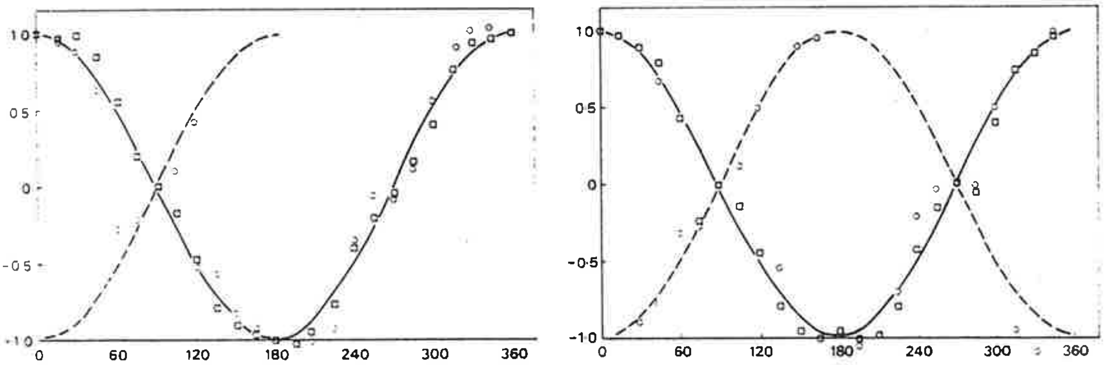
3.1 Calibration in smooth uniform flow

The initial calibrations, during which the shield proportions were progressively altered, were performed by rotating the probe in smooth uniform flow. The final calibration results are shown in Fig.4. Yaw is defined as rotation about the probe stem, pitch as rotation about the sensor wires axes. Guenkel *et al.* reported some dependence on Reynolds number, but did not investigate a sufficiently large velocity range to reveal the full effect. The ideal cosine response is drawn on the figures as a solid line. The dotted line, where included, represents the inverted or "ghost" response that would be obtained if the wrong signal were gated. Ghosting occurred when there was sufficient velocity difference between the sensor wires to offset the thermal interference between them.



(a) 2m/s

(c) 10m/s



(b) 4m/s

(d) 20m/s

Fig.4. Calibration in smooth uniform flow.

The probe was asymmetric owing to the diametrical orientation of the sensor wires and the presence of the probe stem. In yaw, where the flow direction remained in the plane of the sensor wires, ghosting did not occur until 20 m/s. In pitch, however, ghosting began at only 4 m/s and became progressively worse with increasing windspeed. Between about 4 m/s and 6 m/s only one ghost lobe was evident, between 60° and 120° pitch. By 8 m/s a second lobe had appeared, between 150° and 170° pitch; and by 20 m/s two more, complementary to the second lobe, had appeared between 10° and 40° and between 330° and 350° pitch. At the edges of the lobes, the output of the decoder oscillated between real and ghost states, producing a mean output at some intermediate value.

A similar, but less severe, oscillation occurred at all windspeeds when the flow was normal to the probe axis. The probe wires were not fully protected from the lateral velocity vector, and the background turbulence level of the tunnel (0.6%), or perhaps the turbulence generated by the probe itself, was sufficient to cause random switching of the decoder between a small negative and a small positive value. The result was the required zero mean value, but a spurious square wave "turbulence" signal of 12% intensity and random period was generated.

The probe gave a reasonably accurate measure of mean flow vector at speeds below 6 m/s. The single ghost lobe in this speed range was confined to pitch angles 30° either side of the probe stem — an unlikely orientation in use which could easily be avoided.

3.2 Calibration in highly turbulent flow

The flow in the near wake of a three-dimensional bluff body (a common housebrick) was considered to be a sufficiently arduous test of the probe's directional resolution. The incident wind velocity was set at 3 m/s, *i.e.* half-way through the useful range as previously indicated. The results for three locations in the wake are shown in Fig.5, normalised against the indicated

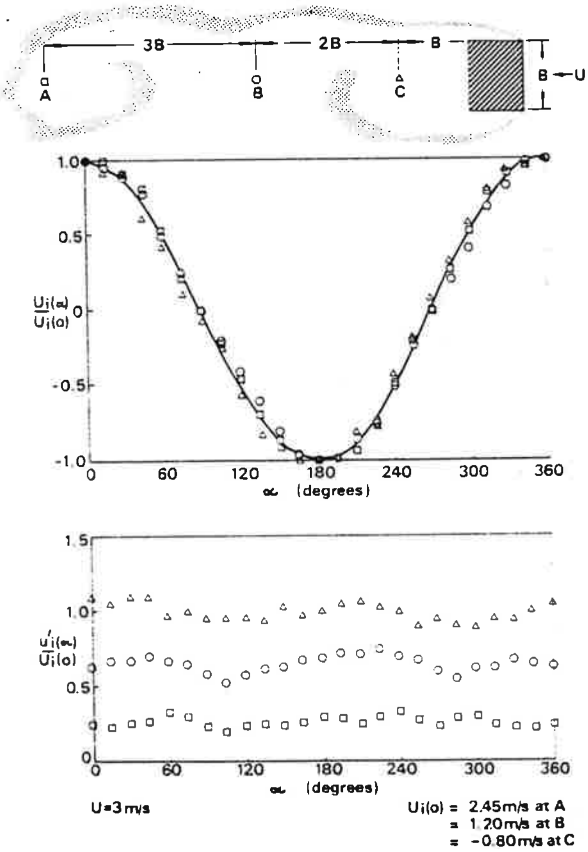


Fig.5. Calibration in highly turbulent flow.

local mean velocity vector, $\bar{U}_i$. A measure of the severity of these test conditions is given by the indicated local turbulence intensity values, u'_i. Position A, where $u'_i = 0.25\ \bar{U}_i$, represents the approximate limit for the use of conventional single-sensor hot-wire probes and is well beyond the limit for the use of X-probes. If we assume the turbulence at A to have been Gaussian, while the probability of a flow reversal $P(\text{rev})$ was sensibly zero, the probability of a flow deviation exceeding ± 70° (limit for single sensors) $P(\pm 70°)$ was 12%, and similarly for a deviation of ± 25° (limit for X-probe) $P(\pm 25°)$ was 50%. Conditions at B and C were more severe; the probability of a flow reversal $P(\text{rev})$ at B being 7% and that at C being 84% (*i.e.* reverse mean flow at C).

Despite the severity of the flow conditions, the mean directional response at all three positions remained close to the ideal cosine form. The variation of indicated turbulence intensity with direction should have followed the form:

$$u'_i(\alpha) = u'_i(\alpha + 180°)$$

owing to the symmetry of the probe, and this was generally true.

3.3 Assessment of dynamic response

No calibration of dynamic response could be made as no alternative measurement technique was available for comparison. However, an estimate was made with some confidence from a knowledge of the general behaviour of bluff bodies, *i.e.* the probe shield, in flow. The sensors were shown to register fluctuations into the kHz range in turbulent flow. Eddy motions of a length scale smaller than the shield diameter D, although registered by the sensors,

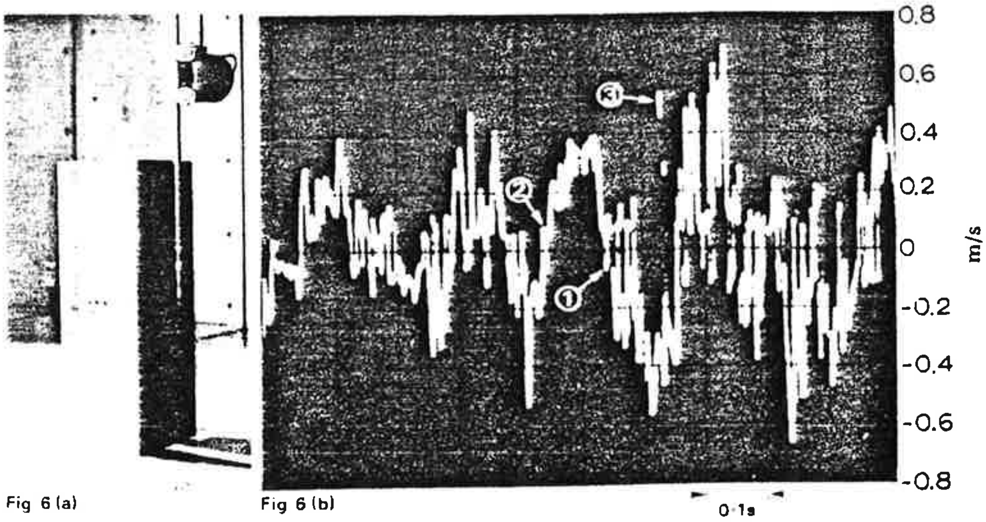


Fig 6 (a) Fig 6 (b)

Fig.6. Response to reversing flow.

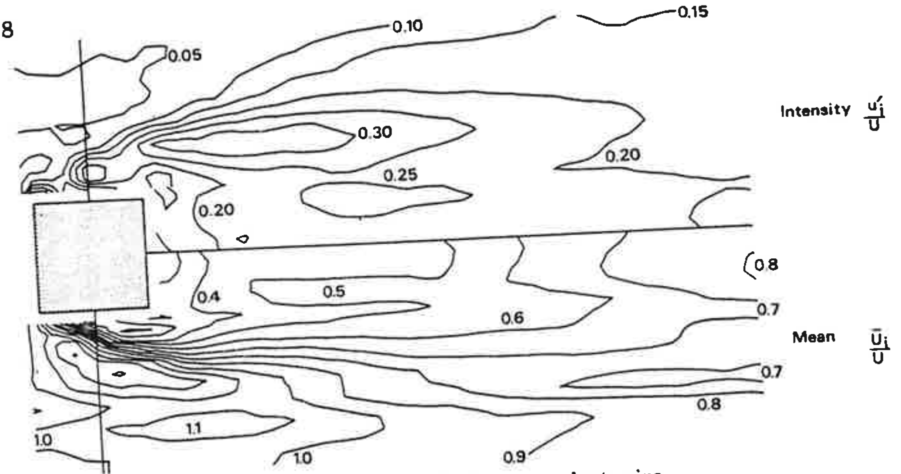


Fig.7. Measurements with conventional single-sensor hot-wire.

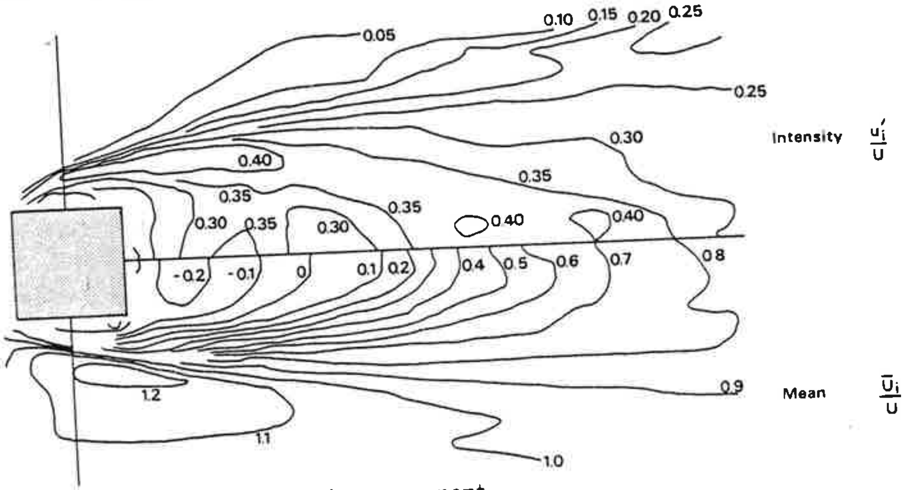


Fig.8. Measurements of streamwise component.

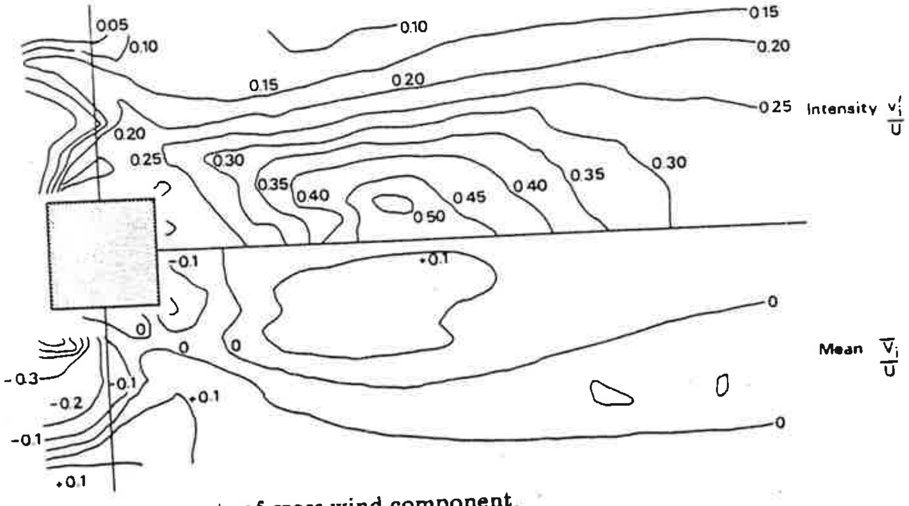


Fig.9. Measurements of cross-wind component.

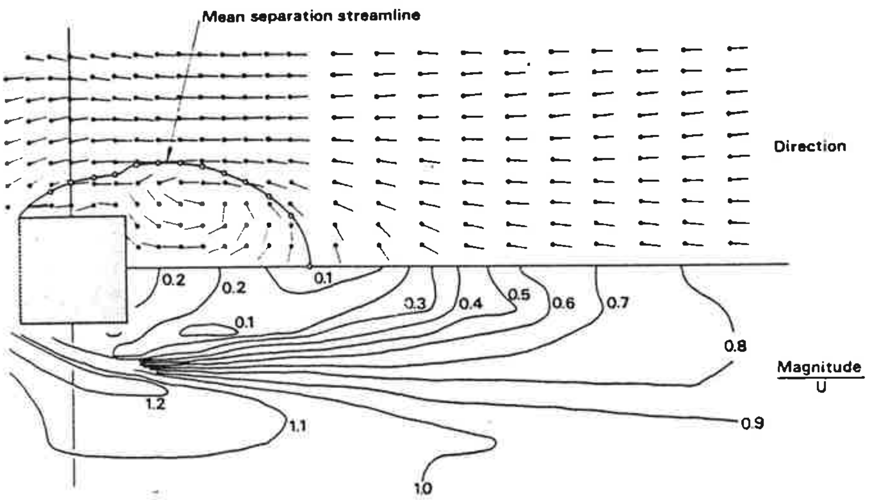


Fig.10. Resultant mean flow vector, magnitude and direction.

will have been grossly distorted by passage through the probe whereas eddy motions an order larger than D would not have been distorted significantly. Dynamic response is therefore dependent on the size of the probe and the velocity of the flow and hence is best expressed in terms of the eddy wavelength λ rather than frequency. In practice, the dynamic response of the probe will be good down to $\lambda = 10D$ (up to 100 Hz at 5 m/s; BRE probe) then become progressively poorer.

As long as a large-scale turbulent motion existed to which the probe could respond quasi-statically without having to linger at zero-crossings, "manufacture" of the spurious square-wave "turbulence" was reasonably well suppressed. For example, Fig.6(a) shows the probe positioned to measure the lateral velocity component near the centre of the downstream face of a tower model, and Fig.6(b) shows a typical trace of the output signal obtained there. At this position the mean of the lateral velocity component was zero, thus the dynamic response of the probe was at its worst, relying entirely on the velocity of the largest eddy motions to convect smaller eddies past the probe. The trace shows clearly the low-frequency narrow-band flow reversals caused by vortex shedding and superimposed high-frequency wide-band turbulence. The spurious square-wave signal is sometimes evident at zero-crossings, as for the 0.05 s period after 1, and at other times not, as at 2. Occasional ghosting appears as detached portions of the trace as at 3. Both these effects have been shown to be considerably reduced by low-pass filtering of the output or, better, of both inputs to the decoder at the expected limit of dynamic response.

4. A typical application

When measurements of the mean velocity and turbulence intensity in the wake of the tower model shown in Fig.6(a) were made with a conventional single-sensor hot-wire [5], the result (Fig.7) did not give a good unambiguous representation of the actual flow. Similar measurements were made using the new probe to resolve the mean flow vector and turbulence intensity in the streamwise direction (Fig.8) and in the cross-wind direction (Fig.9). These results were then combined to give the resultant mean velocity vector in magnitude and direction (Fig.10). In addition, the approximate position of the mean separation streamline was determined from continuity principles and assuming local two-dimensional flow. With the new probe, the separation bubble and recirculating flow are clearly revealed; and the rear stagnation point is seen to be a region of strong cross-flows, with the streamwise turbulence intensity at a minimum and the cross-stream turbulence intensity at a maximum. The turbulence intensity maximum at the side of the tower indicated by the conventional probe is shown by the new probe to be a maximum of the streamwise component and to be formed by lateral movement of the shear layer during the vortex shedding cycle.

5. Conclusions

This paper has described the calibration and typical use of a shielded dual-sensor hot-wire probe for one-dimensional velocity measurements in highly turbulent and reversing flows. The new probe permits measurements to be made in flow conditions which are not amenable to conventional hot-wire techniques. The BRE version of the probe has two clear limitations, a maximum useful flow velocity of 6 m/s and a limit to the dynamic response at about λ = 50 mm (100 Hz at 5 m/s). Both these limitations may be improved by reducing the probe diameter.

Various other techniques have been developed for use in highly turbulent flows, notably the pulsed wire of Bradbury and Castro [3]. However, most require sophisticated control electronics or complex decoding techniques. The main advantages of the shielded dual-sensor hot-wire probe are that standard hot-wire anemometers are used to drive it, the additional decoding electronics are simple and, most important, it is very easy to use.

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References

1 N.J. Cook, A boundary layer wind tunnel for building aerodynamics, J. Ind. Aerodynam. 1 (1975) 3—12.

2 P.M. Downing, Reverse flow sensing hot-wire anemometer, J. Phys. E: Scientific Instruments, 5 (1972) 849—851.

3 L.J.S. Bradbury and I.P. Castro, A pulsed wire technique for velocity measurements in highly turbulent flows, J. Fluid Mech., 49 (1971) 657—691.

4 A.A. Guenkel, R.P. Patel and M.E. Weber, A shielded hot-wire probe for highly turbulent flows and rapidly reversing flows, Ind. Eng. Chem. Fundam., 10 (1971) 627—631.

5 N.J. Cook, The effect of turbulence scale on the flow around high-rise building models, Ph.D. Thesis, University of Bristol, Dept. Aeronaut. Eng., 1972.