A Shielded Hot-Wire Probe for Highly Turbulent Flows and Rapidly Reversing Flows

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A shielded hot-wire probe has been developed which permits the determination of mean velocities, rms velocities, and other turbulence parameters in highly turbulent flow fields and in rapidly reversing flows. The instantaneous velocity vector in the flow field may point in any direction. The shield is a small disk with a hole in its center. Two wires are placed close and parallel to each other inside the hole and normal to the axis of the hole. The effect of the thermal wake of the upstream wire on the downstream wire is used to determine the flow direction instantaneously. Only the thermally undisturbed upstream signals pass through the gate of an amplifier and are further processed. The sign of one of the signals is inverted by the amplifier. The probe has been tested in air flow in the velocity range from 0.3 m/sec to 10.0 m/sec. This corresponds to Reynolds numbers based on the shield outside diameter from 7.4×10^2 to 2.5×10^4.

Standard flow meters like Pitot tubes, yaw tubes, pressure transducer probes, and hot-film and hot-wire anemometers give inconsistent results if used in flows of high relative turbulence intensity or in reversing flows where the velocity vector changes direction frequently. Flow regions having these properties are found in the wake of immersed bodies, near the edge of free jets, in agitated tanks, etc.

In the impeller stream of a stirred tank the mean velocities measured by Rao (1969) with a yaw tube in water were generally higher (up to 100%) than those measured with the hot-film anemometer. Relative turbulence intensities of about 40% are reported by Rao. Measurements by Mujumdar (1970) and by the authors of velocities in an air-filled stirred tank using hot-wire probes and later yaw tubes also did not produce consistent results. The mean velocities measured with the hot-wire probe in the impeller stream were generally higher, in some cases by a factor 4, than the yaw tube results. Relative turbulence intensities between 30 and 90% were obtained. Outside the impeller stream the signals obtained from the hot wire could not be evaluated because an almost constant output was obtained from the anemometer no matter how the wire was oriented. It was concluded that the cooling of the hot wire outside the impeller stream was achieved by the random movement of large eddies changing direction frequently.

The inconsistency in these data is very unsatisfactory, particularly considering the accuracy of results obtained with the same meters in laminar flow or in turbulent flow of low relative intensity. The probe described here was designed to obtain reliable velocity measurements in highly turbulent and reversing flows.

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Errors Associated with Standard Flow Meters

High Intensity Effects. The effect of high-intensity turbulence on hot-wire readings was discussed qualitatively by Hinze (1959). The effective velocity, U_{eff}, sensed by a hot wire placed normal to the mean velocity, $\bar{U}$, in a quasi-steady turbulent flow field was shown to be

$$U_{eff} = \sqrt{(\bar{U} + u_1)^2 + u_2^2} \tag{1}$$

where u_1 and u_2 are the components of the velocity fluctuation parallel to $\bar{U}$ and normal to $\bar{U}$, respectively. The effective mean velocity obtained from a linearized hot wire is then

$$\overline{U_{eff}} = \bar{U}\left(1 + \frac{\overline{u_2^2}}{2\bar{U}^2} - \frac{\overline{u_1u_2^2}}{2\bar{U}^3} + \ldots\right) \tag{2}$$

The effective mean velocity, $\overline{U_{eff}}$, depends upon a series of velocity correlations. At high relative turbulence intensities a considerable difference between $\overline{U_{eff}}$ and the true mean velocity $\bar{U}$ is possible. In addition, the measured fluctuating velocities can be seriously in error as shown by Rose (1962) and Heskestad (1965). Secondary effects on hot-wire readings, *e.g.*, stem and prong interference and longitudinal cooling, are not discussed here. A thorough investigation of these effects has been made by Guitton (1968).

No advantage is gained by employing hot-film probes. Essentially the same type of errors as found with hot-wire probes will be encountered, and furthermore the error analysis is less clear. The effect of turbulent stresses on the readings of Pitot tubes was discussed by Hinze (1959). A correction of the data obtained from a Pitot tube or a yaw tube is possible only if the velocity correlations are known.

Reversing Flow Effects. The response of a hot wire to a rapidly reversing flow is demonstrated in Figure 1. Here the response of a linearized hot wire assembled in a one-dimensional flow field is considered. A plot of the fluctuat-

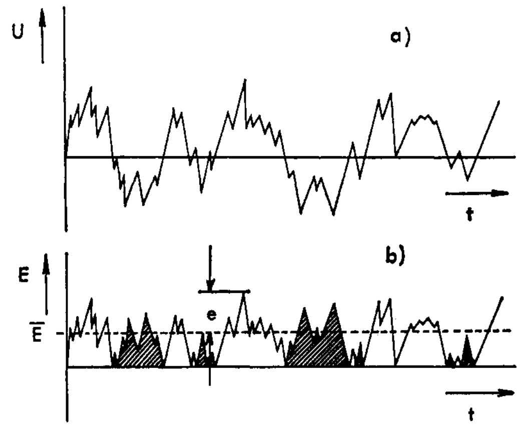

Figure 1. One-dimensional, reversing flow field (a) and response of a linearized hot wire (b)

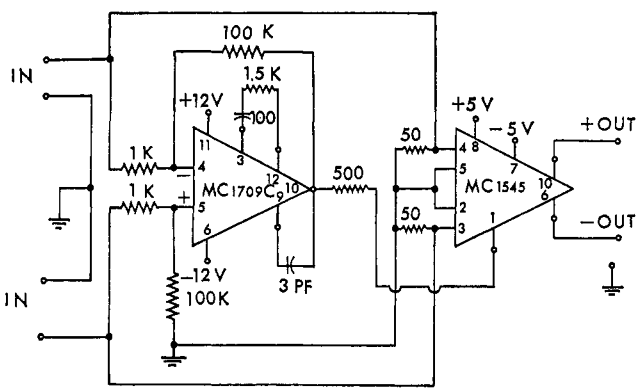

Figure 2. Electronic switching circuit

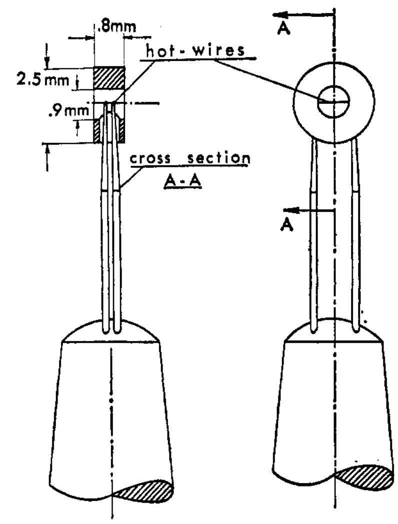

Figure 3. Sketch of hot-wire probe

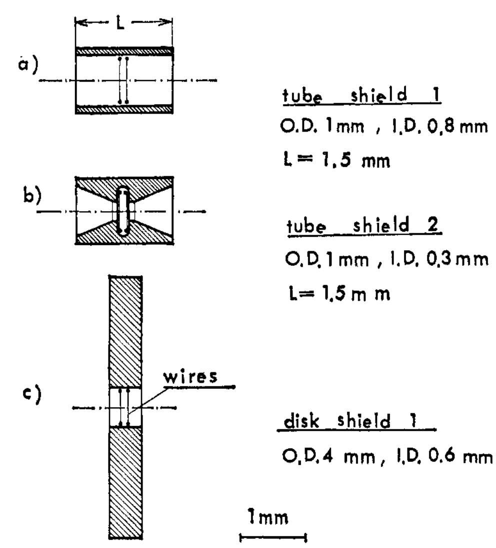

Figure 4. Types of shields tested

ing velocity, U, *vs.* time, t, is shown in Figure 1a. The mean velocity is zero or very small compared to the instantaneous velocity.

In Figure 1b the response of a linearized hot wire to these velocity fluctuations is shown. The wire cannot distinguish between flows coming from different directions and only "positive cooling" occurs. The shaded areas in Figure 1b represent periods of reversed flow. If the signals from the hot wire are fed into voltmeters for further analysis, a dc voltage, $\bar{E}$, and an rms voltage, $\sqrt{\overline{e^2}}$, are obtained. However, from Figures 1a and 1b it can be seen that these voltages cannot be converted to velocities using the calibration curve obtained in laminar flow.

The response of a Pitot tube, a yaw tube, or a pressure transducer probe to a velocity field as shown in Figure 1a is not evaluated here. These probes will not provide reliable data.

Features of the Shielded Hot-Wire Probe

With proper calibration and suitable electronic equipment the shielded hot-wire probe described here has the following characteristics.

(i) The relation between the velocity component to be measured, U_i, and the signal voltage, E, is linear

$$E = CU_i \qquad (3)$$

The constant, C, is determined by calibration.

(ii) The instantaneous velocity component, $-U_i$, in the direction opposite to U_i gives a negative signal voltage

$$-E = -CU_i$$

(iii) The instantaneous velocity vector, $\vec{U}$, deviating by an angle α from the direction of the velocity component, U_i, generates a signal voltage

$$E = C|\vec{U}| \cos \alpha = CU_i \qquad (4)$$

This implies that the probe is not sensitive to velocity components normal to U_i and therefore, for $\alpha = 0$, eq 1 would reduce to

$$U_{eff} = \bar{U} + u_1$$

Development of the Probe

The first of the above stated characteristics, which is easily realized by using a linearizing circuit, is necessary to avoid the error associated with the nonlinear relation between the velocity component U_i, and the signal voltage, E.

The second characteristic is realized by using the thermal wake effect. The physical phenomenon of the thermal wake can be explained as follows. The bridge voltage of a constant temperature anemometer is proportional to the power input into the hot wire. By means of a feedback system the power input is almost instantaneously adjusted to keep the wire temperature at constant level. Under normal operating conditions this temperature is about 300°C. The power supplied to the wire is transferred to the surroundings by conduction and convection. The heat transfer from the wire depends on the physical properties of the fluid surrounding the wire, on the velocity of the fluid swept past the wire, and on the temperature of the fluid. Assuming all other variables to be constant, the power required to keep a wire at a fixed temperature will decrease with increasing temperature of the surrounding fluid. Thus if a hot wire is placed downstream of another wire in a region where the passing fluid has been heated by the upstream wire, less power will be required to keep the downstream wire at its temperature than if it were located in the free stream. The thermal wake effect has been studied by Champagne, *et al.* (1970), and Jerome, *et al.* (1971), have discussed the effect of the thermal wake on the readings of X-wire probes.

The probe developed here consists of two parallel wires, both calibrated and linearized such that the constant, C, in eq 3 is the same for each wire. By means of an electronic switching circuit the magnitudes of the instantaneous signals obtained from the wires are compared. At any instant only the larger of the two signals is passed through the gate of an amplifier, while the smaller signal is blocked. The sign of one of the signals is inverted if it passes through the gate.

The switching circuit is shown schematically in Figure 2. The signals obtained from the two linearized anemometers are fed into an operational amplifier (Motorola MC 1709 C) where the difference between the two signals is amplified. The output of this amplifier is used to trigger the gate of a gated wide-band amplifier (Motorola MC 1545). The gated wide-band amplifier has two channels, only one of which is opened at any particular instant. In one of the channels the sign of the incoming signal is inverted.

The realization of the third feature, stated in the previous section, is achieved by means of a shield which protects the probe against lateral velocity components. The successful design of the shield is shown in Figure 3. The shield and wires are mounted on a standard DISA 55A32 probe. Other types of shields which were tested and found unsatisfactory are shown in Figure 4. The shield shown in Figure 3 was found after testing many modifications. Reasons for the observed failure of the other designs are discussed in the next section.

Calibration of the Probe

Figure 5 shows the schematic arrangement of the electronic equipment used for the experiments. Both wires were connected to a DISA 55A01 constant temperature anemometer and a DISA 55D10 linearizer. By means of suitable gain and exponent adjustments of the linearizers two identical, linear relations between the velocity, U, in the calibration unit and the output voltage, E, of the linearizers were obtained. The calibration for each wire was performed with the wire in the upstream position. The shield was normal to the velocity, U, in the calibration unit.

The calibration curves for each wire are shown in Figure 6. Two identical and linear relations corresponding to eq 3 were obtained. Also shown in Figure 6 is the thermal wake effect resulting from placing wire 1 downstream into the thermal wake wire 2. A significantly smaller output is obtained from the linearizer at corresponding velocities. In Figure 7 the output obtained from the switching circuit is shown. The quiescent voltage of the gated wide-band amplifier obtained at zero input was $E = 0.43$ V. The maximum swing of the amplifier was 2 V. However, at ± 0.8 V from the quiescent

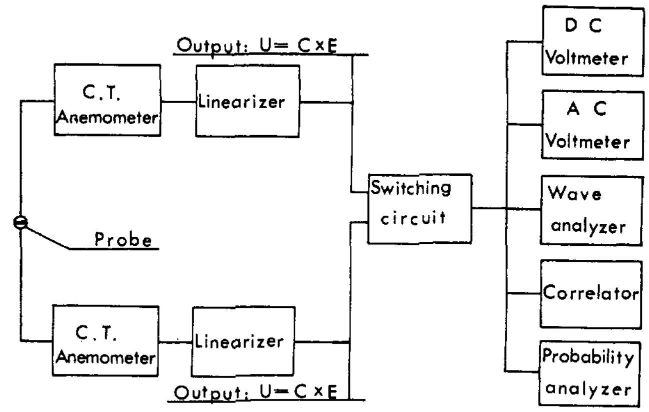

Figure 5. Schematic arrangement of the electronic equipment

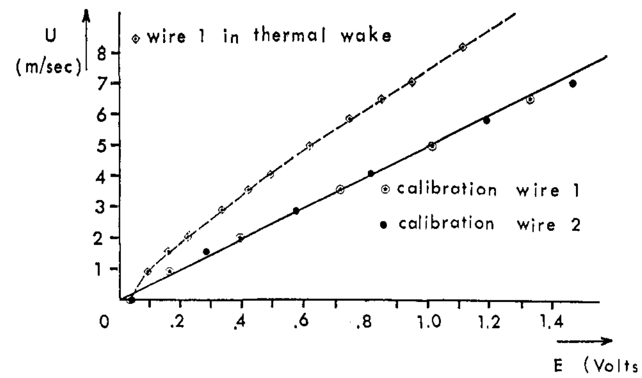

Figure 6. Calibration curve for the hot wires

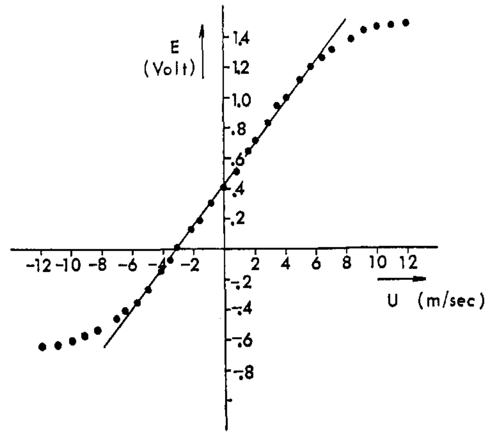

Figure 7. Output of the switching circuit

voltage the amplification started to become nonlinear. This was not a drawback since the gain of the linearizer could be adjusted to decrease the input into the gated amplifier depending on the experimental conditions.

The probe was calibrated in a DISA 55A60 calibration unit which was slightly modified by adding a larger venturi nozzle to the unit. In Figure 8 the relative turbulence intensities obtained with the probe in the low noise calibration unit are shown. The turbulence noise level caused by interference from the shield was always below 1%. This is tolerable since the probe is to be used in flows of high turbulence intensity.

In order to study the protection provided by the shield against lateral velocity components, the directional sensitivity of the probe was determined in the calibration unit. This was

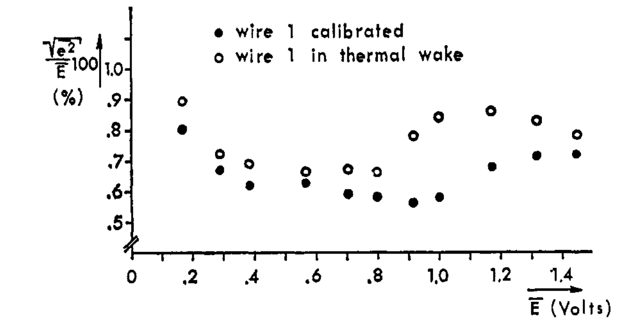

Figure 8. Relative intensities obtained in the low noise calibration unit

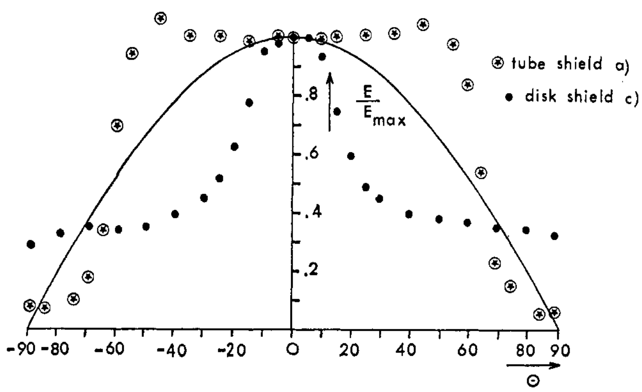

Figure 9. Directional sensitivity of the probe for tube shield (a) and disk shield (c)

done by turning the probe around the axis of the probe stem while keeping the velocity, U, in the calibration unit constant. The first shield tested was the tube shown in Figure 4a. This design was the obvious first choice because it would appear that only the velocity component in the direction of the tube axis would be sensed by the wires inside. The directional sensitivity of a probe using this type of shield is shown in the upper curve of Figure 9. The data show that the probe was almost insensitive to the yaw angle over a wide range (±50°). In order to eliminate the possibility that a non-uniform velocity profile inside the tube was responsible for the observed phenomenon, the nozzle-shaped tube shown in Figure 4b was tested. The velocity profile in the middle of this shield was expected to be flat. The directional sensitivity of this shield was essentially the same as that for the straight tube; however, the maxima at inclinations of ±40° were not as pronounced. Upon closer examination it became clear that the phenomenon observed here is not new. The Kiel probe (1935), which is a Pitot tube shielded in a similar fashion, exhibits the same properties as it is almost insensitive to the yaw angle over a considerable range.

It was then speculated that the flow rate through the shield past the hot wires would depend probably upon the form drag of the shield. The form drag of the tube shield was expected to change drastically when inclined to free stream flow. To study this, a third design, the disk shown in Figure 4c, was tested. The drag of this disk was expected to be less sensitive to yaw. As shown in Figure 9, a completely different directional sensitivity was observed.

The directional sensitivity of both the tube and the disk were not acceptable because the relation described by eq 4 was not sufficiently approximated. An inspection of the curves for these shields suggested that a compromise between the two designs would be better; thus the final version of the

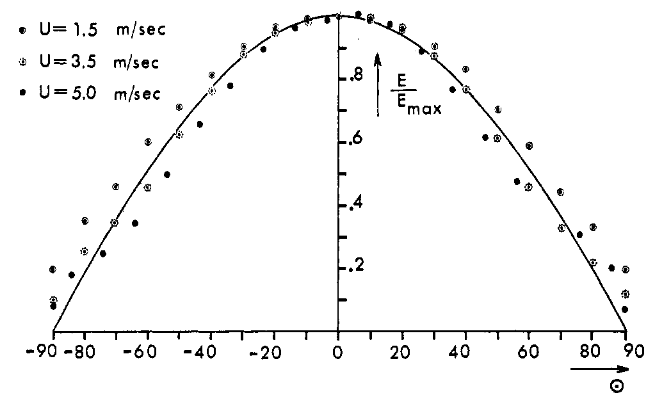

Figure 10. Directional sensitivity of the hot-wire probe

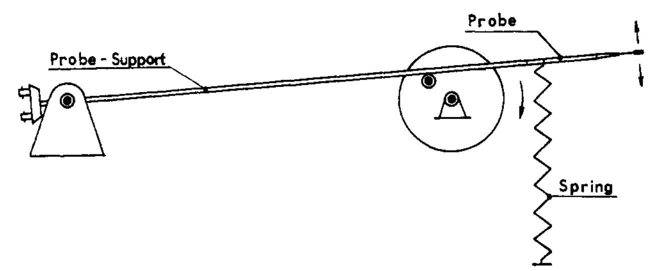

Figure 11. Sketch of probe vibrating mechanism

shield, shown in Figure 3, was obtained. The directional sensitivity of this shield is shown in Figure 10. The line in the figure is the desired cosine relationship. At lower velocities the experimental points fell above the cosine curve while at higher velocities they fell below the curve. At an intermediate velocity the data will coincide best with the cosine law. Since the geometry of the shield was found to be an important factor in determining this velocity, several shields with various diameter ratios were tested. A quantitative analysis has not been made because the shield shown in Figure 2 provided good results in the velocity range of interest in further studies. Based on the data in Figure 10 it was assumed that the probe was well protected against lateral velocity components and that eq 4 is valid.

Tests of the Probe

In order to check the dynamic performance of the probe as well as the switching circuit, two tests were made. First, the probe was vibrated in still air with an amplitude of about 3 cm and a frequency of up to 15 Hz. The vibration mechanism is shown in Figure 11. A disk with a bolt attached to it in an eccentric position is driven by a motor. The position of the bolt and the motor speed could be changed. The support of the hot-wire probe is held against the bolt by means of a spring, but it was free to move. The other end of the probe support was attached to a base such that it could rotate freely. Since the probe support was long compared to amplitude of the movements of the bolt, the rotational movement of the disk caused an approximately translational movement of the probe.

Tracings of the oscilloscope pictures of the signals obtained from the two wires vibrated by this mechanism are shown in Figure 12a. The signals from the wires were not sent to the switching circuit. Although the flow direction with respect to the wires changed, only positive cooling resulted and only positive signals were obtained. These signals consisted of

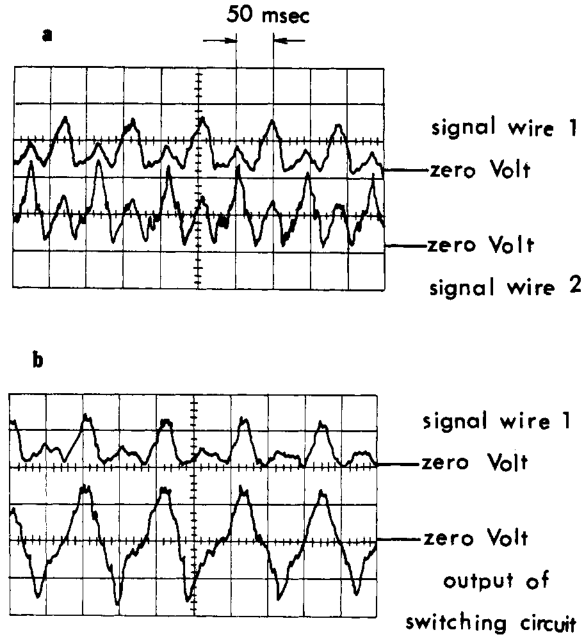

Figure 12. (a) Signals obtained from the vibrating probe; (b) signals from the vibrating probe and from the switching circuit

cycles of alternating small and large amplitudes. When the amplitude obtained from wire 1 was as large, the amplitude of signal 2 was small since wire 2 was in the thermal wake of wire 1. The amplitude ratio of the small to the large signal was in agreement with the ratio expected from the calibration curves of Figure 6.

Figure 12b shows the signal obtained from one of the wires in the upper trace and the output obtained simultaneously from the switching circuit in the lower trace. The zero volt base line corresponds to the quiescent output of the gated wide-band amplifier in the switching circuit. The upper half of the lower signal is identical with the large amplitude cycle shown in the upper trace. The lower half of the lower trace corresponds to the large amplitude of the signal obtained from wire 2. The sign of this signal was inverted. The noise superimposed on the periodic fluctuations in Figures 12a and b was caused by secondary flows generated by the movement of the probe support.

In a second test the probe was placed into the discharge stream of a flat blade turbine impeller. The disk shield was perpendicular to the plane of symmetry of the discharge stream. The relative turbulence intensities measured with a normal single wire probe at the location of the shielded probe were of the order of 50%; the local mean velocity was about 5 m/sec. The probe was then turned by rotating the probe support about its axis. The output obtained for different angular positions is shown by the filled points in Figure 13.

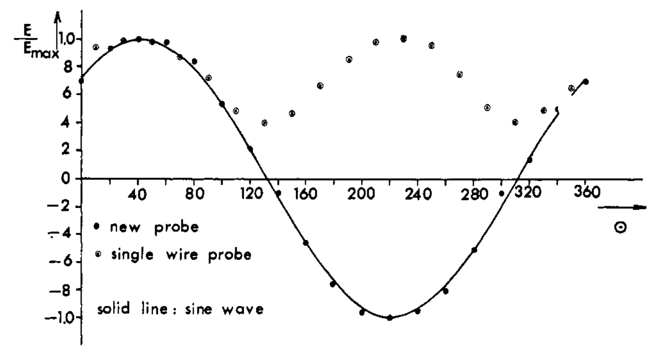

Figure 13. Directional sensitivity of the probe in a highly turbulent (50%) flow field

The maximum output was obtained when the shield is normal to the mean flow. Also shown are the results obtained under the same experimental conditions with a standard single, unshielded wire. The line in the figure is the expected cosine relationship. The improvement achieved with the new probe is clearly demonstrated.

Conclusions

It has been demonstrated that the thermal wake effect can be used to determine flow direction instantaneously. A disklike shield was found, which protected the probe against lateral velocity components in the velocity range between 0.3 and 10.0 m/sec. The performance of the probe in a highly turbulent reversing flow was demonstrated. The probe is certainly not free of error and its range of application is limited by the size of the shield and by the variation of the directional sensitivity with changing free stream velocity. Within its limitations, however, the probe will measure in situations (reversing flows) where other methods fail.

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