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A fast simple hot-wire method of determining the mean velocity vector of complex three-dimensional flows

L. Löfdahl, B. Johansson, C. Ljus, P. Ålleving

Abstract A fast and simple method of determining the mean velocity vector of complex three-dimensional flow fields is outlined. Straight and slanted single hot-wires are rotated in two perpendicular planes. This method increases the angular resolution, which is of importance in flow situations where one of the velocity components dominates and the other changes rapidly from one point to another. The method was calibrated in a wind tunnel and assessed in the internal flow field at the outlet of a fan in a defroster channel. It is shown that the hot-wire method yields good agreement with corresponding flow visualizations determined using a textile thread, and an integration of the measured mean flow yields a flow rate which agrees within a few percent with corresponding direct measurements on an orifice plate.

1 Introduction

The most frequent use of commercial CFD codes in industrial applications requires accurate and reliable information about the initial and boundary conditions. Hence, simple and fast methods for determining mean velocity vector distribution are needed. Today numerous such methods are available, ranging from the simple, five-hole pressure tubes, see e.g. Nitsche (1994), on the one hand to more advanced methods like laser-doppler velocimetry and particle image velocimetry, see Durst et al. (1981) and Lourenco (1993), on the other. In principle five-hole pressure tubes give full information on the velocity vector, however, these probes are rather large, slow in temporal response and sometimes very cumbersome to use because it is required that the instantaneous velocity vector falls within the cone of acceptance of the probe. The more sophisticated laser methods are of course capable of yielding full information on the instantaneous velocity vector. Unfortunately the latter methods are expensive, difficult to handle and require a certain optical accessibility which sometimes might be difficult to realise, e.g. in small channels with complicated geometries.

The hot-wire methods are found somewhere in the middle range of the spectrum of complexity. Numerous reviews of the applications of these methods have been presented through the years, see e.g. Comte-Bellot (1976), Perry (1982) or Bruun (1995), where the performance and the details of handling of the different methods may be found. In the present work, hot-wires were used to measure the mean velocity vector of a three-dimensional complex turbulent flow (3DCTF). Measurements were conducted with a straight and a slanted single hot-wire, and since the slanted wire was used it was only necessary to perform rotation of the probe in two perpendicular planes. Hence the method is very suitable for use in flow situations where one of the two necessary velocity components dominates and the other changes rapidly from one point to another. Using only the assoicated changes in the effective cooling velocity the possibility of calculating the velocity vector in an arbitrary direction is shown. To assess the method the flow field of the outlet of a fan in a defroster channel was studied and comparisons made to flow visualizations and flow rate measurements.

2 Slanted wire method

It is a well-known fact that the effective cooling velocity, U, of a straight hot-wire reaches a maximum when the direction of the flow is perpendicular to the wire. When rotating the probe around its axis, the angular dependence, α, in its simplest version, may be expressed as the so called "cosine law", $U = U_{max} \cos \alpha$. (A more general cooling law may be found in Jörgensen (1971).) In principle, by measuring the effective cooling velocity at a number of different angles and making a curve fit, the local flow angle of a plane perpendicular to the axis of rotation may be determined. Hence, an arbitrary velocity vector of a three dimensional flow may be determined by repeating the above process in two perpendicular planes. The drawback of this method is that the determination of the resultant of the two perpendicular planes is very sensitive to the magnitude of the two components. If the magnitude of one component dominates, a rotation of the straight wire in a third perpendicular plane is required to achieve the necessary angular resolution. Typically, this situation occurs in internal flows and commonly the situation might be even more complicated since the geometry of the channel in context might be narrow as well as curved. Therefore, it might be difficult, or even impossible, to conduct the measurements in all three necessary planes. One way to limit the measurements to only two perpendicular planes and to increase the angular resolution is to use one straight and one slanted hot-wire in combination. The predominant velocity component may be

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L. Löfdahl, B. Johansson, C. Ljus, P. Ålleving
Thermo- and Fluid Dynamics, Chalmers University of Technology
S-412 96 Göteborg, Sweden

Correspondence to: L. Löfdahl

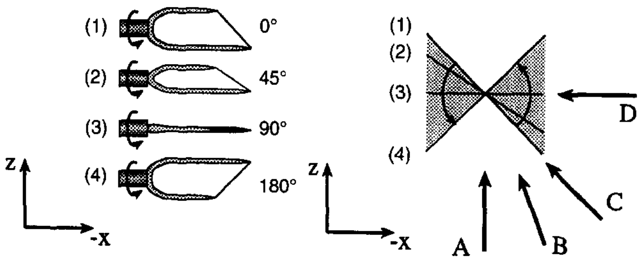

Fig. 1. Rotation of a slanted wire. The longest prong of the probe is always downstream the shorter

determined by the former wire, while the latter wire is used for the smaller component. For the slanted wire, it may be assumed that the velocity vector is situated in a certain plane, e.g. the *xz-plane* of Fig. 1. During the rotation the wire describes a cone and the projection of the wire is rotated 90° in the plane where the angle is to be determined, see Fig. 1. If this velocity is directed as the vector A of Fig. 1, a rotation of the probe yields a symmetrical maximum (same as with the straight wire). In the direction *B*, an asymmetrical maximum results, while in the direction *C* no maximum at all may be detected. For a vector *D* the output voltage is independent of the angle of rotation. It is worthwhile to remark here that the probes need not necessarily be calibrated in order just to determine the direction of the velocity vector.

To calibrate the angular response of the slanted wire the probe was poisitioned in a wind tunnel and the wire was rotated in five degree steps for different angles of inclination. The angle of the probe projection in the plane was then determined from the rotation of the probe axis. Asymmetric maxima, as shown in Fig. 2, were obtained. Noteworthy is the angle offset which is due to uncertainties in the rotation angle and disturbances due to the longer prong. However, this offset angle is easily eliminated in the measurements by the calibration.

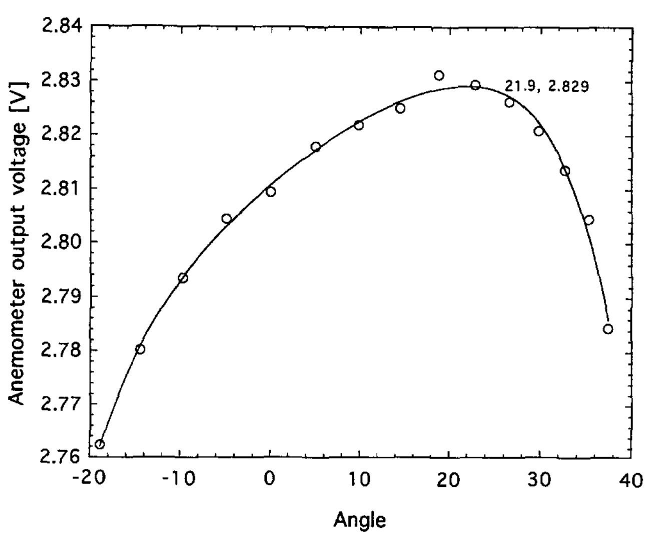

Fig. 2. The anemometer output voltage as a function of the rotation angle. The hot-wire inclination was 20°

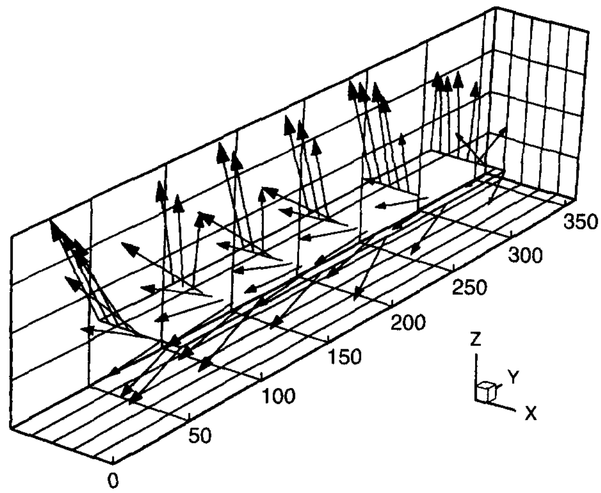

Fig. 3. Results from measurements of the velocity vector in a fan defroster outlet (scale in mm)

3
Use of the slanted wire method in a 3DCTF

To assess the applicability of the above method a 3DCTF formed at the outlet of the fan inside a defroster channel was studied. Figure 3 shows the rectangular outlet. In the horizontal plane a co-ordinate system is defined with the *x*- and *y*-axes in the plane and the *z*-axis perpendicular to it. (The defroster channel continues in the negative *y*-direction.)

A standard straight wire probe with a wire diameter 5 μm and a length 3 mm was used. This high wire aspect ratio implies the employment of the simple cosine law. To conduct the measurements in the *yz-plane* the probe axis was rotated around the *x-axis*. A protractor mounted on the probe axis was used to set the angle of rotation. For each angle of rotation the output voltage was recorded. A curve fit to the data yielded the direction of the velocity vector in the *yz-plane*. The same procedure was employed for the *xy-plane* but here the probe was rotated around the *z-axis*. In some of the measured points the velocity component in the *xz-plane* dominated and the component normal to this plane was not resolvable using a straight wire. Therefore, a slanted wire was rotated around the *x-axis* and the projection of the velocity vector was made in the *xz-plane*. From these two independent measurements with the straight and slanted hot-wire, the directions of the velocity vectors were obtained and are shown in Fig. 3. Once the direction of the velocity vector is determined, it is quite straightforward to determine the magnitude of the vector using ordinary hot-wire technique. The magnitudes of the velocity vectors are included in the figure as well.

A rough estimate of the accuracy of the determination of the velocity vectors may be obtained by comparing the hot-wire results to flow visualizations. Figure 4 shows a comparison of the angular determination in a plane parallel to and close to the *yz-plane*. This plane was chosen since it elucidates the effect of a predominant velocity component and requires the employment of a slanted wire in order to resolve the flow direction. As is evident from Fig. 4 there is a very good agreement between the textile thread visualizations and the hot-wire measurements. Moreover, an indication of the accuracy of the magnitude determination may be achieved by integrating the mean

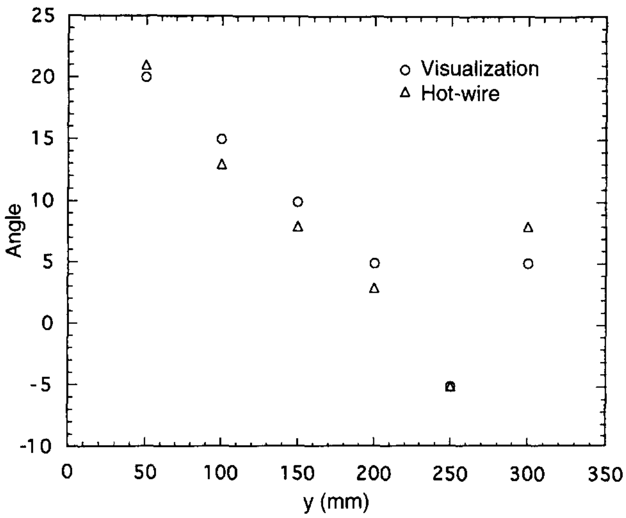

Fig. 4. A comparison of the angular determination in a plane parallel to and close to the *yz-plane*

velocity distributions shown in Fig. 3 to give a flow rate through the defroster channel. The hot-wire measurements agree to within less than 3% with a corresponding direct determination using an orifice plate at the fan inlet.

4
Concluding remark

A method using one straight and one slanted hot-wire has been presented. This technique requires only probe rotation in two perpendicular planes and is suitable for use in 3DCTF where the geometry restricts the probe rotations in all three necessary directions.

The method has been tested in a well known flow field of a wind tunnel and comparisons with flow visualizations reveal good agreement. An estimation of the flow rate by integration of the measured mean velocity distributions agrees to within a few percent with corresponding direct measurements.

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