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Determination of the measuring position in laser-Doppler anemometry

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Abstract. The present paper is concerned with the determination of the measuring position of a laser-Doppler anemometer (LDA) relative to a wall. The proposed method is based on the finding that the output of a hot-wire anemometer increases when the wire, which is mounted in quiescent air parallel to the wall, is brought closer than 800 μm to the wall. For given hot-wire anemometer parameters, the hot-wire anemometer output voltage depends on the wall material and the wire distance from the wall. After suitable calibration for the wall material of the test section, the anemometer reading in a test rig can be used to find the wire position. Moving the measuring volume of a LDA-system across the wire yields an output voltage variation of the LDA-photomultiplier showing a Gaussian shape. When the maximum output voltage is reached, the centre of the measuring control volume is located at the centre of the wire and, hence, the location of the LDA-measuring position is known. All position measurements for the LDA-system are then taken relative to this point using the scale of the LDA-traversing system. If optical effects of transparent test section walls are eliminated by employing refractive index matched liquids, there are other ways to find the measuring position of a laser-Doppler anemometer relative to a wall. One such method and its application to the study of the turbulent near wall flow in a pipe is described in this paper.

1 Introduction

The rapid development of laser-Doppler anemometry (LDA) over the last two decades has resulted in fully developed optical and electronic systems that can be readily used to yield precise velocity measurements in gas and liquid flows. Numerous experimental flow studies have already been carried out using the measuring technique and have provided interesting information, mainly on separated flows, which was not obtainable before the invention and application of laser-Doppler anemometry. The method is nowadays widely accepted as a useful technique in experimental fluid mechanics. Despite this fact, some application problems remain that need to be solved to assure the accuracy of measurements so that laser-Doppler anemometry can be fully utilized in experimental fluid flow studies. One of these problems is the determination of the location of the measuring control volume relative to a fixed wall.

The present paper is an attempt to remedy the existing situation by suggesting a procedure to yield the required location with an accuracy sufficient for many fluid flow studies. The method is based on the experimental finding that the output voltage of a hot-wire anemometer is dependent, even in quiescent air, on the location of the wire relative to a wall. Hence, after external calibration for the particular wall material employed in the test section, the wire location can be determined via the output voltage of a hot-wire anemometer. This is shown in Sect. 2.1 together with results of verification experiments for two different wall materials.

In Sect. 2.2, the known location of a 5 μm hot-wire is employed to find the location of the centre of a LDA-measuring control volume. For this purpose the LDA-optical system is traversed perpendicular to the wire axis, so that the measuring volume is moved across the wire. The light scattered from the wire at each location of the beam, is detected by the light-receiving optics.

A second method to find the measuring position of an LDA-system is described in Sect. 3. It has been used for velocity measurements in test sections with refractive index matched fluids. Under such conditions, and for small particle depositions on the wall, the entrance of the LDA-measuring volume into the wall is marked by a distinct change in the slope of the measured velocity profile.

Conclusions and final remarks are presented in Sect. 4 and suggestions for further research are made.

2 Determination of measuring position using hot-wire sensors

2.1 Determination of wire position close to a wall

In recent experimental studies of near-wall turbulence, Bhatia et al. (1982) and Durst et al. (1985) developed and employed a method to determine the location of a hot-wire mounted parallel to a wall. The method is based on the finding that the hot-wire anemometer output-voltage

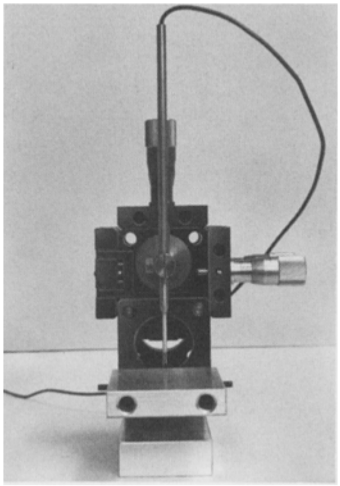

Fig. 1. Photograph of hot-wire probe holder and traversing arrangement

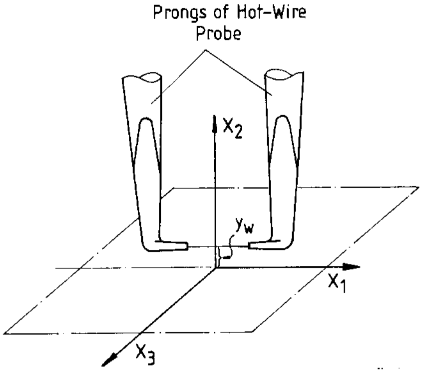

Fig. 2. Hot-wire arrangement to determine location of LDA-measuring volume

increases in a deterministic manner if the wire distance to the wall is decreased and if it is less than approximately 800 μm. A closer look shows that the output-voltage is not only dependent on the wire location relative to the wall, but also on the settings of the bridge parameters of the hot-wire anemometer, on the flow velocity, and on the test section wall-material. Keeping the hot-wire bridge settings constant and performing measurements in quiescent fluids, yields an output-voltage dependence on two parameters only: (i) the distance of the wire to the wall, and (ii) the heat conductivity of the wall-material.

External calibration of the output-voltage, for given wall materials, results in a (output-voltage) to (wire distance) relationship that can be subsequently employed in the test section to obtain the wire distance from test-section walls. Of course, the wall-material in the calibration experiment must be the same as that of the test section wall and the calibration and the measurements in the test section must be performed for the same fluid. It is also important that the position of the wire and the wall relative to the direction of the developing natural convection, caused by the overheating of the wire, is the same as in the test rig.

In order to utilize the method described above, a wire distance calibration device was constructed which consisted of a two-dimensional traversing unit, designed to hold a hot-wire and base plates of different materials (Fig. 1). The hot-wire probe was mounted with its axis parallel to the wall (Fig. 2).

With this traversing gear, various locations of the hot-wire relative to the base plate can be set and the corresponding hot-wire output voltage measured. This results in (output-voltage) to (wire distance) responses as they are shown in Fig. 3 for a metal plate (aluminium) and a plate of heat insulating material (laminated plywood), respectively.

The zero location of the wire might be found by direct contact with the wall detected by the zero resistance output of the hot-wire (zero overheat) bridge. Alternatively and preferably, careful observation of the wire and its image from the plate through a magnifying microscope provides the zero-position with sufficient accuracy. Using this position information, all other wire positions relative to the wall can be obtained as scale readings from the employed traversing device, using the distance calibrated output-voltage of the hot-wire system. An increased accuracy is obtained if every wire position is observed through a special microscope objective with a scale for vertical distance measurements. In this case, position readings from the wire traverse and the microscope objective must agree before the wire position is read and the corresponding output voltage is measured. Bhatia et al. (1982) and Durst et al. (1985) have successfully employed this method to yield accurate wire positions in boundary layer flows. Another method has recently been given by Tagaki (1985)[1].

2.2 Employment in laser-Doppler anemometry

The knowledge of the distance of the location of a thin wire from a test section wall can be utilized to determine, with high accuracy, the location of the centre of the measuring control volume of a laser-Doppler anemometer relative to the same wall. To demonstrate this, a dual-beam laser-Doppler anemometer was set up operating in the forward scatter mode as shown in Fig. 4. To find the location of the LDA-measuring control volume relative to the wall, a hot-wire connected to an anemometer bridge was brought close to the wall. It was traversed downwards until the output-voltage of the anemometer responded to the wall proximity. Using the externally obtained calibra-

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[1] During the printing stage of this paper the authors attention was drawn to the following paper: Vagt, J. D.; Fernholz, H. H.: A discussion of probe effects and improved measuring techniques in the near wall region of an incompressible three-dimensional turbulent boundary layer. AGARD Conference Reprints No. 271, 1979. This paper also reports on the method for finding the distance of a hot-wire from walls as it was described by Bhatia et al. (1981).

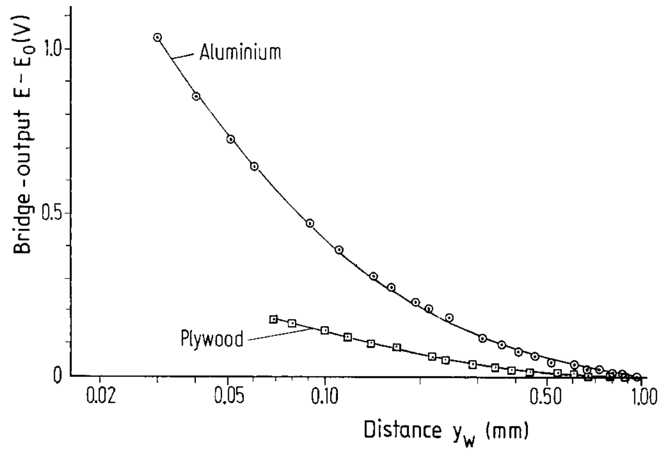

Fig. 3. Hot-wire anemometer output-voltage versus wire position relative to a wall for a metal box plate (aluminium) and a plate of laminated plywood

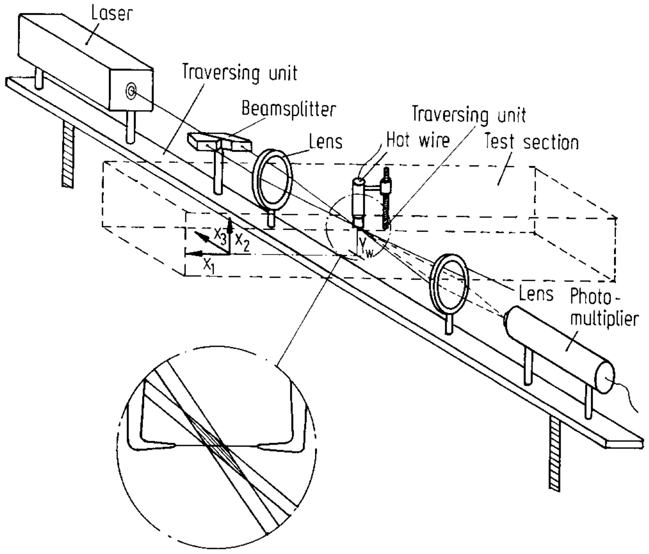

Fig. 4. Hot-wire location relative to a wall and relative to two beames of employed LDA-system

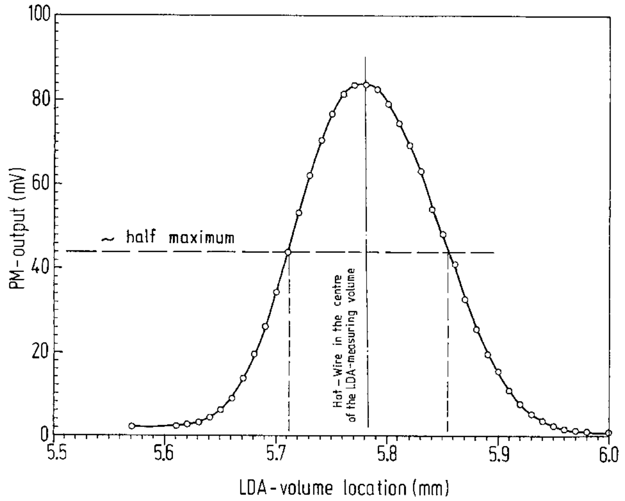

Fig. 5. Example of scattered light intensity measurement versus LDA-volume location

tion curve for the wall distance, the wire location relative to the test section wall could be obtained with high accuracy. It was measured at various locations to check the position obtained from the output-voltage readings against the scale of the hot-wire traverse. To ease the operation with the LDA-system, the wire was traversed to a distance of approximately 1 mm, where it was maintained parallel to the wall and perpendicular to the axis of the laser-Doppler anemometer.

Subsequently, the dual-beam laser-Doppler anemometer was traversed perpendicular to the test-section wall. Prior to this, the measuring volume was adjusted to have its centre approximately at the same x_1-x_3-location as the wire. Starting from this location, a x_2-traverse resulted in a Gaussian intensity variation of the light scattered by the wire. This was readily detectable at the output of a DC-coupled photomultiplier and was recorded to yield an intensity versus position response curve as shown in Fig. 5. From this reading, the position of the centre of the measuring control volume of the laser-Doppler anemometer relative to the wire could be found. The position of the anemometer is identical to the wire position when the scattered light intensity shows its maximum. A higher accuracy is obtained when the centre point between the locations of points of half the maximum intensity is taken as the wire position.

3 Determination of measuring position in refractive index matched systems

3.1 Basic ideas, their employment and verification

LDA-measurements require optical access to the flow region to be investigated. The employment of laser-Doppler systems to the experimental study of internal flows is greatly facilitated by employing a transparent fluid which possesses a refractive index identical to that of the test section wall. If the entire test section is submerged in a fluid with matched refractive index, and if the test section is put into a container with straight walls, a test section arrangement results which permits the light beams of a laser-Doppler anemometer to reach the measuring point without any optical disturbances. Hence, the employment of a fluid with a refractive index matched to the test section walls, permits the test section wall effects on the laser beams to be eliminated. In this way undisturbed velocity measurements can be carried out with laser-Doppler anemometry despite the presence of complex flow boundaries.

A pipe flow test section was designed and built by Durst et al. (1981) to carry out velocity measurements in turbulent pipe flows of dilute polymer solutions. The test section was designed to be operated with refractive index matched liquids, e.g. with a mixture of Diesel oil and Palatinol. For this purpose, the glass pipe was mounted

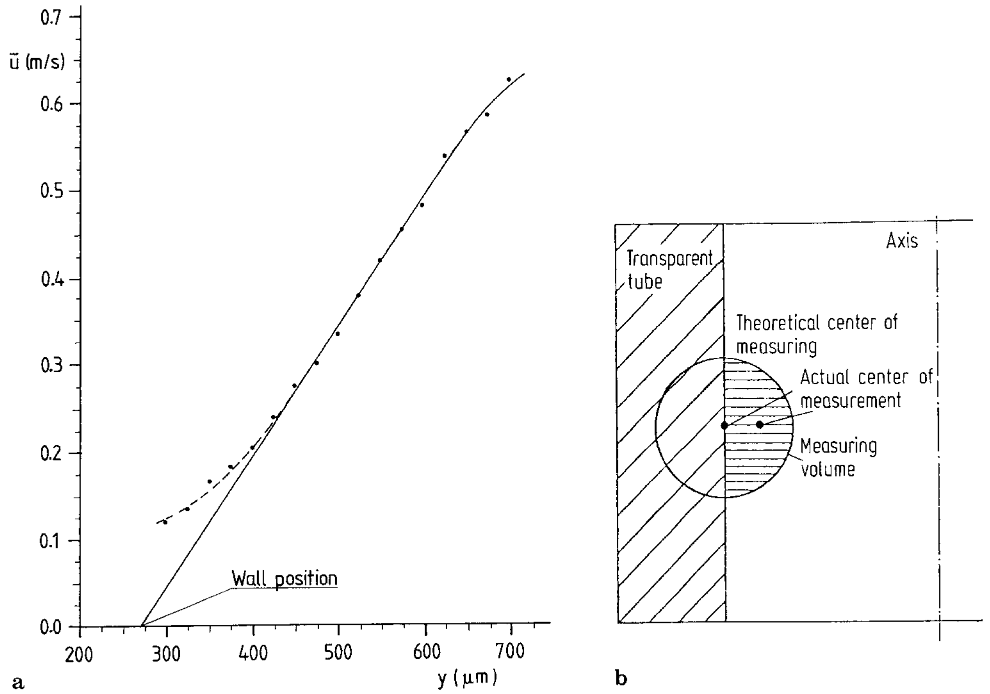

Fig. 6. **a** Velocity profile near pipe wall plotted versus position reading of traversing system; **b** measuring volume entering the wall of the pipe

inside a box of square cross section which was also filled with refractive index matched liquid. The entire test section had a length of 1 m and could be flanched between metal pipes to produce fully developed pipe flow.

To carry out laser-Doppler measurements in fully developed pipe flows, Durst et al. (1981) used a two-dimensional LDA-optical system using polarization properties of the incident laser beams. The laser-Doppler anemometer was an integrated system mounted vertically on a high precision traversing-gear which could be moved along the pipe test-section and positioned at any axial location. The support of the optical traverses could then be moved in the horizontal and vertical directions to obtain traverses for measurements of mean velocities and turbulence properties.

All measurements were carried out traversing in the horizontal direction using a stepping motor with a 1 µm resolution. The smallest distance increment used in the measurements was 10 µm.

In the present study, the above LDA-system was employed for single component velocity measurements only. The longitudinal velocity component in a fully developed pipe flow was measured, in order to obtain information on the universality of the $U^+=f(y^+)$ distribution and for this reasons very precise knowledge of the location of the measuring volume relative to the pipe wall was requested. This was obtained from a distinct change in the slope of the mean velocity profile (Fig. 6 a), which was caused by a partial intrusion of the measuring volume into the test section wall when traverses towards the wall were carried out (Fig. 6 b). This deviations are readily understood by considering the sketch of the measuring volume partially entered into the test section wall. For a clean test section wall, e.g. only a relatively small number of particles has collected at the wall, the major contribution to the LDA-signal will result from that part of the measuring volume through which fluid with scattering particles passes. The resultant mean velocity should be located at the centre part of the control volume which is covered by the fluid. It is general practice, however, to assign it to the location of the centre of the total measuring control volume, and, hence, too high velocity components are measured, as shown in Fig. 6 a. The slope of the velocity profile changes when the wall distance of the centre of the measuring volume is less than 1/2 of the measuring volume diameter. With this information the location of the wall can be found using one or both of the methods described below:

- The point, where the slope of the measured velocity profile changes abruptly, is taken as the first measuring point, having a distance from the wall of 1/2 of the measuring volume diameter.
- Linear extrapolation of the velocity distribution measurements, prior to the change in slope, is carried out to find the zero-velocity point which is taken to be the wall location.

Using both of the above techniques yielded agreement between the wall location measurements of ± 8 µm.

3.2 Application for measurements of mean velocities in turbulent pipe flows

The test section described in Sect. 3.1 was employed to carry out mean velocity profile measurements in a turbulent pipe flow. To carry out measurements of longitudinal velocity, the LDA-system was operated in the forward scatter mode using measuring positions that were selected with the help of the three-dimensional traversing system. In a first step, the measuring position along the axis of the pipe was chosen and the plane of measurements was fixed by locking screws preventing further motion of the traversing system in the flow direction. In a second step, the center of the measuring volume was positioned in the pipe center by traversing perpendicular to the axis of the optical system and perpendicular to the flow. In this way the position of the maximum velocity was found and this position was compared with the center location obtained from complete velocity traverses. Similarily, the maximum velocity along the axis of the optical system and perpendicular to the flow direction was also obtained by complete velocity traverses and by comparing this finding with the measured position of maximum velocity. Starting from this measuring position, traverses were carried out in the direction perpendicular to the flow and perpendicular to the axis of the optics. Near-wall measurements were carried out primarily in order to find the location of the wall as described in Sect. 3.1. Starting with the zero location (wall position), velocity profile measurements were obtained across the entire half width of the pipe. Very small traversing steps were taken in the immediate wall vicinity and these permitted the measured velocity profile to be utilized to obtain the velocity gradient close to the wall. Using this information and the available information on the viscosity of the Dieseloil-Palatinol mixture at the temperature of the flowing fluid, permitted the wall shear stress to be computed. This information was employed to compute the friction velocity:

$$u_\tau = \sqrt{\frac{\tau_w}{\varrho}} = \sqrt{\nu\left(\frac{\partial u}{\partial y}\right)_w} .$$

With this information, the resultant velocity profiles could be plotted in a normalized form. Examples of measurements are provided in Fig. 7. These measurements show, that the well known logarithmic law of the wall:

$$u^+ = \frac{1}{\kappa}\ln y^+ + A$$

and the viscous sub-layer profile:

$$u^+ = y^+$$

were well represented by the LDA results without any further corrections. To obtain also the turbulence intensity, the size of the measuring volume must be matched to the highest velocity gradient in the vicinity of the wall, e.g. see Durst et al. (1987).

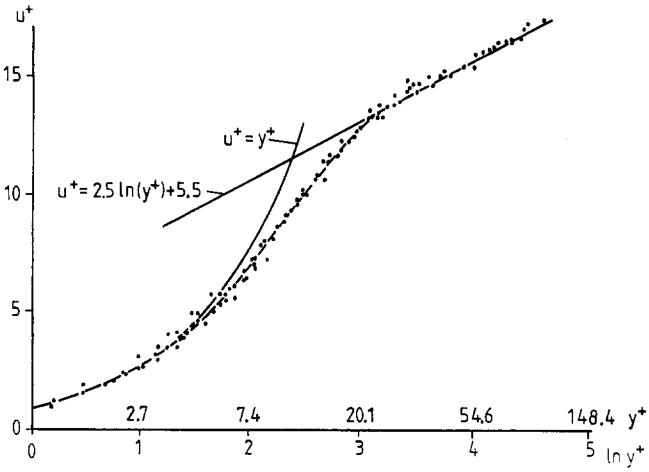

Fig. 7. Close wall velocity measurements for various Reynolds-numbers demonstrating accuracy of wall position of measuring control volume

4 Conclusions and final remarks

The present paper describes methods to find the location of the centre of the measuring control volume of a laser-Doppler anemometer relative to test section walls. Two methods are described, one being mainly suitable for finding the LDA-measuring position in test sections where hot-wires can be located in order to find the relative position to a wall using a method described by Bhatia et al. (1981) and Durst et al. (1985). This method is summarized in Sect. 2.1. It is shown that the knowledge of the location of a wire relative to a test section wall permits the location of the measuring control volume of a laser-Doppler anemometer to be found with an accuracy of ±5 μm. In this way, velocity profiles become possible with laser-Doppler anemometry showing a high accuracy in estimating the location of the measuring point relative to test-section walls.

In laser-Doppler anemometry refractive index matching of the test section wall material and the flowing fluid are often employed in order to eliminate the effects of transparent test section walls on the passage of the light beams. This is explained in Sect. 3.2 where a refractive index matched pipe flow test section is decribed. It is demonstrated that the velocity profile measured by the LDA-system using a linear traversing mechanism shows a sudden change in the slope of the profile when the measuring control volume enters the pipe walls. Using this information and information on the dimension of the measuring control volume permits the center of the volume to be accurately located relative to the wall. In this way, accurate velocity profile measurements become possible using laser-Doppler anemometry.

To the authors knowledge there are no other methods described in the literature that permit precise locations of measuring control volumes of laser-Doppler anemometers relative to walls. It is recommended to use the methods described in this paper to obtain accurate locations of LDA measuring volumes and in this way precise velocity measurements.

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