HETERODYNE LASER DOPPLER VELOCITY PROFILE SENSOR USED FOR SHEAR FLOW MEASUREMENTS WITH MICROMETER RESOLUTION

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Abstract

We report about the application of a heterodyne laser Doppler velocity profile sensor for spatially high resolved shear flow measurements. The profile sensor employs a two-wavelength technique, which generates a measurement volume with convergent and divergent fringes for each wavelength. The evaluation of the ratio of the resulting two Doppler frequencies yields the position inside the measurement volume with up to micrometer accuracy. A profile sensor with heterodyne technique is realized together with a validation procedure for the coincident signals in order to measure small velocity down to zero at the wall surface. We report about the application of the sensor for the measurement of laminar boundary layers and for the determination of the wall shear stress. A good agreement was obtained between the measured velocity and the theory based on the Blasius solution. The measured smallest velocity was less than 0,1 m/s. This can be decreased further by using proper setting of the conditions for the measurement.

1. Introduction

The flow velocity close to the wall is one of the most important information in the fluid mechanics. In a turbulent flow the smallest (Kolmogorov) scale of vortices becomes smaller and the thickness of boundary layer becomes thinner when the Reynolds number increased (Tennekes and Lumely 1972). Typically the Reynolds number of an industrial flow reaches the order of 10^6 and the thickness of the turbulent boundary layer becomes around 10^{-5} m. In such a high Reynolds number flow a steep velocity gradient exist near the wall (Fischer et al 2001). For the measurement for such a flow non-intrusive technique should be applied with high spatial resolution.

Laser Doppler Anemometer (LDA) has relatively high spatial resolution without disturbing the flow by the sensor probe. The spatial resolution of velocity measurement is generally determined by the length of the measurement volume. Although correction methods based on the near-wall velocity-distribution has been proposed to decrease the spatial average effect for the measurement in fully developed turbulent flows (Durst et al 1996, 1998), they can not be applied for flow field with an arbitrary velocity distribution.

To overcome these limitations a laser Doppler velocity profile sensor has been proposed (Czarske 2001, Czarske et al 2002, Büttner and Czarske 2003). It uses two different interference fringe systems, which are superposed to create a measurement volume. The position as well as the velocity of a tracer in the measurement volume can be determined by the measured Doppler frequencies and a calibration function. As the sensor does not assume any velocity distribution, it can be applied for a flow with arbitrary velocity profile. Besides, in contrast to the micro-PIV / PTV techniques the spatial resolution of the velocity profile sensor is not based on imaging whose spatial resolution is limited by diffraction (Meinhart and Wereley 2003), that of the profile sensor can be potentially achieved down to sub-micrometer scale. Since the profile sensor is an extension of the conventional LDA, it can have a long working distance, which will be suitable for several industrial measurement applications.

In this study we investigate the applicability of a heterodyne LDA velocity profile sensor. The sensor utilizes intermediate frequency of two acousto-optic modulators for enabling the small velocity down to zero, which was not possible to be measured by the former velocity profile sensors without the heterodyne technique, e.g. due to the pedestal of a Doppler signal (Czarske et al 2003). First the principle will be described. Then the spatial resolution and relative velocity measurement accuracy will be estimated with experimental results. The sensor was applied for the measurement in laminar boundary layer on a flat glass plate. The wall shear stress was estimated by the measured velocity profile close to the wall.

2. Laser Doppler velocity profile sensor

2.1 Principle

The velocity measurement is based on the evaluation of the Doppler burst signal generated by a particle passing through the measurement volume (Albrecht et al 2002). The measurement volume is formed by interference fringes in the cross section of two coherent laser beams. Taking into account the spacing d of the fringe system, the velocity U of a particle crossing the measurement volume is calculated according to $U = f\,d$, with f denoting the measured Doppler frequency. Conventionally, a velocity distribution over the entire measurement volume is obtained. In contrast, the profile sensor allows to perform the velocity measurement with spatial resolution inside the measurement volume. The position along the optical axis z as well as the velocity U of a particle inside the measurement volume can be determined (Czarske 2001, Czarske et al 2002).

The principle of the profile sensor is based on the generation of two fringe systems with different fringe spacing gradients $\partial d_i(z)/\partial z$,. i = 1,2, in the same measurement volume. A separate measurement of two respective Doppler frequencies f_1 and f_2 can be realized by using two different laser wavelengths (wavelength division multiplexing: WDM) or by employing frequency division multiplexing techniques (FDM). The *z*-position of the scattering object can be determined by the quotient of the two Doppler frequencies:

$$q(z) = \frac{f_2(U,z)}{f_1(U,z)} = \frac{U(z)/d_2(z)}{U(z)/d_1(z)} = \frac{d_1(z)}{d_2(z)}, \tag{1}$$

where the Doppler frequency is given by $f_i = U/d_i$, i = 1,2, and with U being the transverse component of the velocity perpendicular to the fringes.

The quotient $q(z)$ is independent of the velocity U as it can be seen in equation (1). Thus, the position of the scattering object is calculated from the two Doppler frequencies f_1 and f_2, respectively, via the calibration function $q(z)$. An unambiguous measurement of the position requires a monotonic calibration function, which can be achieved by adjusting each of the fringe spacing for the two measurement channels in opposite slopes. The calculated *z*-position allows to determine the actual fringe spacing $d_1(z)$ and $d_2(z)$, resulting in a precise measurement of the velocity:

$$U(z) = f_1(U,z) \cdot d_1(z) = f_2(U,z) \cdot d_2(z) \,. \tag{2}$$

Based on equations (1) and (2), the position as well as the velocity of scattering particles can be determined without influence of fringe spacing variations.

2.2 WDM Setup

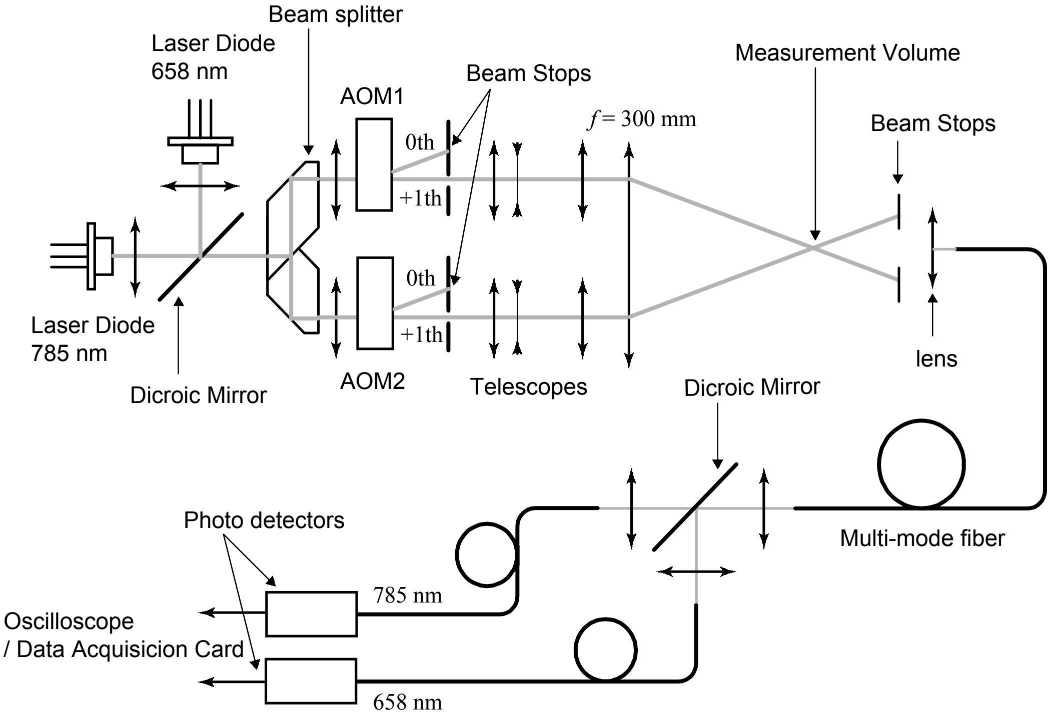

Fig. 1: WDM setup using a prism beam splitter and two AOMs.

The sensor system consists of the interference fringes with two wavelengths of lasers. The sensor head integrates all the optical components inside the measurement head including laser diodes and two phase-locked acousto-optic modulators. The beams of two transverse single-mode laser diodes (λ_1 = 658 nm, λ_2 = 785 nm) were collimated with aspheric lenses and collinearly superposed by means of a dichroic mirror at 45° incidence (see Fig. 1). The laser diodes could be adjusted with respect to the collimating lenses to adjust the positions of the beam waists relative to the crossing plane. A prism beam splitter was used for generating two coherent partial beams for each wavelength. In order to be able to measure low velocity down to zero, a carrier frequency technique was applied. Therefore, each of the partial beams was directed through an acousto optic modulators (AOMs), which were stabilized to a difference frequency of 2 MHz using driver frequencies of 78 MHz and 80 MHz, respectively. Only the +1st diffraction orders were imaged into the measurement volume by two telescopes

for beam diameter adoption and a front lens with 300 mm focal length; other orders were blocked by means of beam stops in front of the telescopes.
For signal detection, the scattered light of particles crossing the measurement volume was collected and coupled into a multi-mode fibre by the use of a single biconvex lens. After separating the two wavelength again with a second dichroic mirror, the scattered light was guided towards two silicon photo detectors for opto-electrical signal conversion. Data acquisition and further signal processing was done with a standard PC. A data validation based on a LabVIEW program was accomplished.

2.3 Adjustment, calibration and measurement accuracy

Each of the lasers and optics were adjusted so that each pair of beams crosses close to one point and the fringe spacing has an opposite slope (Büttner 2004). The calibration of the sensor was done by scanning the measurement volume perpendicular to the z-axis with a tungsten wire of 4 µm diameter, which was fixed at an optical chopper. The chopper was mounted on a motorized translation table and rotated with stabilized angular speed. A PC with a 12 bit two-channel analogue/digital converter card was used for data acquisition and controlled by a LabVIEW program. The power spectrum for the both channels were calculated by means of Fast-Fourier-Transformations (FFT) and the Doppler frequency was estimated by Gaussian fit to the spectrum peak, respectively. At each position several 20 samples were taken in order to reduce the statistical uncertainty by averaging. Fig. 2 shows the variation of the amplitude of each spectrum, which corresponds to the irradiance inside the measurement volume. The figure shows that the intersection volumes overlap well for the coincident measurement of two channels. The size of the measurement volume seems nearly 1 mm but the actual size was about half a millimeter in the flow measurement. It can be seen that the peak position is not at the same position but 200 µm shifted each other. This is caused by the remaining chromatic aberration in the optics. Fig. 3 shows the variation of the fringe spacing. The opposite slopes, which are necessary for an unambiguous position measurement, are shown. The resulting monotonic calibration function *q(z)* is depicted in Fig. 4.

The steepness $\partial q / \partial z$ of this calibration function determines the spatial resolution. The spatial resolution of the sensor at the center of the measurement volume is theoretically estimated by Czarske et al (2002):

$$\delta z \approx \sqrt{2}\left|\frac{\partial z}{\partial q}\right|\frac{\delta f}{f}\,. \tag{3}$$

In contrast, the relative statistical measurement error of the velocity is only depending on the relative uncertainty of the frequency estimation $\delta f / f$ and can be written simplified as Czarske et al (2002):

$$\frac{\delta U}{U} \approx \sqrt{\frac{3}{2}}\frac{\delta f}{f}\,. \tag{4}$$

Using the mean slope of calibration curve in the Fig. 4 (dq/dz = 0,38 mm^{-1}) and assuming the relative accuracy of the frequency estimation $\delta f/f$ ~10^{-3}, the spatial resolution and the relative velocity accuracy are estimated to be δz ~3,7 µm and $\delta U/U$ ~ 0,12 %, respectively. The measured spatial resolution by tungsten wire is shown in Fig. 5. The average spatial resolution with different wire velocities was 5,4 µm, which agrees well with the theoretically estimated value. The average relative velocity measurement accuracy was 0,16 %, which also agrees with the theoretically estimated value. The deviations from the theoretically estimated values attributes to the stability of the optical chopper.

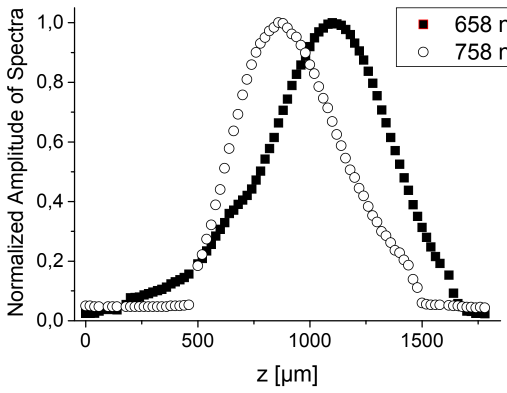

Fig. 2: Amplitude of power spectra

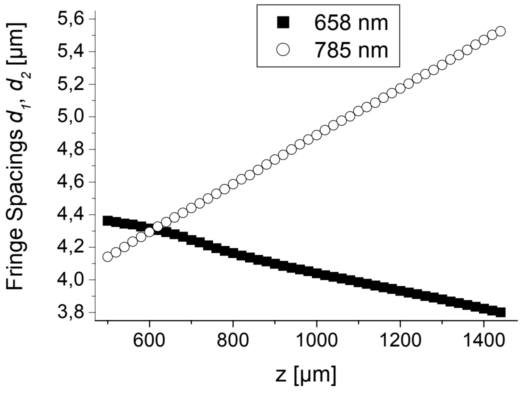

Fig. 3: Fringe spacing variation along the optical axis.

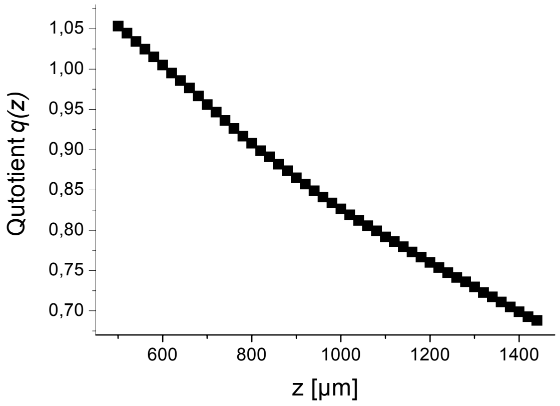

Fig. 4: Calibration function *q(z)*

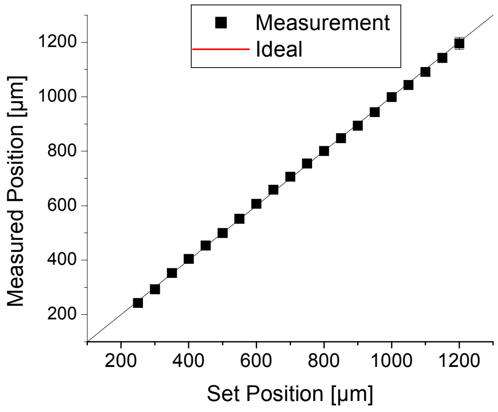

Fig. 5: Tungsten wire measurement (wire velocity was U_{wire} = 3.8 m/s)

3. Wind tunnel measurements

Measurements in a laminar boundary layer on a flat glass plate were conducted in a Eiffel-type wind tunnel in the PTB. A water-glycerine mixture with micron size particles was used for seeding the flow. For the fluid flow measurements, the LabVIEW program was used with a validation procedure to avoid outlier data. Signals were validated only when the signal-to-noise ratio of both channels exceeded a certain threshold (coincidence validation) and when the estimated quotient of the Doppler frequencies was within the range of calibration defined by Fig. 4. The measured velocity profiles are shown in Fig. 6 with different free stream velocities. Due to the thick boundary layer the measurement was conducted with traversing the measurement volume inside the boundary layer. The actual measurement volume was about 500 µm which was smaller compared to Fig. 2, which was due to the difference of the irradiance of the scattering object between tungsten wire and a tracer particle. Each profile consists of seven measurement ranges. The measured profiles were in good agreement with the Blasius solution (Fig. 7). This indicates that the sensor has a capability of measuring the velocity distribution inside the boundary layer. The lowest measured velocity was less than 0,1 m/s. Even lower velocity can be measured by setting proper setting of the measurement conditions (i.e. sample frequency and record length of the signals).

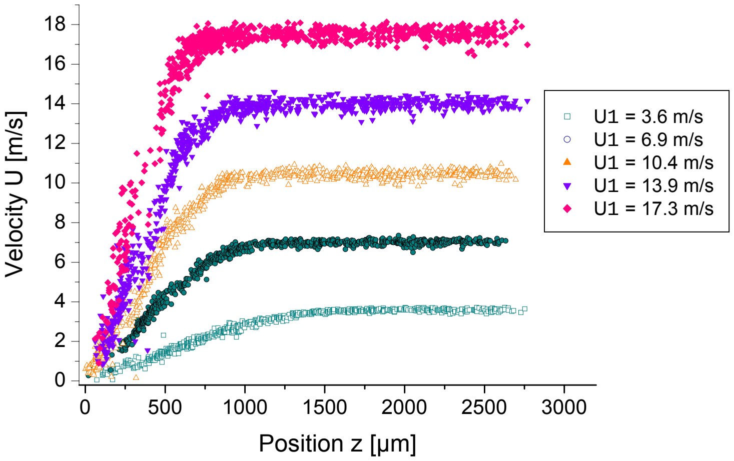

Fig. 6: Velocity profile in a laminar boundary layer for different free stream Velocities. Each of the points is calculated from one Doppler burst signal pair.

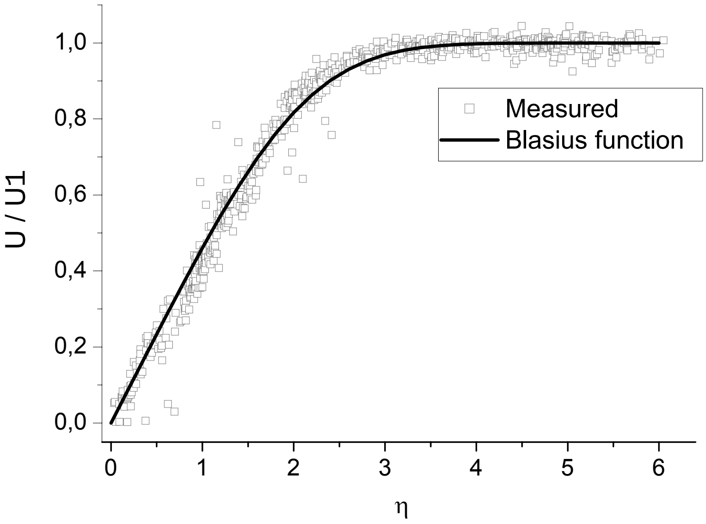

Fig. 7: Comparison of the measured velocity profile with the Blasius solution

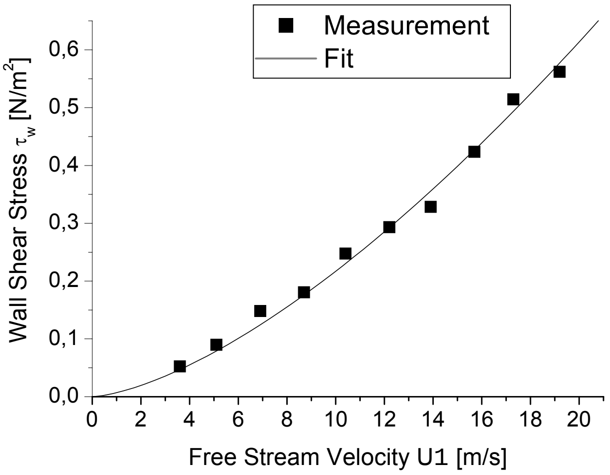

Fig. 8: Wall shear stress obtained by the measured velocity profile near the wall (solid curve is fit)

In our previous work the sensor was not provided with AOMs and so the frequency evaluation was done in the baseband. Here, the velocity of zero corresponds to the frequency of zero as well as the pedestal caused by the DC-part of the burst signal. To cut off the pedestal, a high-pass filter was applied, which, on the other hand, restricted the minimum measurable velocity to about 0,5 m/s (Czarske et al 2002). The current sensor is provided with two AOMs in different operating frequency, so that the frequency evaluation proceeds in the intermediate frequency range. In this case zero velocity corresponds to the difference of the AOM frequency shift (here: 2 MHz), whereas the pedestal is still located at zero frequency. Consequently, the pedestal and the Doppler-frequency peak for small velocity is physically distinguishable and small velocities down to zero can be measured without being influenced by the pedestal part of signals. The minimum measurable velocity could be improved down to about 0,05 m/s (Figs. 6 and 7). However, the measurement points close to the wall are less dense since the seeding particles are passing only rarely in this region.

The wall shear stress is defined by the product of the viscosity and velocity gradient at the wall (Schlichting and Gersten 2000):

$$\tau_w = \mu \left. \frac{\partial U}{\partial z} \right|_{wall} , \tag{5}$$

which was calculated from the linear part of the velocity profile close to the wall. The calculated values are plotted in Fig. 8 together with the fit curve based on the Blasius solution (Schlichting and Gersten 2000).

4. Conclusions and Future Work

A LDA velocity profile sensor with heterodyne technique was realized which allows the instantaneous determination of both velocity and position of a tracer particle passing through the measurement volume. The sensor is based on a two-wavelength technique which generates two overlapping interference fringe systems, one with converging and the other with diverging fringes. The evaluation of the ratio of the Doppler frequencies obtained from each fringe systems allows to determine the position inside the fringe systems. In order to measure small velocities down to zero at the solid wall, a heterodyne technique was utilized by taking the intermediate frequency of two acousto optic modulators. With the heterodyne technique a velocity measurement close to the wall surface can be done without being disturbed by the pedestal part of Doppler signals.

The sensor has a spatial resolution of about 5 µm and the relative measurement accuracy of about 0,16 % within measurement volume of 500 µm at a working distance of 300 mm. Laminar boundary layer measurements on a flat glass plate were conducted in a Eiffel-type wind tunnel in the PTB. The measured velocity profile is in good agreement with the Blasius solution. The low velocity was measured less than 0,1 m/s. The wall shear stress calculated from the measurement results fit well with the curve based on the Blasius solution.

The sensor will be used for the near-wall measurement of turbulent flows, where small velocity measurement with high spatial resolution is desired. Work packages on a novel profile sensor for the investigation of turbulent shear flows in the refractive-index-matched oil-channel in the LSTM were initiated. A profile sensor using a powerful green Nd:YAG laser as well as FDM (frequency division multiplexing) techniques was realized. One advantage is that dispersion effects between the two measurement channels does not exist. A new signal processing technique with high data rate and validation steps was developed based on Linux system and ANSI-C++. Data rates around 1 kHz are possible with a standard PC.

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