HIGH SPATIALLY RESOLVED TURBULENT BOUNDARY LAYER MEASUREMENTS BY FIBER-OPTIC HETERODYNE-VELOCITY-PROFILE-SENSOR

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ABSTRACT

A fiber-optic LDA-velocity-profile-sensor was realized for high spatially resolved velocity measurements in turbulent boundary layers. The sensor can resolve the position of a tracer particle passing through the measurement volume along optical axis. Therefore velocity measurement with a high spatial resolution is possible compared with a conventional LDA (laser Doppler anemometry). The measurement accuracy of the sensor was investigated with respect to the velocity measurement and the spatial resolution. The sensor successfully resolved the velocity distribution in a laminar boundary layer on a flat plate. Then it was applied to turbulent boundary layers in a fully developed duct flow. The measured results showed fairly good agreement with a direct numerical-simulation result. However, the improvements are necessary for obtaining reliable statistics.

INTRODUCTION

Flow velocity close to the wall is one of the most important information in fluid mechanics. In a turbulent flow the smallest scale of vortices becomes smaller as the Reynolds number increases. Typically the Reynolds number of an industrial flow reaches the order of 10^6 and the thickness of the viscous sublayer becomes around 10^{-5} m. In such a flow a steep velocity gradient exists near the wall, where a non-intrusive measurement technique should be applied with a high spatial resolution.

Laser Doppler anemometry (LDA) is a well-established non-intrusive measurement technique with a relatively high spatial resolution. The spatial resolution of an LDA is generally determined by the size of the measurement volume. Most of commercial LDAs have measurement volumes of typically some hundreds micrometers length, which is not enough for resolving small vortex structures in a high Reynolds-number flow. Focusing laser beams strongly enables to achieve smaller size of the measurement volume, and hence higher spatial resolution. However this causes non-uniformity of fringe spacing inside the measurement volume and smaller numbers of fringes, which lower the accuracy of Doppler frequency measurement (Büttner et al. 2001). In consequence both of these degrade the accuracy of the velocity measurement.

LDA velocity-profile sensor has been proposed to overcome the spatial resolution problem (Czarske 2001, Czarske et al, 2002). The sensor utilizes a measurement volume formed by two different interference-fringe systems. The position as well as the velocity inside the measurement volume of a tracer is determined by the measured Doppler frequencies together with a calibration function. The velocity profile is obtained without traversing the sensor head hundreds of times. The sensors have been realized by using a wavelength-division-multiplexing (WDM) technique, and they have been successfully applied to laminar boundary layers (Czarske 2001, Czarske et al. 2002).

In the present study we developed a new fiber-optic LDA-velocity-profile-sensor with a frequency-division-multiplexing (FDM) technique. The FDM sensor was realized to investigate the velocity distribution down to the wall, where the flow velocity approaches to zero and steep velocity gradient exists. The aim of the study is to investigate the velocity distribution of flow near the wall with a high spatial resolution, which was not possible with other measurement techniques. First the principle of the sensor is explained, followed by the description of the setup. The sensor is calibrated and the measurement accuracy is investigated. The sensor was tested in a laminar boundary layer at first. Then it is applied in turbulent boundary layers in a fully developed channel flow.

PRINCIPLE

The principle of the profile sensor is based on the use of two fringe systems in the measurement volume. They allow velocity measurements to be made with a 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 is evaluated from the measured Doppler frequencies with a calibration curve (Czarske 2001, Czarske et al. 2002).

Two fringe systems with different fringe spacing gradients $\partial d_i(z)/\partial z_i$ (i = 1, 2), are formed in the same measurement volume (Fig. 1). The z-position of the tracer particle is determined by the quotient of the two Doppler frequencies:

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

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 can be calculated from the two Doppler frequencies f_1 and f_2, respectively, via the calibration function $q(z)$. 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 technique) or by employing two different frequency ranges (frequency-division-multiplexing technique). The calculated z-position allows to determine the actual fringe spacings $d_1(z)$ and $d_2(z)$, resulting in a precise measurement of the velocity:

$$U(z) = f_1(U,z) \cdot d_1(z) = f_2(U,z) \cdot d_2(z). \qquad (2)$$

Therefore the position as well as the velocity of a tracer particle can be evaluated without the influence of fringe-spacing variations.

The measurement accuracy is determined by the accuracy of the frequency estimation. The spatial resolution depends on the accuracy of the frequency estimation and the steepness of the calibration function (Czarske et al. 2002). With a profile sensor the spatial resolution of typically several micrometers was obtained inside a few millimeters of measurement volume. Since it provides the position as well as the velocity of each tracer particle, the spatially high resolved velocity profile is obtained without mechanical traversing. In contrast to the micro-PIV / PTV techniques the spatial resolution of the profile sensor is not based on imaging, the spatial resolution of which is limited by diffraction (Meinhart et al. 2003). The spatial resolution can be further improved to some hundreds nanometers without losing its long working distance (distance between the measurement head to the measurement volume) and high velocity measurement accuracy, which is suitable for various measurement applications in turbulent shear flows.

FDM SENSOR

In the former studies the velocity-profile sensors were realized by a WDM technique (Czarske 2001, Czarske et al. 2002). However, one of the disadvantages of the WDM profile-sensor was the dispersion effect caused by the optics. For that reason a new profile-sensor system was designed with a FDM technique. The new sensor system utilizes only one wavelength. It has less dispersion effect and is more robust compared with the former profile sensor based on a WDM technique. Furthermore, flexible use of fiber-optics is possible due to the separation of the opto-electrical components and measurement head.

Setup

Fig. 2 shows the setup of the FDM profile-sensor. The beam from a laser (wavelength: 532 nm, output optical power: 100 mW) was divided into four partial beams by using a beam splitter cube and two subsequent acousto-optic modulators (AOMs). Each of the AOMs was operated with a frequency shift of 60 MHz and 80 MHz respectively. Only the beams of the 0^{th} and the $+1^{st}$ diffraction order by the AOMs were used and all the other beams were blocked. One of the 0^{th} order beams was led through another AOM with 120 MHz frequency shift. Each of the resulting four partial beams, which experienced different frequency shifts of 0 MHz, 120 MHz, 60 MHz and 80 MHz respectively, was coupled into respective single-mode fiber (SMF) and guided to a commercial two-components LDA-measurement-head. The optical fibers were connected to the head so that two pairs of fringe systems with 20 MHz and 120 MHz are obtained (Fig. 3). This combination of beams were carefully chosen in a way that all other pairs of difference frequencies between two individual beams do not coincide with the two carrier frequencies of 20 MHz and 120 MHz. Remaining parasitic frequencies in Doppler signals were eliminated by the low-pass filters so that they would now disturb the measured signals.

The measurement volume is formed at the intersectional area of beams, which is at about 300 mm apart from the measurement head. Because of the arrangement of the beams at the head, the two fringe systems were tilted about 3.6 degrees (7.2 degree between each fringe systems) with respect to the optical axis (Fig. 4). Hence the effective size of the measurement volume is smaller than that of the individual fringe systems.

Fig. 4 shows the detection part. The scattered light from a tracer particle passing through the measurement volume was coupled into a multi-mode fiber (MMF) and guided into a photo detector. The electrical output from the detector is signal was split into two channels. The signal of each channel was mixed down into the base band with each carrier frequency of 20 MHz and 120 MHz, which were created by using the reference outputs of the AOM drivers. The 20 MHz reference signal was generated by mixing the 60 MHz and 80 MHz driver signals and by applying a band-pass filter with a central frequency of 20 MHz. Then low-pass filter was applied to respective output of the down mixing to suppress the parasitic signals. A major advantage of the setup is the robustness to the drifts in the AOM driver frequencies. Even if the driver frequency shifts changes, it does not give any serious influence on the measurement since the same oscillators are used for frequency shifting and down mixing. Thus a complex circuitry is not necessary for frequency stabilization. The use of the down mixing enables the measurement close to zero velocity since no DC-pedestal occurs in the power spectra.

Measurement data were acquired with a two-channel 12-bit A/D converter card contained in a standard PC. Signals from the both channels were simultaneously acquired and a LabVIEW program controlled the measurements. For signal processing two different methods were tested in the following measurements. One was a real time processing and the other was a processing after the measurement. In the real time processing the position and the velocity information were evaluated in real time during the measurement. The power spectra in the two channels were calculated by means of fast Fourier transform (FFT). The maximum three points in each spectrum were fitted by a Gaussian function to estimate the Doppler frequencies. Three validation steps were used for evaluating only valid data: signal-to-noise ratio (SNR), peak height of the power spectra, and the calibration range. The other method was applied mainly for the measurements in turbulent boundary layers. Triggered signals were stored as raw time signals without any processing in real time during the measurement and they were processed after the measurement. This was necessary to detect signals with wide range of velocity in the measurement volume especially close to the wall. The use of fixed frequency filter fails for detecting both signal of high and low velocity. A MATLAB program was used for signal processing. The program detects the signal part with a dynamic filtering technique and evaluates each detected pair of signals in both channels. This method effectively detects the signals from very low velocity to high velocity and improves the validation rate compared with the real time processing.

Calibration and Measurement Accuracy

First the beams at the sensor head were adjusted to create the measurement volume. They were adjusted so that they cross at one point and create two fringe systems whose fringe spacing becomes diverging and converging along the optical axis. Then the calibration of the sensor was done with a tungsten wire of 4 μm. The wire acted as a scattering object and it was attached on wheel of an optical chopper, which was rotated at a stabilized angular speed. The chopper was mounted on a motorized translation table and scanned through the measurement volume along the optical axis. The fringe spacings $d_1(z)$ and $d_2(z)$ at each position along the optical axis were calculated from the known constant velocity of the wire and the measured Doppler frequencies. At each position several 10 samples were taken and averaged to reduce statistical uncertainty. Finally the quotient curve $q(z)$ was determined from the measured Doppler frequencies (Fig. 5). The actual size of the measurement volume was estimated to be about 1 mm from the frequency amplitude of the power spectra.

The measurement accuracy and the spatial resolution of velocity-profile sensor were estimated in a way based on Czarske et al. (2002). Relative velocity-measurement accuracy is mainly determined by the accuracy of Doppler-frequency estimation. The spatial resolution of the sensor depends on the accuracy of Doppler-frequency estimation and the slope of the calibration curve. From the calibration relative velocity-measurement accuracy was estimated to be 0.26 % and the spatial resolution was about 5 μm in the central region of the measurement volume.

FLOW MEASURMENT

Laminar Boundary Layer

The FDM sensor was first tested in laminar boundary layers to examine its ability. The measurement was done in a laminar boundary layer in a Göttingen-type wind tunnel. A glass plate was inserted in the uniform flow and the signal was detected in a forward-scatter mode. For tracer particles DEHS (diethyl-hexyl-sebacate) was used with an atomizer.

Turbulent Boundary Layer

The FDM sensor was applied to turbulent boundary layers. The flow was a fully developed two-dimensional air channel flow. The dimensions of the cross-section were 600 mm x 50 mm, which ensures the condition of the two dimensionality of the flow. The flow was tripped at the entrance of the channel to enhance the transition to turbulence. The details of the flow apparatus are described in Zanoun et al. (2003). The measurement was conducted at about 6000 mm from the inlet and it corresponds to 120 H (H: channel height of wall to wall). This length was considered to be sufficient to obtain a fully developed condition of turbulent flow. At the measurement point a glass plate was attached to obtain a light access for the measurement in forward scatter detection. The plate was mounted flash to the wall so that no flow disturbance occurs by inserting the plate.

The measurements were conducted in different conditions of Reynolds numbers. We define the Reynolds number as

$$\mathrm{Re} = \frac{U_B H}{\upsilon}, \qquad (3)$$

where the U_B denotes the bulk mean velocity, and it was independently measured by the manometer reading of pressure near the inlet of the flow.

RESULTS AND DISCUSSION

Laminar boundary layer

Fig. 6 shows the measurement result in a laminar boundary layer with theoretical curve of Blasius solution. The velocity was normalized by the free stream velocity U_∞ and the horizontal axis was normalized by the parameter (White, 1991):

$$\eta = z\sqrt{\frac{U_\infty}{2\nu x}}, \qquad (4)$$

where ν is the kinematic viscosity of the fluid and x is the distance from the leading edge to the measurement point. The plot consists of about 2500 individual data points measured in the flow without any smoothing or averaging. The measured result clearly shows the velocity profile and it agrees well with the Blasius profile. For this measurement the measurement head was traversed 10 times because of the thickness of the boundary layer. Due to the use of the down mixing no DC-pedestal occurs in the power spectra and hence the velocity measurement close to zero was possible. The smallest velocity measured was 0.03 m/s and this indicates the sensor is suitable for measurement closed to the wall in boundary layer flows.

Turbulent Boundary Layer

Fig. 7 shows the measured mean velocity-profile of the channel flow at $Re_B = 4\text{x}10^4$. In the plot every 200 data points in the neighborhood were averaged about their position and velocity. It means that each point consists of the average of 200 points with respect to both the position and the velocity. This method was chosen for the effective use of the measured information about the position and velocity of each particle. The sensor head was traversed 34 times to obtain this profile and total number of 30024 points were validated after the signal processing out of 67125 stored data. The present result shows fairly good agreement with a result by DNS calculation (Abe et al., 2001) although it shows some deviation near the wall. This is considered due to the different Reynolds number of the flows and relatively small number of data points in the present measurement.

In Fig. 8 and 9 the normalized profiles of mean-velocity and fluctuating-velocity are shown. The flow Reynolds number was $Re_B = 1.8\text{x}10^4$. The axes were normalized with friction velocity $u_\tau = \sqrt{\tau_w / \rho}$ (5) (ρ : the fluid density). The wall shear stress τ_w is defined by

$$\tau_w = \mu \left.\frac{dU}{dz}\right|_{wall}, \qquad (6)$$

(μ: viscosity) and it was determined by linear fitting the velocity measured velocity profile close to the wall. The statistics were calculated for every 100 points in neighborhood with respect to the position and the velocity. The mean-velocity profile is shown with the linear fit equation in the viscous sublayer and the log-law fit equation:

$$U^+ = (1/\kappa)\ln z^+ + B\,. \qquad (7)$$

The constants κ and B obtained by the fit were κ=0.29, B=6.5 which is different from the value k=0.41, B=5.5 in general (Bernard and Wallace, 2002). This is due to the low accuracy of linear fit close to the wall. The friction velocity obtained by the fit was lower than the value estimated from the Reynolds number with a empirical equation by Dean (1978). This was caused by outlier points and they made lower estimate for the velocity gradient close to the wall. The use of side-scatter detection and a stable laser with higher optical power could reduce the outliers. The fluctuating velocity (Fig. 9) shows similar trend that the value is higher than the results by other experiments and simulations. It is also due to the low estimate of the friction velocity, which is used for the normalization. The position where the fluctuation has a peak is around z^+~11, which is lower than the position z^+ ~15 reported in general (Bernard and Wallace, 2002). The distribution shows large fluctuation and it is because of relatively small number of data points used for calculating the statistics.

CONCLUSIONS

A fiber-optic LDA-velocity-profile-sensor was developed with a frequency-division-multiplexing (FDM) technique. The sensor can resolve the position of a tracer particle passing through the measurement volume, and hence high spatially resolved velocity measurement is possible. The use of fiber optics and FDM technique enables flexible and robust measurement compared with the former velocity-profile sensors. The present sensor has a working distance of about 300 mm and the relative velocity measurement accuracy of 0.26 %. It has a spatial resolution of the sensor about 5 µm inside the measurement volume of about 900 µm. The sensor was tested in a laminar boundary layer at first. The sensor successfully resolved the velocity distribution close to the wall. Then it was applied in turbulent boundary layers in a fully developed flow. Measurements were conducted with a signal-processing program with a dynamic filtering to detect signals particles with both low and high velocity. The measurement results were shown with the calculated statistics of every certain numbers of neighbor data points. The measured results showed fairly good agreement with a DNS calculation result. However, there were discrepancies between the present results and others. They were considered due to relatively small numbers of data points in the present measurements and the low estimate of friction velocity caused by outlier data points. These will be reduced by taking more measurement data and by using side-scatter detection together with the use of a stable laser source with high optical power.

ACKNOWLEDGEMENTS

We appreciate Mr. P. Pfeiffer for developing the experimental setups.

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FIGURES

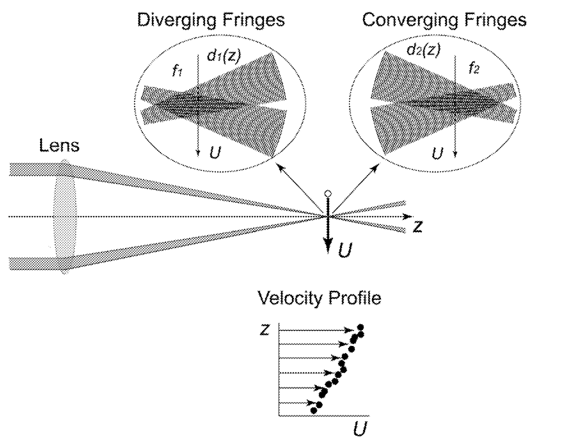

Fig. 1: Principle of the velocity-profile sensor: The use of two fringe systems realizes the measurement of the position as well as the velocity of a tracer particle.

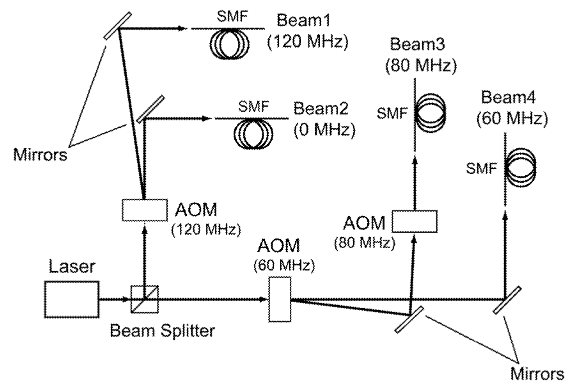

Fig. 2: Optical setup of the FDM velocity-profile sensor.

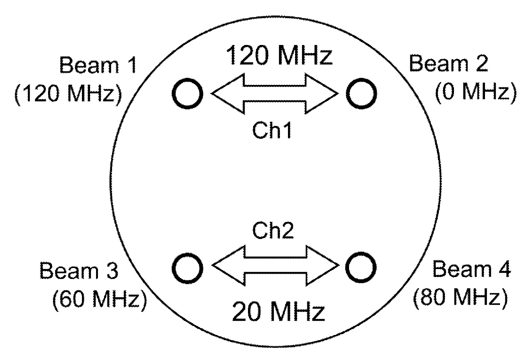

Fig. 3: Configuration of the four beams at the measurement head (front view)

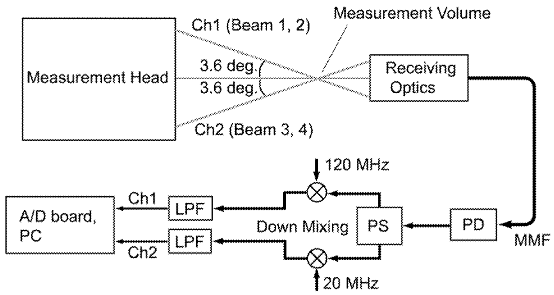

Fig. 4: Measurement head and the detection part of the FDM velocity-profile sensor. (MMF: multi-mode fiber, PD: photo detector, PS: power splitter, LPF: low-pass filter)

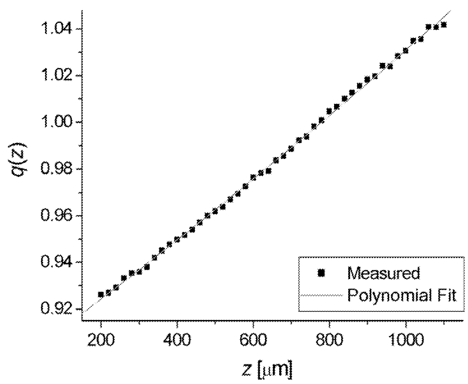

Fig. 5: Calibration function along the optical axis used for the measurements in turbulent boundary layers.

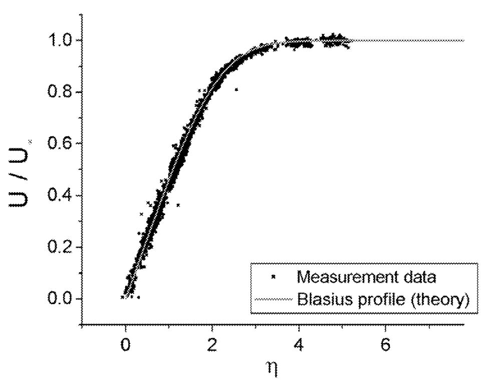

Fig. 6: Measured velocity profile in a laminar boundary layer compared with Blasius profile. No average was used for this plot.

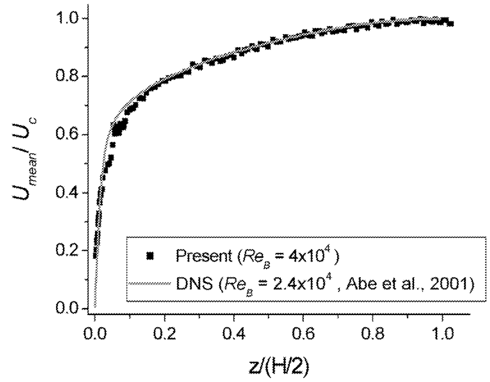

Fig. 7: Mean velocity-profile in measured in a turbulent channel flow. (Axes are normalized with channel-centerline velocity and half width.)

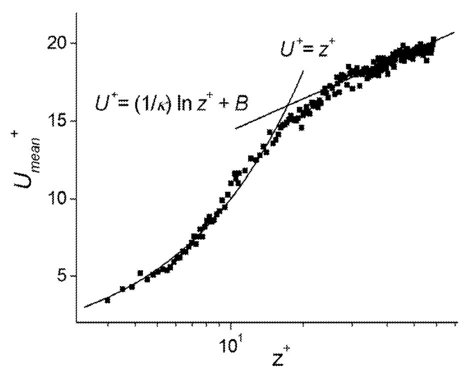

Fig. 8: Mean velocity distribution near the wall (Re_B = 1.8×10^4)

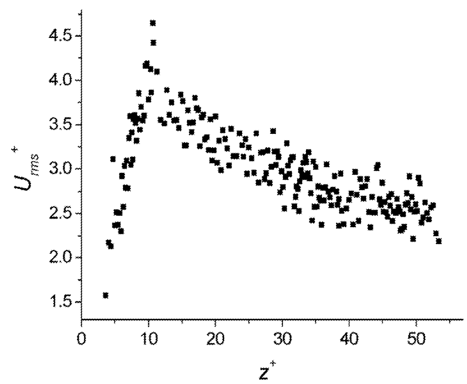

Fig. 9: Fluctuating velocity distribution near the wall (Re_B = 1.8×10^4)