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MEASUREMENTS IN A TURBULENT CHANNEL FLOW BY MEANS OF AN LDV PROFILE SENSOR

S. Pasch, D. Gatti, R. Leister, B. Frohnapfel, J. Kriegseis
Institute of Fluids Mechanics (ISTM), Karlsruhe Institute of Technology (KIT), Germany

R. Örlü
Linné FLOW Centre, Dept. Engineering Mechanics, KTH Royal Institute of Technology, Stockholm, Sweden

INTRODUCTION

Measurements of mean velocity profiles and fluctuations in turbulent flows are of great interest for the development and evaluation of flow control concepts. The mean flow velocity gradient in the wall-near region offers the possibility to directly estimate the wall shear stress and skin-friction coefficient, but its experimental determination is still a challenging task.

For particle image velocimetry (PIV), for instance, high velocity gradients require a large dynamic range and a trade-off has to be made between the spatial resolution and the size of the field of view [3]. While, for general laser Doppler velocimetry (LDV) measurements, the spatial resolution is limited to the size of the measurement volume in the order of magnitude of several hundred μm [10], a laser Doppler velocity profile sensor (LDV-PS) can spatially resolve a velocity profile within the measurement volume (MV) [1]. The LDV-PS measurement technique has been shown to be capable of measuring turbulent channel flow mean velocity profiles as well as fluctuations in the main flow direction [9]. In the present work, a newly developed commercial LDV-PS system is employed for flow measurements in a turbulent channel and the experimental procedure and measurement results will be discussed from an application perspective. The experiments build upon the experience gathered in measurements of a laminar Couette-like flow [5] and an experimental characterization study [7], which examined the interplay of the Fast Fourier Transform (FFT) signal processing parameters, the scattering object size and the measurement uncertainty.

MEASUREMENT TECHNIQUE AND SETUP

The LDV-PS measurement technique is based on two overlapping convergently-divergently oriented interference fringe systems with different wavelengths in the same plane as illustrated in Figure 1. Consequently, the fringe distances $d_i, i = 1, 2$ are a function of the y' position within the MV. The position y' of a particle passing through the MV can be determined by means of a calibration function from the quotient q of the detected scattered light frequencies $f_i, i = 1, 2$ of both fringe systems according to

$$q(y) = \frac{f_2(y', u)}{f_1(y', u)} = \frac{u/d_2(y')}{u/d_1(y')} = \frac{d_1(y')}{d_2(y')}. \tag{1}$$

The particle velocity is calculated as $u = f_i d_i$. The frequencies f_i of the scattered light signals are determined using FFT.

In previous experiments with the LDV-PS measurement system [5, 7], it was observed that the velocity uncertainty was generally small, while the position uncertainty strongly depends on the applied boundary conditions. For increasing flow velocities, the position standard deviation decreased for constant FFT parameters, i.e. sample frequency and sample number. However, when the sampling frequency was adjusted to the flow velocity, these effects could be avoided. These findings imply that the data processing routines are to be chosen accordingly. It is suggested to calculate flow statistics by averaging position values in u-range bins when velocity profiles are evaluated at very small flow velocities.

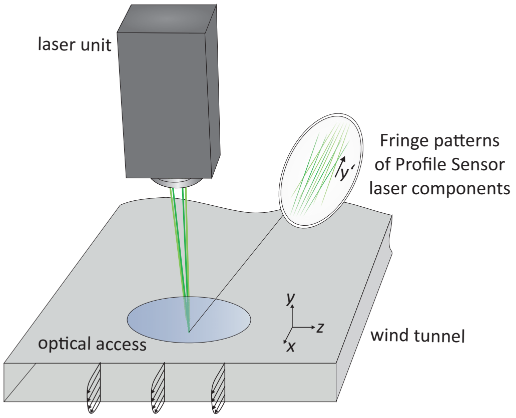

Figure 1: Experimental Setup; LDV-PS above wind tunnel.

A commercial *ILA R&D 1D2C* LDV-PS comprised of two Nd:YAG lasers ($\lambda = 532\,\text{nm}$ and $\lambda = 552\,\text{nm}$) with a 5 MHz Bragg-shift was employed to measure the flow velocity u in main flow direction and y position above the lower channel wall by detecting Di-Ethyl-Hexyl-Sebacate tracer particles. The sensor was positioned above a glass window of 1 mm thickness in the channel and tilted by 20° around the x axis as shown in Figure 1 to avoid reflection issues. The measured position values were accordingly corrected by means of trigonometric relations. The MV of 2000 μm length was traversed in 500 μm steps to acquire velocity profile data in the lower channel half. The FFT sample frequency was chosen to 100 MHz with a sample number of 2048. The channel length, width and height were 4000 mm, 300 mm and 25.2 mm and the measurements were conducted 100 mm upstream the outlet. The high aspect ratio enables comparison with skin friction coefficient data from pressure drop measurements in an identical tunnel.

RESULTS AND DISCUSSION

In total, 624 000 burst events of particles passing through the MV were detected at 29 different traverse positions over the semi-channel height. The measured velocity and y-

position values are shown in Figure 2. Just above the wall at small flow velocities the y-position scattering of bursts is observed to increase, which has been found to be a characteristic phenomenon for measurements with constant FFT parameters [5, 7]. Correspondingly, the first data point of the mean velocity profile in Figure 3 is not determined correctly.

The wall position was determined by means of a linear extrapolation of the velocity profile near the wall based on averaged measured position values in 0.25 m/s-wide u bins.

The centerline velocity u_{cl} and corresponding channel half-hight position marked with the black asterisk in Figure 2 has been determined as the maximum of a quadratic fit function based on averaged measured velocity values in y-position bins in the central channel region.

The observed scattering of detected bursts is a superposition of turbulent fluctuations and measurement uncertainty. The latter has been found to decrease with increasing velocity and is therefore approximately constant at a certain velocity level [7]. Considering the burst distribution in the y range between 2 000 μ and 12 000 μm, decreasing fluctuations are implied towards the middle of the channel. Consequently, the wider burst band closer to the wall implies the registration of the characteristic fluctuation profile which corresponds to the typical distribution in turbulent channel flows [8].

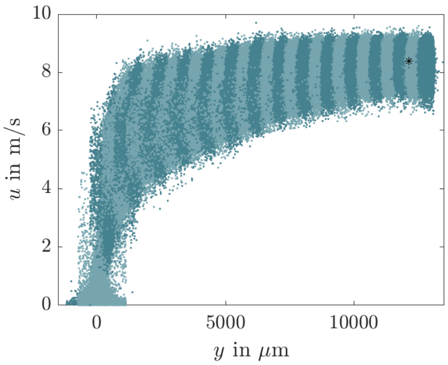

Figure 2: Velocity and position values of all detected bursts. Two different shades of blue indicate the individual measurements; the asterisk marks u_{cl} and the channel semi-height.

To compare the measured velocity profile with direct numerical simulation (DNS) data allowing to evaluate the quality of the measurements, a transformation into viscous units is to be conducted. Figure 3 shows the mean velocity profile gained by statistical averaging of y values in u bins for smaller velocities and averaging of u values in y bins for larger velocities. The wall shear stress is estimated from the centerline velocity using the skin-friction correlation suggested by Dean [2], thus allowing a simple yet approximate transformation to viscous scales. Additionally, measurement data from stereo PIV measurements [3] and DNS data by Hoyas [4] is provided. In the wall-near region of the viscous sublayer, the LDV-PS measurements provide data points with a good spatial resolution. However, an advanced measurement processing routine needs to be developed for the velocity and position estimation in this region comprising high velocity gradients, as the deviation from the expected linear near-wall behaviour shows.

For further evaluation of the mean velocity profile, different approaches for the transformation to viscous scales will be evaluated and compared in the coming months. Firstly, as described by Hehner [3], fitting of the presented data with respect to a universal description of a turbulent velocity profile by Luchini [6] will be conducted. Alternatively, the wall shear stress can be determined directly from the wall-near velocity gradient. As shown before, the LDV-PS provides a good spatial resolution in the viscous sublayer so that this approach seems promising for more accurate further evaluations.

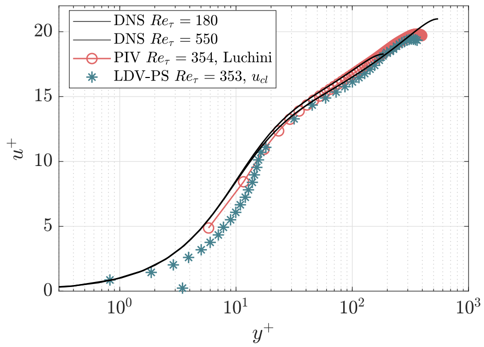

Figure 3: $u^+ - y^+$ profile of averaged LDV-PS data transformed to viscous scales using u_{cl} and a correlation by Dean [2], PIV data [3] transformed to viscous scales with a fitting function by Luchini [6] and DNS data by Hoyas [4]

In continuation of the acquisition of measurement data presented here, advanced processing routines for the estimation of mean velocity profiles will be developed. Different methods for the conversion to viscous scales will be applied to enable an evaluation of the results. Finally, those evaluation approaches will be comparatively discussed.

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