Measurement Technique Comparison in a Turbulent Boundary Layer

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Abstract

A precise characterization of velocity profiles in turbulent boundary layer (TBL) flows is essential for advancing research in fluid mechanics and flow control. This study provides a comparative assessment of three measurement techniques applied to a canonical zero-pressure-gradient turbulent boundary layer (ZPG TBL), with particular attention to near-wall resolution. Hot-wire anemometry (HWA), a long-established benchmark in TBL measurements, is used as a reference method. The first optical technique, Defocusing Particle Tracking Velocimetry (Defocusing PTV, DPTV), employs a single-camera setup and enables volumetric velocity measurements with wall-normal depth of approximately 3 mm, capturing all three velocity components. The second optical technique, Shake-the-Box (STB), is a multi-camera (Lagrangian) particle tracking method operated in a two-pulse mode to resolve the flow with high spatial fidelity. Experiments are conducted to evaluate the capability of these optical methods to resolve high-resolution velocity profiles, especially within the viscous sublayer. Measurements are carried out at free-stream velocities U_∞ of 6, 12, and 18 m/s, corresponding to momentum-thickness Reynolds numbers $Re_\theta = U_\infty \theta / \nu$ of 930, 1420, and 1900, respectively, at a fixed streamwise position of $x = 2.1$ m from the leading edge. The primary focus is on the accuracy and reliability of near-wall velocity data, a critical region for understanding wall-bounded turbulence. The diagnostic plot reveals higher streamwise fluctuations of the STB results compared to HWA, which can be attributed to camera vibrations, which need to be quantified in future experiments. The study concludes by discussing future directions for improving experimental techniques in high-resolution near-wall shear flow measurements based on the insights gained.

1 Introduction

High-resolution velocity measurements in the near-wall region of wall-bounded turbulent flows are crucial for both advancing the fundamental understanding and assessing the effectiveness of various flow control strategies. In this context, experimental studies of turbulent boundary layers (TBL) frequently rely on well-characterized reference flows, enabling direct and systematic comparisons between the canonical base flow and the modified flow resulting from control interventions.

The first attempts to actively manipulate and control TBL flows can be traced back to Ludwig Prandtl (Schlichting and Gersten, 2017) with the usage of suction in order to prevent separation. The topic has been studied ever since highly motivated by the demand to reduce viscous drag (Wilkinson et al., 1988; Spalart and McLean, 2011), where more and more complex flow structures could be revealed (Ganapathisubramani et al., 2003; Hutchins et al., 2011). Experimental efforts, however, are accompanied by the difficulty of limited spatial resolution close to the wall. Örlü and Vinuesa (2020) provide a comprehensive overview of the different direct and indirect techniques available for the estimation of the mean wall-shear stress τ_w and its fluctuations.

The purpose of the present study therefore centers around a comprehensive measurement technique comparison with the aim to provide high-resolution velocity information of the full flow including the sublayer region of the TBL flow. Therefore, three different techniques are compared on a flat plate, along which a turbulent boundary layer is evolving. The first technique is Hot-Wire Anemometry (HWA), which serves as long-established benchmark in TBL measurements and is used as a reference method for this investigation. The second technique, Defocusing Particle Tracking Velocimetry (Defocusing PTV, DPTV) is an optical technique, which utilizes a single-camera setup and enables volumetric velocity measurements with wall-normal depth of approximately 3 mm, capturing all three velocity components. As third technique, Shake-the-Box (STB) is used. This technique is a multi-camera Lagrangian particle tracking method. For the current investigation it is operated in a two-pulse mode to resolve the flow with high spatial fidelity.

2 Experimental Procedure

2.1 Wind-tunnel facility

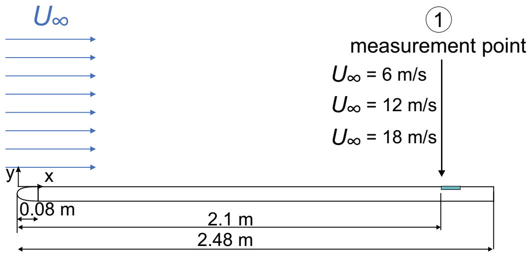
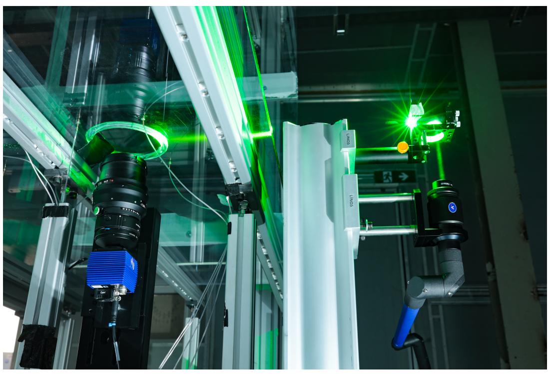
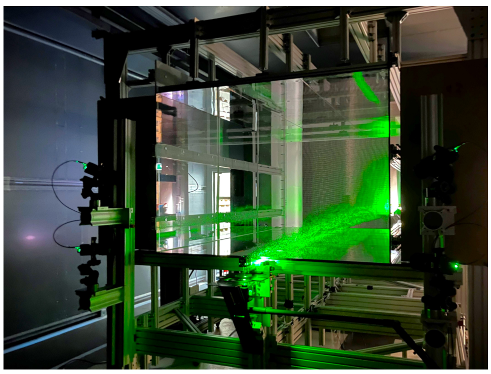


Figure 1: Sketch of the boundary layer test rig with relevant geometrical dimensions and flow information. The main flow direction is along the x-coordinate, while the y- and z-position represent the wall-normal and cross-plane direction, respectively.

The experiments were conducted in a newly constructed boundary layer test facility at the Institute of Fluid Mechanics (ISTM), employing an open-jet wind tunnel of Göttingen type. The tunnel has a nozzle exit of 1.40 m in height and a width of 1.80 m with a overall plenum chamber size (W × H × L) of 5.5 m × 3.3 m × 8.8 m. A housing with optical access around the plate was manufactured for the study with a cross-section of 1.40 m × 0.97m, such that bleeding air including the boundary layer of the nozzle is allowed to pass outside of the housing. The measurement plate has a length of 2.48 m and a width of 1.40 m. Free-stream velocities U_∞ of 6, 12, and 18 m/s were used, corresponding to Reynolds numbers $Re_\theta = U_\infty \theta / \nu$ of 930, 1420 and 1900, respectively at the measurement location $x = 2.1$ m downstream of the leading edge and centric in z-direction. The flow is tripped at $x = 0.08$ m. Figure 1 shows a sketch of the experimental test set-up with the geometrical values as well as the used coordinate system.



(a)



(b)

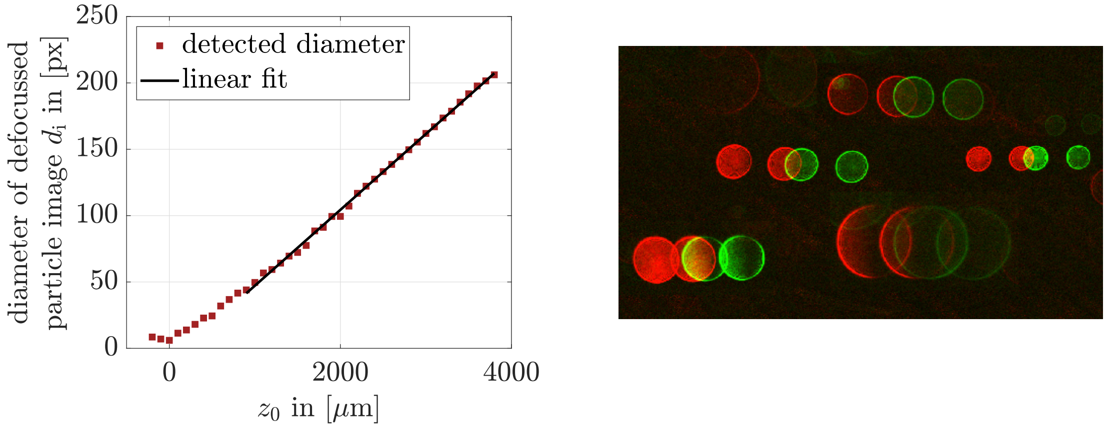
Figure 2: Set-up and turbulent boundary layer test facility (a) Defocusing PTV experiments with view from below the plate. The laser beam is entering from the rear edge. The camera is positioned below the plate. (b) Image of the test facility during STB measurement with four cameras in backward-to-side scattering mode.

2.2 Experimental set-up

Hot-Wire measurements were performed using a *Streamline Pro* anemometer by *Dantec*, employing a single 2.5 µm diameter platinum wire with a nominal sensing length of 0.5 mm. To be able to perform measurements very close to the wall the Hot-Wire probes are designed specifically for boundary layer measurements having bent down prongs (Örlü et al., 2010). Due to its high sampling rate of 24 bit a universal measurement data acquisition system (*Quantum X*) was used for the record of accurate time series of the measurement channel. A sampling frequency of 48 kHz has been selected for Hot-Wire measurements, while during signal conditioning a low-pass filter with a cut-off frequency of 30 kHz has been selected.

For the Defocusing PTV measurements an optical access from below is needed in order to set the focus layer parallel to the plate. A coated high-precision optical glass window (*Edmund Optics*) was embedded into the plate. These measurements were performed using one CMOS camera (Imager CX-12, *LaVision*, resolution 4080 px $\times$ 2984 px, pixel size: 2.7 µm, image depth: 12 bit) equipped with a 50 mm Macro lens (Milvus 2/50M, *Zeiss*, Interlock version). The aperture was fully opened, yielding a projected physical diameter of $D_a = 25$ mm. Volumetric illumination was provided by two combined Nd:YAG Evergreen lasers (max. repetition: 15 Hz, energy: 200 mJ, wave length: 532 nm, *Quantel*) together with a volumetric light optic (*LaVision*), in order to span a height of several millimeters. The laser beam entered from the rear edge of the plate. The time distance between the four lasers pulses was set to 150 µs - 50 µs - 150 µs for the case of $U_\infty = 6$ m/s and was shortened accordingly for the higher velocities. The reason for a larger time distance between the two outer particle pairs is the reduction of overlapping particles. Since the two first laser pulses are in the first frame and pulse 3 and 4 are in the second camera frame, these pulses should have larger distances in between. Figure 3(b) shows a raw data image where five defocused particle images with different diameters are visible. Depending on their position and velocity the overlapping becomes more pronounced. Here a trade-off between the timing distance and the defocusing sensitivity needed to be found.

The particle supply is provided by a seeder (PIVPart40, *PIVTEC*), where seeding fluid (PIVlight, *PIVTec*) is atomized by several Laskin-nozzles. The typical diameters of such droplets are in the range of $0.3-0.4$ µm (Fuchs et al., 2023). To extract the defocusing calibration function the camera needs to be traversed several times. A motorized linear translation stage (LTS150C/M *Thorlabs*) was used for a traveling distance of 4 mm. Figure 3(a) shows the detected diameter of one stationary particle sticking on the glass plate at different defocusing stages. The focal plane is positioned at $z_0 = 0$. At this location, the diameter deviates from a straight line due to additional out-of-focus effects come into play, as described in (Olsen and Adrian, 2000; Leister et al., 2023). Details on the additional set-up and processing routines used for the present defocusing measurement can be found in Leister et al. (2024). The defocusing function together with a visual impression of the defocus diameter range given by a raw data image can be found in Figure 3. The defocusing sensitivity s_Z can be stated as 17.5 µm/px.



(a) (b)

Figure 3: (a) Defocusing function extracted through traversing along a distance of four millimeters. (b) Raw data double-image with false colors. ○: frame A; ○: frame B.

For the STB measurements the imaging set-up consists of four CMOS cameras (Imager CX-12 *LaVision*) each equipped with a 100 mm lens (Milvus 2/100M, *Zeiss*) and a Scheimpflug adapter v3 (*LaVision*). The set-up resembles the Defocusing experiment, despite only one laser and four cameras were used. The calibration of the multi-camera set-up is done with a dual-level calibration plate (053-1-1, *LaVision*). The two-pulse Shake-the-Box evaluation (Schanz et al., 2016; Novara et al., 2023)

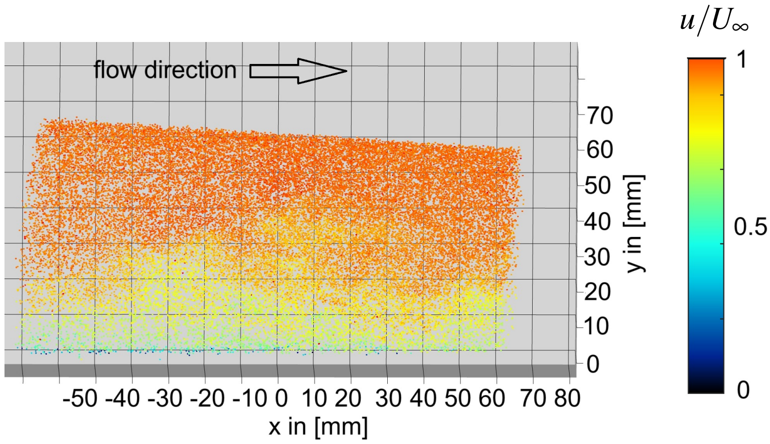


Figure 4: Instantaneous flow state at a free-stream velocity $U_\infty = 6\,\mathrm{m/s}$. The coordinate system sets the measurement location of $x_1 = 2.1\,\mathrm{m}$ as reference. Instantaneous high-speed and low-speed regions can be distinguished.

implemented in DaVis 11 (*LaVision*) was used to extract the velocity field for each recorded image pair. 5,000 double images were captured for each run. Figure 4 gives an impression on the instantaneous flow with the velocity $U_\infty = 6\,\mathrm{m/s}$. Regions of higher and lower velocity at the same y-position can be distinguished. The flow direction is towards positive x-values and the wall normal coordinate is represented by the y-direction, where $y = 0$ indicates the estimated position of the plate. Figure 4 contains approximately 48,000 Lagrangian particle tracks with a length of two.

The estimation of the wall position is conducted differently, depending on the measurement technique. For HWA data, where regions close to a solid are difficult to reach, an elaborated fitting approach was used as developed by Chauhan et al. (2009), where the entire profile, including friction velocity can be reconstructed on the base of the assumption of a ZPG turbulent boundary layer. For the Defocusing PTV data the diameter of stationary particles sticking at the wall is directly extracted from the raw data. Here, the only caveat lies in the fact that this wall diameter can be a function of the sensor position, caused by aberrations of the lens. Since this technique relies only on one camera with a wall-normal viewing angle, no viewing-angle-dependent light reflections are present and the wall position can be estimated with high precision. For the STB data, the positioning of the target provides an initial estimation of the wall position. The fine adjustment was done with the means used by parallax PTV (Cierpka et al., 2013), as the velocity profile is mirrored directly at the wall.

3 Results – Velocity-profile evaluation

After the extraction of the sparse-seeded and highly-seeded flow field with Defocusing PTV and Shake-the-Box, respectively, the spatio-temporally averaged wall-normal profile $U(y)$ of the stream-wise velocity component $u(x,y,z,t)$ is generated for a comparison with the HWA results. Figure 5(a) shows the normalized streamwise velocity U along the wall normal coordinate y for all three measurement techniques. HWA data range from around 0.5 mm to the outer region of the TBL flow, while the STB data show bin distances of around 50 µm. The Defocusing data reach an outer limit of around 3 mm with the closest wall distance of 30 µm to the wall. Consequently, the STB technique is able to deliver flow information of the entire flow of interest, while HWA and Defocusing PTV technique for the present measurement campaign nicely complement each other. Figure 5(b) shows the streamwise velocity in viscous units, where $u_\tau = \sqrt{\tau_w/\rho}$ – with τ_w obtained through the velocity gradient at the wall or where no data in the viscous sublayer is at hand through Chauhan et al. (2009) – is used to formulate the quantities $u^+ = u/u_\tau$ and $y^+ = yu_\tau/\nu$.

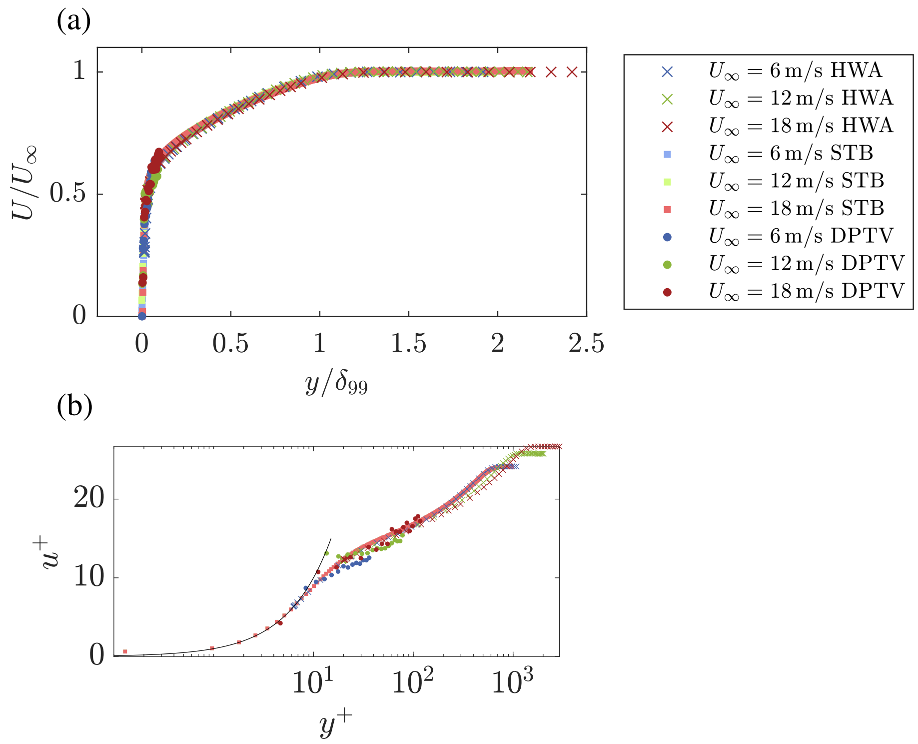


Figure 5: Averaged streamwise velocity profiles (a) in physical coordinates and (b) converted into viscous units. Symbols indicate the different measurement techniques HWA (×) and STB (□) and Defocusing PTV (○), while the colors denote the free stream velocities.

Despite inherent inaccuracies in determining the absolute wall position and wall shear stress (Örlü et al., 2010), the quality of a turbulent boundary layer can still be assessed by employing the diagnostic plot introduced by Alfredsson and Örlü (2010), which has since evolved into a robust tool for the experimental analysis of wall-bounded turbulent flows (Alfredsson et al., 2021). Figure 6 presents a comparison of the data from all three measurement techniques in the diagnostic plot, thereby removing uncertainties in the absolute wall position and wall shear stress. The experimental results from all methods align qualitatively with the theoretical curve proposed by Alfredsson et al. (2011) which is valid for $U/U_\infty > 0.6$, i.e. in the outer region of the flow. However, the discrepancy around the straight line in the diagnostic plot indicates that the turbulence intensity, in particular for the STB measurements, is higher. This might might be attributed to observed vibrations of the cameras or ghost particle tracks generated through a high seeding density.

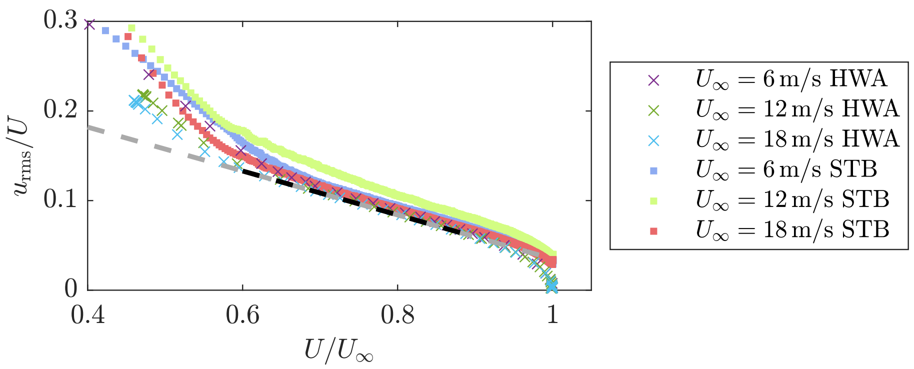


Figure 6: Diagnostic plot for the HWA (×) and STB (□) velocity profiles together with the reference equation (valid for the outer layer region) with the updated constants given by Sanmiguel Vila et al. (2017).

4 Conclusions

This study presents a comparative assessment of three measurement techniques – Hot-Wire Anemometry, Defocusing Particle Tracking Velocimetry, and Shake-the-Box – for resolving velocity profiles in a zero-pressure-gradient turbulent boundary layer. Particular emphasis was placed on evaluating their ability to resolve the near-wall region, which is critical for accurate characterization of wall-bounded turbulent flows, but also the outer region where the low signal-to-noise ratio and background noise of various laser-optical techniques are usually higher than those of HWA.

The experimental results demonstrate that HWA continues to serve as a high-fidelity reference for TBL measurements, particularly valuable for its proven reliability in capturing the velocity distributions up-to $y^+ \approx 10$ in the present case. However, it is limited in resolving the flow in the viscous sublayer due to additional heat losses to the wall.

Defocusing PTV, with its single-camera setup and high wall-normal resolution, effectively resolves all three velocity components within a volumetric domain near the wall. It bridges the resolution gap left by HWA in the immediate vicinity of the wall, achieving wall distances as small as 30 µm. However, it relies on optical access.
Shake-the-Box (STB), as a multi-camera Lagrangian method, offers high spatial resolution across the entire boundary layer, combining broad field coverage with the capability to resolve fine-scale flow structures. Its suitability for dense seeding and volumetric reconstruction makes it particularly versatile. However it showed increased fluctuations in streamwise direction in the present case with might be attributed to camera vibrations.

Overall, while these techniques are often applied individually with high confidence in their respective results, direct comparative measurements are less common. Yet, as demonstrated here, such comparisons reveal remaining discrepancies that warrant further attention. The complementary strengths of the techniques suggest that a hybrid measurement approach – leveraging HWA's precision, DPTV's near-wall accuracy, and STB's volumetric coverage – provides a promising and more comprehensive methodology for future high-resolution studies of wall-bounded turbulence. These insights not only lay a strong foundation for improving experimental diagnostics in flow control research but also highlight the need for continued efforts to better understand and address the limitations of current techniques, particularly in near-wall measurements.

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