Comparison of Holographic and Tomographic Particle-Image Velocimetry Turbulent Channel Flow Measurements

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Abstract. Based on velocity measurements of a fully developed turbulent channel flow, the methods of holographic and tomographic particle-image velocimetry (PIV) are compared. The emphasis of this comparison is on the measurement of time-dependent three-dimensional small-scale flow structures, i.e., structures at a characteristic length on the order of the Taylor scale since such flow patterns can be hardly captured by any two-dimensional experimental technique. The findings show that the holographic PIV method is useful to measure flow patterns in larger volumes whereas the tomographic PIV should be used to resolve three-dimensional small-scale structures.

1. Introduction

To quantitatively measure highly intricate unsteady three-dimensional flow structures, an adequate three-dimensional, three-component (3D3C) measurement technique must be identified. Such flow structures can be any vortical structure in a wall-bounded or free shear layer or any flow pattern in an unsteady flow field the unsteadiness of which does not allow any two-dimensional decomposition of the significant flow structures. The three-dimensional measurement technique should be able to not only detect massive flow patterns but also slender structures in the range of the Taylor scale or a few Kolmogorov scales, respectively, as for example so-called dissipation elements (Wang & Peters, 2006).

To the best of the authors’ knowledge, at present the only 3D3C measurement techniques which are potentially adequate to detect small instantaneous structures in turbulence are photogrammetric holographic and tomographic PIV. It is the objective of this paper to assess and compare the capabilities of holographic and tomographic particle-image velocimetry (PIV) to capture small instantaneous 3D structures. The pros and cons of the measurement techniques are juxtaposed with respect to the setup, the processing, and the resulting measurement data. In the following section, the experimental setup and procedure regarding the holographic and tomographic PIV arrangements, respectively, are discussed. Subsequently, the results and the comparison of the two measurement techniques are presented. The paper closes with a summary and conclusions.

First the test facility and then the fundamentals of the holographic and tomographic particle-image velocimetry setup including the associated processing procedures are discussed.
1.1. The test facility

The measurements are conducted in the core region of a fully developed turbulent channel flow within a special Eiffel type wind tunnel sketched in figure 1. The flow within the test section has been evaluated by two-component particle-image velocimetry (2C-PIV) and laser Doppler velocimetry (LDV) showing an excellent agreement with the data of Moser et al. (1999) and Niederschulte (1989), respectively (see Schäfer et al., 2011).

1.2. Holographic PIV

As sketched in figure 2 an off-axis configuration with two reference beams to obtain image separation of the two laser pulses, i.e., the two time steps, is used. To determine a 3D3C velocity field the measurement volume is recorded in two views (±45°) using a so-called relay-lens module (Konrath, 2003). The tracer particles, Expancel Microspheres at a diameter of 40 µm, are immersed in the flow via a pressurized reservoir and illuminated by an injection seeded Quanta-Ray Nd:YAG laser at 532 nm and 400 mJ/pulse. To preserve a comparatively high seeding concentration the flow is seeded selectively (cf. figure 2). With regard to a high particle concentration, the HPIV measurements are performed at a smaller Reynolds number based on the bulk velocity and the channel half-height $Re_U=3.8 \times 10^3$ than the TPIV measurements at $Re_U=1.7 \times 10^4$.

The particle images are reconstructed using a phase-conjugate illumination of the hologram.
with a continuous wave laser where the relay-lens module is turned by 180° about the vertical axis of the hologram plate. This reconstruction procedure eliminates image deformations caused by the optics and the wind tunnel window, respectively. For each view, two images \((t_1\) and \(t_2\)) are scanned separately using a CCD-camera equipped with a telecentric lens that is translated through the holographic particle field by a three-axis traverse as presented in figure 3. Using an in-house MATLAB program, the two-dimensional particle displacements are determined by an FFT-based adaptive cross correlation for each sampled plane. Next, the two-dimensional velocity data from both views are recombined to determine the 3D velocity distribution. In a final step, an artificial image displacement resulting from the misalignment of the reference and the reconstruction beams is corrected by a reference hologram.

![Figure 3. HPIV sampling configuration.](image)

### 1.3. Tomographic PIV

In figure 4 a schematic of the tomographic PIV system is shown the essential features of which are briefly discussed next. For details of the TPIV measurements (see Schäfer et al., 2011). To perform the measurements DEHS particles (diameter \(\approx 1\) µm) are added to the flow at the blower inlet. The particles are illuminated by the same laser as in the HPIV measurements. To increase the light intensity in the test volume a mirror is positioned below to reflect the light sheet. The imaging system consists of four CCD (Charge-Coupled Device) cameras which are positioned as shown in figure 4. The recorded image size is 16-bit at 2048 × 2048 px² resolution. All cameras are equipped with macro lenses and are assembled on turnable mounts including Scheimpflug adapters. The commercial PIV software DaVis (LaVision) is used for the entire TPIV procedure, i.e., calibration of the imaging system, recording, and preprocessing of the particle images, reconstruction of the three-dimensional particle field, and calculation as well as postprocessing of the velocity distribution. To allow the detection of small scale turbulent structures an optical setup with a comparatively high magnification \((M = 0.6)\) is used. This tends to decrease the depth of focus, i.e., the depth of the test volume. Hence a comparatively small aperture \((f/\# = 22)\) is used which increases the depth of focus such that the velocity distribution is determined within a test volume of \(17.75 \times 17.75 \times 6\) mm\(^3\) \((1656 \times 1656 \times 576\) voxel). The loss in recorded light intensity is compensated by the mirror below the measurement volume that approximately doubles the light intensity in the measurement volume.

### 1.4. Comparison of holographic and tomographic PIV setup features

The HPIV setup is extremely complex at a cumbersome chemical processing and sampling of the hologram plate. Testing different interrogation window sizes or overlaps requires a completely new sampling of the entire hologram and reference hologram. Depending on the
requested resolution this can take a few hours. Furthermore, this technique does not allow 'online' measurements such that it takes hours to obtain the result of the experiment. This fact extremely complicates a parameter variation to optimize the holographic recordings. Regarding the tracer particles tested DEHS droplets have been only visible for one view and one time step, i.e., on one holographic image out of four, since their scatter properties were insufficient to ensure visibility also on those holographic images which are less intense. For this reason, larger polystyrol particles (Expancel Microspheres) at a diameter of 40 $\mu$m and a mass density of 25 kg/m$^3$ had to be used.

Unlike the HPIV the TPIV is comparatively easy to set up and it is straightforward to change the measurement volume. The image quality can be checked 'online' and the measurements can be performed right after the quality requirements are satisfied. Since DEHS particles are well recorded a comparatively high seeding concentration can be used to enhance the spatial resolution of the measurements. When the images are recorded various interrogation volume sizes and overlaps can be used to analyze the flow physics. Where HPIV allows only one recording at a time, i.e., at a time shift of several minutes, TPIV allows to subsequently record an arbitrary number of time-shifted measurement volumes such that even time-resolved measurements can be conducted.

2. RESULTS

In this section the holographic and tomographic PIV measurements within the core region of the turbulent channel flow are compared. For clarity the positions of the holographic and tomographic test volumes are sketched in figure 5. The resulting instantaneous velocity field and velocity fluctuations, respectively, are visualized within exemplary test volumes in figures 6 (a)-(d). Obviously, the flow field from the TPIV measurements possesses more structures than that from the HPIV measurements. This is due to the smaller Reynolds number in the HPIV measurements where the smaller turbulent structures are less pronounced.

In the HPIV measurements a spatial resolution of 1.6 mm corresponding to an interrogation window of 256 px is obtained using the aforementioned in-house MATLAB evaluation software.

Figure 5. Positions of the HPIV- and TPIV measurement volumes, top view (not to scale).
Figure 6. Upper figures: Exemplary velocity field from the HPIV measurements at $Re_U = 3.8 \times 10^3$, interrogation window 256 px, 75% overlap and vector spacing 0.4 mm. (a) Instantaneous velocity field where every second vector is shown. (b) Velocity field with subtracted mean velocity. Lower figures: Exemplary velocity field from the TPIV measurements at $Re_U = 1.7 \times 10^4$, interrogation window 96³ voxel, 75% overlap and vector spacing 0.25 mm. (c) Instantaneous velocity field where every second vector is shown. (d) Velocity field with subtracted mean velocity. For clarity only the outer vector planes are shown.

The resulting vector spacing is 0.4 mm due to an overlap of the interrogation windows of 75%. The three-dimensional velocity distribution is determined in a test volume of $14.4 \times 13.6 \times 14$ mm³ yielding $37 \times 35 \times 36$ velocity vectors. Concerning the TPIV measurements the commercial PIV software Davis is used to identify the velocity distribution in a test volume of $17.75 \times 17.75 \times 6$ mm³ with a minimum vector spacing of 0.25 mm and a final interrogation volume of 96³ voxel at 75% overlap. Since Davis applies window deformation (Raffel et al., 2007) during the correlation process the use of an overlap improves the spatial resolution above the size of the interrogation window and volume, respectively. Hence, in the present case, a spatial resolution below 1 mm, i.e., in the range of 0.8 mm, is assumed. That is, apart from the highly complicated setup, the HPIV measurement technique is superior to the TPIV method when larger flow structures or mean quantities are to be captured since it allows the resolution of a comparatively larger measurement volume with a depth-to-width ratio of 1. However, regarding the current configuration the TPIV yields a higher spatial resolution.

To evaluate the quality of the HPIV and TPIV measurement data the root-mean-square
(rms) values of the velocity fluctuations \( u' \), \( v' \), and \( w' \) are determined and compared with laser Doppler velocimetry (LDV), standard particle-image velocimetry measurements (Schäfer et al., 2011) and numerical data (Moser et al., 1999), respectively. Regarding the TPIV data the rms-velocity is averaged over planes at constant \( z \) and the 50 measurement volumes, respectively. Since the boundaries of the HPIV measurement volume are not parallel to the channel walls the corresponding velocity data is interpolated onto a channel-parallel grid before averaging over \( z = \text{const} \) planes. The distribution of the rms-velocities along the \( z \)-axis is shown in figures 7 (a) and (b). Although the amount of data samples is limited for the HPIV measurements especially in the outer \( z \)-planes, there is still a good agreement of the \( u' \) and \( v' \) rms-velocities with the reference data. However, the rms-level of the \( w' \)-component exceeds the reference distribution, albeit the HPIV technique possesses the same accuracy at all velocity components \( u \), \( v \), and \( w \). The TPIV data in figure 7 (b) show an excellent match with the corresponding \( u' \) and \( v' \) reference data. The deviation of the \( w' \)-component results from the higher measurement uncertainty along the \( z \)-axis (Raffel et al., 2007). Nevertheless, concerning the TPIV method all the velocity components possess a satisfactory rms-distribution along \( z/\delta \) with a minimum in the center of the channel at \( z/\delta = 0 \) and a slight slope in the outer region.

![Diagram](image_url)

**Figure 7.** Comparison of the normalized rms-velocities as a function of \( z/\delta \) where \( \delta \) denotes the channel half-width. (a) rms-distribution from the HPIV measurements. The black solid markers represent the average value of the associated HPIV rms-velocity distribution. (b) rms-distribution from the TPIV measurements. DNS data from Moser et al. (1999), standard PIV and LDV, respectively, are plotted for comparison.

### 3. SUMMARY AND CONCLUSIONS

HPIV and TPIV have been compared based on velocity measurements of the core region of a fully developed turbulent channel flow. Both measurement techniques have been discussed with respect to the experimental setup and the experimental procedure to receive the raw data, the data-processing, the spatial resolution, and the resulting rms-distributions. In terms of the HPIV measurements the spatial resolution has been 1.6 mm and approximately 0.8 mm in the TPIV measurements. Since the HPIV measurements have been conducted at a smaller Reynolds number than the TPIV experiments a resolution on the order of the Taylor scale could be achieved in both measurement campaigns. Due to the highly-concentrated DEHS particles that
could be used in the TPIV measurements a higher resolution than in the HPIV measurements has been obtained. The complex setup and procedure and the choice of adequate tracer particles represent the main difficulties in the HPIV measurements. The detection of small structures requires a high spatial resolution and as such a high seeding concentration which can be achieved, for instance, by vaporized oil-particles (e.g. DEHS). However, regarding the HPIV measurements the scatter properties of the tested DEHS particles were insufficient such that larger polystyrol particles \((d \approx 40 \mu m)\) had to be used. That is, the current holographic PIV method represents a compromise between the visibility of the tracer particles, the attainable spatial resolution, and the measurable turbulence characteristics. The HPIV allows larger measurement volumes than the TPIV method, i.e., volumes at width-to-depth-ratios of 1 against 0.25 for the TPIV method. Although the optical components of the HPIV measurements are well adjusted, slight misalignments of the different views during image sampling will remain. Additional errors regarding the velocity distribution, especially when a high spatial resolution is required, arise from the fact that the depth of focus due to the diffraction diameter of the particle image and the sampling lens, respectively, is not infinitesimally small. That is, particles in front and behind of the actual sampling plane contribute to the result of the cross correlation. The TPIV setup is extremely easy, quality checks can be immediately performed, and several time-shifted volumes can be recorded enabling even time-resolved measurements. Regarding the current configuration, the easier setup, the more straightforward postprocessing, and the higher resolution make the TPIV to be the more promising method to measure small scale three-dimensional structures in turbulence.

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