An industrial light field camera applied for 3D velocity measurements in flow past confined cylinder

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Abstract. Light field cameras have some advantages over classic cameras in a narrow field of application, such photography, cinematography surveillance and quality control in industry. Light field cameras have larger depth of field, compare to regular camera, but lower spatial resolution along optical axis then binocular system. However, 3D velocity measurements using light field are reasonable alternative to modern 3D PIV measurements. The nature of light field image requires extra reconstruction step which affects overall accuracy. In this article, light field PTV was compared to Tomo-PIV. Both techniques were used to measure 3D velocity fields in a turbulent wake past confined cylinder.

1 Introduction

Modern light-field optical devices have been started to use in experimental fluid dynamics research. Output images of the light-field cameras contain extra information which is used to get the third spatial coordinate. Several reconstruction algorithms for light field images have been proposed [1, 2, 3, 4]. In general, calculation of a depth map from a light field image is an ill-posed problem, since a target equation system is underdetermined, similar to 3D reconstruction from several 2D projections. To get a reasonable approximation of a solution some assumption on reconstructed objects of research should be done. The better results require compliance between the object of study, camera settings and reconstruction algorithms.

In the present work, experimental whole-field measurements of the velocity of fluid flow in a slotted jet [5] and the wake of a cylinder using a light field camera are performed. The experiment was carried out in a modified closed hydrodynamic test section [5] with a tank of constant level at $Re \sim 3500$. The used Light-Field PTV reconstruction techniques, results of the experiment, and comparison of the results with a reference Tomo-PIV measurements are described below.

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2 Methods

In this section we describe main steps of the data processing. In the beginning an image of a uniform white background is captured to get microlens coordinates (see Fig. 1). Known microlens structure of the image allows performing a program refocus procedure. The program refocus procedure focuses a raw image on an arbitrary plane. In this case off-focus areas become blurred, similar to classic camera images. This procedure is convenient to convert an image from the light field model to a normal image.

A developed 3D reconstruction algorithm is based on a refocusing procedure. The structure of repeated images depends on a virtual depth and determines an actual depth value. If the virtual depth is correct, then the reconstructed image will be on focus. The idea of the proposed algorithm is to calculate the standard deviation between intensity values corresponding to an object point visualized by different microclenses to assess to the depth of the object point. The closer the obtained virtual depth to a true value, the lower the standard deviation is. An initial image is divided into small rectangular areas that are reconstructed independently. For each of these areas the algorithm finds a virtual depth that minimizes standard deviation value. The found virtual depths form a depth map for the registered object. Then refocusing algorithm reconstructs each part of the image according to the depth map. That patchwork image is called "total focus", since every element is in focus [5].

The virtual depth matching to a real depth is done analyzing of several calibration images, similar to matching pixels to planar coordinates. Tracer's XY coordinates are found on total focus images. Tracer's Z coordinate is taken from the depth map at XY position, in assumption that tracers do not overlap. "No overlap" assumption could be eliminated by using other reconstruction algorithm to reconstruct full 3D image instead of the total focus and the depth map. That algorithm is slower but has better accuracy, that is why we plan to use this algorithm in the future.

Fig. 1. Light field camera images: calibration or "white image" (left) and raw experimental image (right).

We used in-house software "ActualFlow" to process the acquired data in both LF-PTV and Tomo-PIV experiments. For these two cases 1000 particle pair input samples were analysed. A simple 3D-PTV algorithm with the nearest neighbour particle pairing and area search radius 20 px was used to create 3D velocity fields on unstructured grids. Later 3D-PTV velocity fields were used to build a mean velocity distribution on a regular grid with spatial resolution for a single vector $1.36 \times 1.36 \times 0.68$ mm in order to have the same spatial resolution to compare the LF-PTV results with the tomographic measurements. Average number of samples used to calculate a single average velocity vector on the regular grid was near 500. It depended on the average number of particle pairs found for one

instantaneous velocity field, which equaled to ~ 1100 .

For Tomo-PIV the size of a reconstructed 3D object was $640 \times 824 \times 77$ voxels. A self-calibration procedure was done to align all camera models directly using experimental particle images to get perfect multiple ray correspondence throughout the measurement volume. The tomographic reconstruction was done by SMART algorithm [6]. Correlation analysis was performed using the iterative multigrid algorithm with continuous interrogation box shifting. The total number of iterations was four: two steps were performed with a resolution of $64 \times 64 \times 32$ voxels and two extra iterations with a final resolution of $32 \times 32 \times 16$ voxels. The grid-overlapping factor was set to 75%; therefore, the final correlation domain size for the calculation of a single velocity vector was $1.36 \times 1.36 \times 0.68 \text{ mm}^3$.

3 Experiment setup

The experimental setup consisted of hydrodynamic contour, including a tank, a pump, flow meter, and measurement section. The measurement section was a narrow channel with length 390 mm, width 200 mm and depth $h = 4 \text{ mm}$, inside which the cylinder was installed. The cylinder with diameter $D = 10 \text{ mm}$ and width $h = 4 \text{ mm}$ was located on distance $14 D$ from honeycomb on the axis of the channel (see Fig.2). The data were acquired for the Reynolds numbers $Re = DU_0/\nu = 3\,500$, where U_0 is the bulk flow velocity. Measurements were carried out in a zone $2.8 D \times 3.0 D \times 0.4 D$, located behind cylinder. The single-camera LF-PTV and the four-camera Tomo-PIV [7] were used to obtain volumetric distributions of scattering light from tracers.

Fig. 2. Experimental setups: Tomo-PIV (left) and LF-PTV (right).

During LF-PTV measurements the system consisted of Nd:YAG laser EverGreen (50 mJ, 532 nm, 15 Hz), the light-field camera Raytrix (R11M-D-CL-A095-GS-B $4032 \times 2688 \text{ pix}^2$, 9 μm pixel size 192×168 microlenses, 24 pix diameter of microlens, 12 bit, 10 Hz at full resolution) with the lens Carl Zeiss Makro-Planar 2/100 ZF.2, and synchronizing device Berkeley Nucleonics BNC 575. Particle image concentration for LF-PTV during experiment was maintained at a level 0.003 ppp. Frame separation time was set at 300 μs in order to keep the maximum particle image displacement less than 20 px .

In the case of Tomo-PIV experiment the measurement system consisted of a high-speed Nd:YLF New wave Pegasus (50 mJ, 527 nm, at 1 kHz) laser, four high-speed PCO.1200 hs ($1024 \times 1280 \text{ pix}^2$, 12 μm pixel size, 10 bit, 636 Hz at full resolution) cameras and Polis synchronizing device. We used SIGMA AF 50 mm f/2.8 EX DG MACRO lenses for the optical setup. The cameras were installed at horizontal plane along circle with center

located in the same place as the center of the cylinder. The thickness of the laser sheet was 4 mm in both cases. Mean particle image density at the projections was kept at 0.025 ppp. Frame separation time in this case was 1350 μ s.

4 Results and conclusion

A comparison between results of LF-PTV and Tomo-PIV was carried out in the present work. Well qualitative agreement was observed for the 3D structure of the flow in terms of distributions of longitudinal and transverse components of mean velocity. They are shown in the form of 3D isosurfaces and the cross-stream sections (see Fig 3, 4). In spite of the difference in particle image concentration, which affects the number of averaged samples to produce a single mean velocity vector for LF-PTV, quantitative comparisons between the velocity profiles of the longitudinal velocity carried out in the central plane showed good agreement. These results show great potential for volumetric PIV measurements using a single light field camera.

Phantom particles did not have significant influence in LF-PTV measurements, due to presence of several copies of particle images, corresponding to a real tracer, registered by the light field camera. The used algorithm assumed sharp texture, which was the case in the experiment. We expect better accuracy could be achieved by adapting for tracer features during reconstruction process: Gaussian intensity distributions on a black background.

Fig. 3. Comparison of normalized longitudinal mean velocity Tomo-PIV (left) and LF-PTV (right).

Fig. 4. Comparison of normalized transverse mean velocity Tomo-PIV (left) and LF-PTV (right).

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