Refined Particle Position Localization in Digital Holographic Particle Image Velocimetry

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In particle image velocimetry a flow seeded with tracer particles is illuminated by laser light. The scattered light field is recorded and by reconstructing the movement of the scattering particles the behaviour of the fluid flow is measured indirectly. Classical PIV utilizes pulsed laser light illuminating the particles in one light sheet. Hence, only two velocity components in a two dimensional plane (2C 2D) are retrieved. The work presented here deals with an approach to access full 3D 3C resolution. In-line digital holographic particle image velocimetry (DHPIV) makes use of only a single camera. Furthermore, continuous wave lasers can be applied, as the strong forward light scattering generates sufficient light intensities. Hence, the temporal resolution is no more limited by the repetition rate of the laser pulses but by the frame rate of the camera facilitating the usage of high speed cameras. In spite of its advantages, DHPIV is not yet widely distributed as especially the large depth of focus limits its applicability. Additionally, the complex fields generated by particles are sampled by sensors with low resolution and small dimensions in comparison to film-based recordings. This yields poorly sampled light fields and edge effects caused by the truncation of interference fringes [Gire], which facilitates false and multiple particle detections. Traditionally, most algorithms for the reconstruction of particle positions are based on the intensity distribution of the reconstructed volume. Digital holography offers direct access to the complex amplitude of the light field. Hence, also the phase information can be utilized. Still, up to now it has only received attention by comparatively few algorithms, for example by [Yang], [Pan] and [dejong]. In our work a novel approach using the full complex wave reconstructed from the recorded holograms is used in order to reduce reconstruction errors. The measurement method is tested with a water flow induced by a magnetic stirrer. The algorithm subdivides in the steps hologram preprocessing, reconstruction of the complex light field in the sample volume, detection of particle positions and finally tracking of particles. In the reconstruction as well as in the detection step novel approaches have been utilized in order to avoid misinterpretation of random constructive interference structures (speckles) as particles and to increase the precision of the particle localization.

Fig. 1 Experimental setup for hologram recording. The expanded laser light illuminates a water flow induced by a magnetic stirrer in a glass cuvette, is diffracted by polystyrene microparticles in the water, and is recorded as in-line hologram on a CMOS camera chip. The experimental setup is shown in figure 1. The expanded and collimated light of a Nd:YAG laser illuminates a glass cuvette filled with water and monodisperse particles of an approximate average diameter of 9µm. The light scattered by these particles, the object beam, and the remaining light, the reference beam, interfere on the sensor of a camera capable of recording more than 600 frames per second. In the cuvette a flow is induced by a magnetic stirrer. From the recorded holograms three dimensional complex light fields are reconstructed by using a common convolution approach [Kreis] in the Fresnel approximation [Goodman]. The reconstructed volumes are the basis for the detection of particle positions. Three dimensional correlations of both, intensity and phase, values in these volumes with reference patterns are calculated. For this purpose complex light fields surrounding reconstructed particle positions have been intensively studied. A strong impact of the transverse particle location, i.e. of the particle position in the plane perpendicular to the optical axis, on the reconstructed light field is observed experimentally. This is confirmed by numerical simulations.

These observations are used in the developed algorithm. The first approximation, using a single complex reference pattern for the detection of particle positions in the entire sample volume, is refined by means of computer generated particle holograms. With their aid complex light patterns for different transverse particle positions are simulated. Hence, after having identified the approximate transverse position of a particle, simulated reference patterns are generated. These correspond to the phase and the intensity distributions expected from a particle in this transverse location. Three dimensional correlations are executed of the intensity as well as the phase distribution surrounding a suspected particle position. This yields a refined transverse and depth localization in the volume. Positions detected with the proposed algorithm are passed to a particle tracking algorithm written by [Blair] following the algorithm developed by [Crocker]. The generated particle trajectories are fitted with polynomials in order to further reduce reconstruction errors by using several reconstructed positions for one trajectory.

The impact of transverse particle positions on the complex light patterns reconstructed from the respective hologram will be illustrated numerically and experimentally, and the achieved improvements of particle localization by means of the novel algorithm will be explained.