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Three-dimensional instantaneous velocity field measurement using digital holography microscope

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Abstract. In the present study, a digital holography microscope has been developed to study instantaneous 3D velocity field in a square channel of $1000 \times 1000\ \mu m^2$ cross-section. The flow field is seeded with polystyrene microspheres of size $d_p = 2.1\ \mu m$. The volumetric flow rate is set equal to $20\ \mu l/min$. The instantaneous 3D velocity field is obtained by correlating the particles obtained from the 3D numerical reconstruction of holograms using particle tracking velocimetry (PTV).

Keywords. Holography; velocity measurements; laminar flow in microchannel.

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1. Introduction

Digital holography is a nonintrusive optical technique having immense potential for 3D flow field measurements. The 3D velocity field can be determined from the location of seeding particles at different time instants. A sequence of holograms of tracer particles is acquired using digital sensors in real time with the flow by using laser pulses of short durations. Each hologram is subsequently reconstructed over several transverse planes to determine the location of the particles in 3D volume, which are ‘frozen’ during recording at different time instants. The time evolution of the particle field is subsequently used to calculate the velocity field information.

Murata and Yasuda [1] have examined the potential of digital holography for particle field measurement and reported the error in particle location and size using intensity field information. Malek *et al* [2] reported the influence of particle density, size of measurement volume and size of particles on reconstruction effectiveness using intensity-based reconstruction approach. A novel approach has been proposed by Singh and Panigrahi [3] for accurate determination of size and depth location of particle field using real-amplitude (i.e. intensity) distribution in the reconstruction volume. This approach alleviates the problem of out-of-focus particles and there is no restriction on the size of the object particles. Singh and Panigrahi [4] reported a technique that provides threshold value automatically, which is based on signal-to-noise ratio (SNR) of reconstructed particle field to segment particles from the background. Satake *et al* [5] developed digital holography microscope (DHM) to measure instantaneous velocity field in a micropipe. Ooms *et al* [6] applied DHM for measuring a flow in a T-shaped micromixer. In the present study, DHM has been developed to study instantaneous 3D velocity field in a square channel of $1000 \times 1000\ \mu\text{m}^2$ cross-section. The flow field is seeded with polystyrene microspheres of size $d_\text{p} = 2.1\ \mu$m and volumetric flow rate $Q = 20\ \mu$l/min. The instantaneous 3D velocity field is obtained by correlating the particles obtained from the 3D numerical reconstruction of holograms using particle tracking velocimetry (PTV). In the present study, 50 holograms have been generated from the flow. The time interval between two consecutive holograms is $\Delta t = 100$ ms.

The particle field is illuminated by parallel plane monochromatic light r during in-line holographic measurement. The part of the incident light that is obstructed by particles is diffracted and forms an object wave at the recording plane and unobstructed part of the light serves as a reference wave. These object and reference waves interfere and the resulting interference pattern (hologram) is recorded on the digital recording media

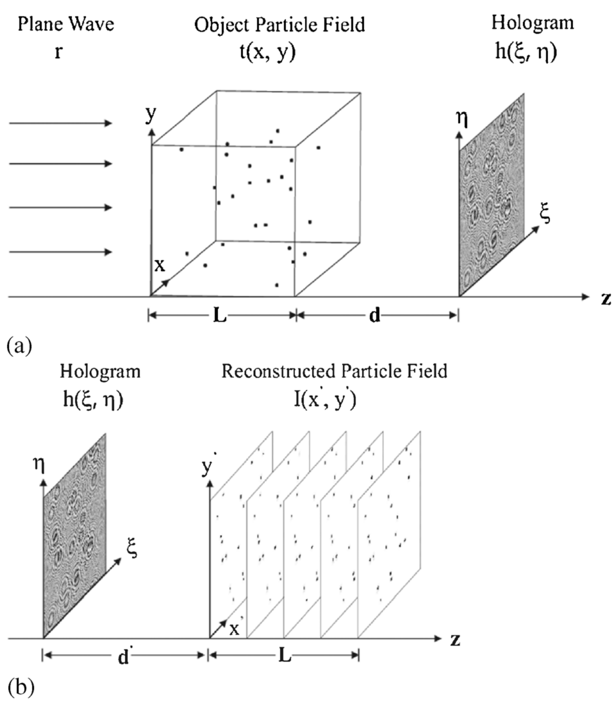

Figure 1. Schematic of recording and reconstruction of particle field [3]: (**a**) hologram generation of 3D particle field using plane-wave illumination and (**b**) planewise 3D numerical reconstruction of particle field from digital hologram of (**a**).

(CCD chip). Figure 1a shows the hologram recording of a three-dimensional particle field. The recorded hologram is stored in a computer and a 3D image of the object field is generated by 3D numerical reconstruction (i.e. reconstruction is carried out on many transverse planes) of the hologram (see figure 1b). The complex amplitude of real image in the (x', y') plane at a distance d' from the hologram plane is determined by using Fresnel–Kirchhoff's formulation [7,8] as follows:

$$E\left(x', y'\right) = \frac{\exp\left(ikd'\right)}{i\lambda d'} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} h(\xi, \eta) \times \exp\left\{ i\frac{k}{2d'}[(x'-\xi)^2 + (y'-\eta)^2)] \right\} \mathrm{d}\xi \mathrm{d}\eta, \quad (1)$$

where $h(\xi, \eta)$ is the intensity distribution of the hologram in the recording plane (ξ, η), λ is the wavelength of the laser light and k is the wave number. For sharp focussed image, $d' = d$, where d is the distance of the particle from the recording plane. The complex amplitude of the real image wave has been determined using convolution approach [7]. The intensity distribution of the reconstructed real image of the particle field can be obtained as follows:

$$I\left(x', y'\right) = \left|E\left(x', y'\right)\right|^2. \quad (2)$$

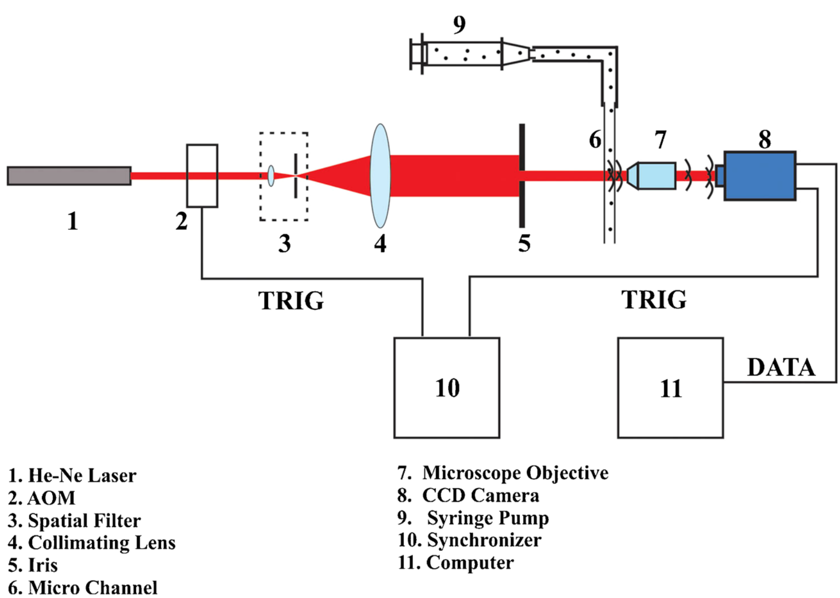

Figure 2. Schematic of the experimental set-up of digital in-line holography microscope (DHM) for 3D instantaneous velocity field measurements in microchannels.

2. Results and discussions

Figure 2 shows the schematic of the experimental set-up of digital in-line holography microscope (DHM) for 3D instantaneous velocity field measurements in microchannels. The continuous light from He–Ne laser source is converted into pulses using acousto-optic modulator (AOM). This light is then passed through a spatial filter and collimating lens to obtain clean and collimated laser light of 25 mm diameter. The spatial size of the collimated light is reduced according to the aperture size of the microscope objective (MO) by using an iris. Thus, the flow is illuminated by spatially controlled laser pulses. The microinterference structures (hologram) that are generated by the light scattered by tracer particles and unobstructed laser light at the focal plane of the microscope objective are imaged at CCD sensor. A sequence of holograms is captured and transferred to a computer for 3D numerical reconstruction to obtain the locations of tracer particles in 3D volume, which were ‘frozen’ during recording at different time instants. AOM and CCD camera are synchronized using a synchronizer.

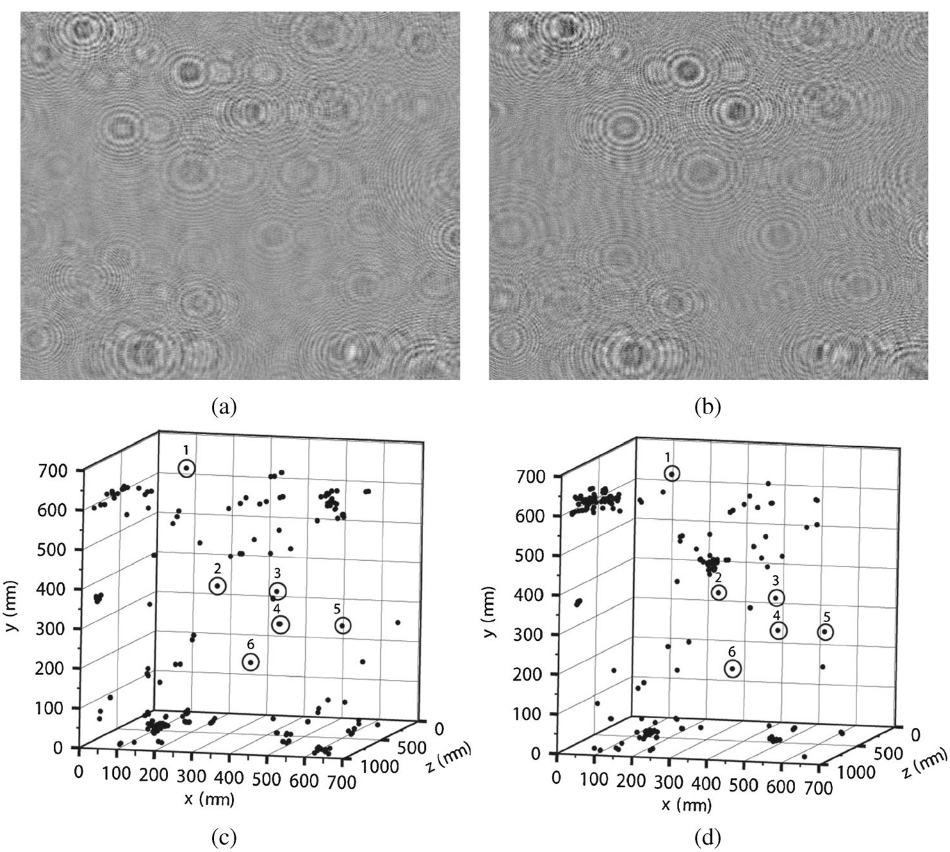

Figure 3. Holograms generated from tracer particles at time $t = 0$ and $t = 100$ ms are shown in (**a**) and (**b**), respectively. The 3D distribution of particles shown in (**c**) and (**d**) are reconstructed from holograms (**a**) and (**b**), respectively.

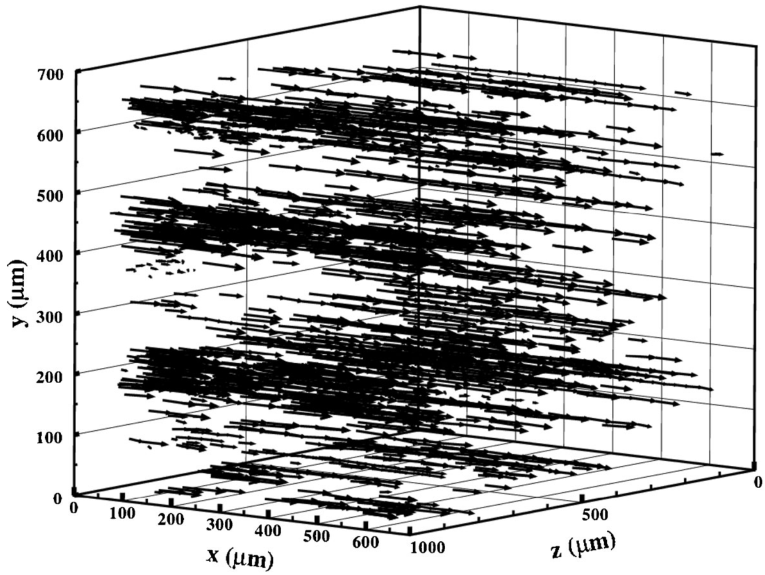

Figure 4. The instantaneous 3D vector field is shown. The total number of vectors are 2428, which have been obtained from the reconstruction of 50 holograms, which were captured at time interval $\Delta t = 100$ ms.

In the present study, the measurement of velocity field is carried out in a microchannel of square cross-section of size $1000 \times 1000\ \mu\text{m}^2$. The flow medium is water, which is seeded with polystyrene particles of size, $d_{\text{p}} = 2.1\ \mu$m. The constant pressure-driven flow is maintained using a syringe pump. The volumetric flow rate $Q = 20\ \mu$l/min. The flow is illuminated by a laser pulse of duration $\Delta t = 100$ ms, where illumination and delay time are 50 ms each. The magnification of MO is 10×. The sensor size is 1024×1024 pixels [2], where the size of each pixel is $6.45 \times 6.45\ \mu\text{m}^2$. Thus, the lateral size of the sensor is $6.6 \times 6.6\ \text{mm}^2$. Therefore, the field of view of the flow field at the MO's focal plane is $0.66 \times 0.66\ \text{mm}^2$. The size of measurement domain is $0.66(X) \times 0.66(Y) \times 1.0(Z)\ \text{mm}^3$.

Figure 3 shows the holograms and reconstructed particle field at two different time instances. The holograms generated at time $t = 0$ and $t = 100$ ms are shown in figures 3a and 3b, respectively. The 3D distribution of particles reconstructed separately from holograms 3a and 3b are shown in figures 3c and 3d, respectively. In figures 3c and 3d, the displacement of a few particles in the time interval of $\Delta t = 100$ ms is highlighted by circles. It is also clear from these figures that the few particles present in figure 3c are absent in figure 3d, and vice versa. The particles that are present in both distributions of figures 3c and 3d are correlated using PTV based on velocity gradient tensor (VGT). Figure 4 shows the instantaneous 3D vector field obtained from the reconstruction of 50 holograms. The time interval between two consecutive holograms is $\Delta t = 100$ ms. A total of 2428 vectors are obtained using PTV.

The present study reports successful implementation of the 3D velocimetry technique using DHM. The developed technique is being evaluated for characterization of flow field, i.e., corner vortex and interfacial motion in MEMS.

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