Direct Measurement of Three-Dimensional Velocity by a Doppler-Phase-Shifting Holography

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In order to understand the details of the flow field in the micro- and nano-fluidic devices, it is necessary to measure the three-dimensional velocity under a microscope. One solution is the use of holography, but it has been known that the resolution in the depth direction is very poor for the commonly used in-line holography. Presently, the Doppler-phase-shifting holography has been used for the three-dimensional measurement of an object. This method extracts the signal of a fixed frequency caused by the Doppler howling between the object light and the reference light. The frequency of the howling is determined by the velocity difference between the object light and the reference light. This implies that the velocity of an object can be measured by its frequency. In this study, a 5 yen coin has been traversed at arbitrary angles and its shapes and its three-dimensional velocities have been measured accurately. Digital holography observes the interference of the observed light scattered at the surface of an object and the reference light. Then, the three-dimensional shape of an object can be reproduced by calculating the diffraction in the computer. But, in the commonly used in-line holography, the diffraction is contaminated by the 0-order object light and the accuracy in the depth direction is deteriorated. In order to improve this drawback, several phase shifting methods have been proposed, which can calculate only the 1-order diffraction and thus the longitudinal accuracy is guaranteed. Presently, Doppler-phase-shifting holography is chosen. Figure 1 shows the experimental setup. The complex intensities of the object light and of the reference light are expressed as follows:

\[ E_o(x, y, t) = a_0(x, y) \exp \left( i \phi_0(x, y) - \omega_o(\tau t) \right) \]

(1)

\[ E_R(x, y, t) = a_\varphi \exp \left( i \phi_\varphi(x, y) \right) \]

(2)

where \( a \) is the amplitude, \( \phi \) is the phase angle and \( \omega \) is the angular velocity. \( \phi_0(x, y) \) and \( \phi_\varphi(x, y) \) denote the phases of the object light \( O \) and of the reference light \( R \). If the object travels at velocity \( v_o \) and the reference mirror travels at \( v_\varphi \), the angular velocities are shifted by the Doppler effect of light as follows:

\[ \omega_{o, \varphi}(\tau t) = \omega_o \frac{1 + 2v_{o, \varphi}(\tau t)/c}{1 - 2v_{o, \varphi}(\tau t)/c} \]

(3,4)

where \( \omega_o \) is the angular frequency of the light source and \( c \) is the speed of light. Consequently, the superposition intensity of the holograms detected by the image sensor contains the +1-order diffraction spectrum of a fixed frequency at \( \omega_o - \omega_{o, \varphi} \), which is free from the effect of the 0-order diffraction. Thus, the accurate reconstruction of an object can be achieved by extracting only the signal at \( \omega_o - \omega_{o, \varphi} \), which is caused by the Doppler howling. Originally, the Doppler-phase-shifting is invented to measure the shape. But, as the frequency of the Doppler howling is proportional to the velocity difference between the object light and the reference light, the longitudinal velocity of an object can be measured by this beat frequency. A concave mirror of the radius of curvature is \( R = 30 \) m is traversed at \( v_o = 100 \) µm/s. The interference images are recorded by a high-speed camera whose resolution is 1024x1024 and its frame rate is 2000fps. Figures 2 shows the time series intensity fluctuation of the central pixel and its spectrum. It is obvious that the peaks of Doppler howling is seen and its frequency is \( \pm 386.7 \) Hz, which corresponds to \( v_o = 99.4 \) µm/s. While the surface profile of the concave mirror is also reproduced with the rms error of 3.27 nm.

Fig. 1 Setup for Doppler phase-shifting digital holography

Fig. 2 Time series intensity of a pixel and its spectrum

The actual measurement of the three-dimensional velocity is done for the 5 yen coin. The angle of the moving stage is set at \( \theta = 76^\circ \) and it travels at \( v_o = 413.4 \) µm/s, which corresponds to \( v_{o, \varphi} = 100.0 \) µm/s. Figures 3 show the reconstructed images of the 5 yen coin at two different timing. The velocity vectors are obtained by PIV algorithm. By the combination of the longitudinal velocity measurement by the Doppler frequency, three-dimensional velocity measurement of an object has been achieved.

Fig. 3 Displacement of 5-yen coin measured by PIV

Presently, a new three-dimensional velocity measuring technique based on a Doppler-phase-shifting holography has been developed. It can measure the three-dimensional velocity of an object very accurately by the single camera observation. This method can be adapted to the micro- and nano-flows and the three-dimensional particle velocities can be measured simultaneously.

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