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3D velocity measurement by a single camera using Doppler phase-shifting holography

Nao Ninomiya, Yamato Kubo, Daisuke Barada and Tomohiro Kiire

Department of Optical Engineering, Utsunomiya University, 7-1-2 Yoto, Utsunomiya 321-8585, Japan

E-mail: nino@utmu.jp

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Abstract

In order to understand the details of the flow field in micro- and nano-fluidic devices, it is necessary to measure the 3D velocities under a microscopy. Thus, there is a strong need for the development of a new measuring technique for 3D velocity by a single camera. One solution is the use of holography, but it is well known that the accuracy in the depth direction is very poor for the commonly used in-line holography. At present, the Doppler phase-shifting holography is used for the 3D measurement of an object. This method extracts the signal of a fixed frequency caused by the Doppler beat between the object light and the reference light. It can measure the 3D shape precisely. Here, the frequency of the Doppler beat is determined by the velocity difference between the object light and the reference light. This implies that the velocity of an object can be calculated by the Doppler frequency. In this study, a Japanese 5 yen coin was traversed at a constant speed and its holography has been observed by a high-speed camera. By extracting only the first order diffraction signal at the Doppler frequency, a precise measurement of the shape and the position of a 5 yen coin has been achieved. At the same time, the longitudinal velocity of a 5 yen coin can be measured by the Doppler frequency. Furthermore, the lateral velocities are obtained by particle image velocimetry (PIV) method. A 5 yen coin has been traversed at different angles and its shapes and the 3D velocities have been measured accurately. This method can be applied to the particle flows in the micro- or nano-devices, and the 3D velocities will be measured under microscopes.

Keywords: digital holography, 3D measurement, Doppler phase-shifting, velocity measurement

(Some figures may appear in colour only in the online journal)

1. Introduction

According to the development of computer and imaging devices, the new measuring techniques based on flow visualization have been developed and utilized in many different fields. The typical examples are so-called PIV, i.e. particle image velocimetry [1, 2], and PTV, i.e. particle tracking velocimetry [3]. The principal setup of PIV utilizes one high-resolution camera and a laser light sheet, which illuminates the tracer particles suspended in the fluid flow. By calculating the displacement of particles, the 2D distribution of the 2D velocities can be obtained. By implementing multiple cameras and the careful calibration of the 3D coordinates, 2D distribution of all the three velocity components can be measured by Stereo PIV [4] and the 3D measurement of the 3D velocities can also be achieved by so-called Tomographic PIV [5].

In order to understand the details of the flow field in the micro- and nano-fluidic devices, it is necessary to measure the 3D velocities under a microscope. The use of confocal PIV [6, 7] is a challenge, but it is not capable of depth-wise tracking and is very expensive. Thus, the development of a new measuring technique for the 3D velocities by a single camera observation is strongly needed. One solution is the use of holography [8]. The principle of the holography was

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invented in the 1960s [9, 10] and the digital reconstruction of the hologram [11, 12] together with the use of CCD camera [13] has made digital holography [14] possible. PIV was originally invented as a film-based technique [15] and then integrated to a digital method [16]. At the same time, it is well known that the accuracy in the depth direction is very poor for the commonly used in-line holography because of the contamination by the zero order beam. In order to overcome this shortcoming, the use of two sets of orthogonal holography [17] has been proposed, but it cannot be applied to the measurement under microscopy. Recently, several new methods to shorten the depth-of-focus have been invented [18–21]. On the other hand, many kinds of the phase-shifting [22] are the hope to accurately calculate the particle position. Yet, the spatial phase-shifting needs 3 or 4 cameras whose CCD pixels are carefully aligned. Otherwise, 2 × 2 phase shifting array device [23] or tilting technique [24] has to be used even though these method sacrifices spatial resolution. Whereas the temporal phase-shifting cannot be applied to the moving objects. As for the holographic measurement under microscopy, many studies have been conducted [22, 25] and the PIV measurements have also been done extensively [26–28]. But, it is not easy to apply the phase-shifting to the microscopic PIV. Notwithstanding, the time tracing algorithm for the densely distributed moving particles does not have great progress from the time-consuming cross correlation method [29] or the traditional PTV algorithm [30, 31].

Presently, the Doppler phase-shifting holography [32] is used for the 3D velocity measurement of an object. This method extracts the signal of a fixed frequency caused by the Doppler beat between the object light and the reference light. The frequency of the beat is determined by the velocity difference between the object light and the reference light. This implies that the velocity of an object can be calculated by the Doppler frequency. In this study, the shapes and its 3D velocities have been measured accurately for a moving Japanese 5 yen coin at different angles.

2. Fundamental techniques

Digital holography observes the interference of the reference light and the observed light scattered on the surface of an object. Then, the 3D shape of an object can be reproduced by calculating the diffraction by a computer. But, in the commonly used in-line holography, the diffraction is contaminated by the 0th 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 1st order diffraction and thus the accuracy in the longitudinal direction is guaranteed. Presently, Doppler phase-shifting holography is chosen because it is capable of unsteady measurement and does not need multiple cameras. Figure 1 shows the experimental setup of a Doppler phase-shifting holography.

The complex intensities of the object light and of the reference light are expressed as follows:

$$E_{\mathrm{O}}(x,y,t) = a_{\mathrm{O}}(x,y)\exp\{\mathrm{i}[\phi_{\mathrm{O}}(x,y) - \omega_{\mathrm{O}}(t)t]\ \} \qquad (1)$$

$$E_{\mathrm{R}}(t) = a_{\mathrm{R}}\exp\{\mathrm{i}[\phi_{\mathrm{R}} - \omega_{\mathrm{R}}(t)t]\} \qquad (2)$$

where a_{O} and a_{R} represent the amplitudes, ϕ_{O} and ϕ_{R} are the phase angles and ω_{O} and ω_{R} are the angular velocities of the object light and the reference light. If the object travels at velocity υ_{O} and the reference mirror at υ_{R}, the angular velocities are shifted by the Doppler effect of light as follows:

$$\omega_{\mathrm{O}}(t) = \omega_0\left(\sqrt{\frac{1+\upsilon_{\mathrm{O}}(t)/c}{1-\upsilon_{\mathrm{O}}(t)/c}}\right)^2 \cong \omega_0\left(1+\frac{2\upsilon_{\mathrm{O}}(t)}{c}\right) \qquad (3)$$

$$\omega_{\mathrm{R}}(t) = \omega_0\left(\sqrt{\frac{1+\upsilon_{\mathrm{R}}(t)/c}{1-\upsilon_{\mathrm{R}}(t)/c}}\right)^2 \cong \omega_0\left(1+\frac{2\upsilon_{\mathrm{R}}(t)}{c}\right) \qquad (4)$$

where ω_0 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 is expressed as follows:

$$\begin{aligned} I(x,y,t) &= |E_{\mathrm{O}}(x,y,t) + E_{\mathrm{R}}(t)|^2 \\ &= a_{\mathrm{O}}^2(x,y) + a_{\mathrm{R}}^2 + 2a_{\mathrm{O}}(x,y)a_{\mathrm{R}}\cos[\Delta\phi(x,y) - \Delta\omega(t)t] \end{aligned} \qquad (5)$$

here,

$$\begin{aligned} \Delta\phi(x,y) &= \phi_{\mathrm{O}}(x,y,t) - \phi_{\mathrm{R}} \\ \Delta\omega(t) &= \omega_{\mathrm{O}}(t) - \omega_{\mathrm{R}}(t) \end{aligned} \qquad (6)$$

The Fourier transformation of equation (5) in the time domain is

$$\begin{aligned} \mathcal{F}_t(I)(x,y,\omega_b) &= [a_{\mathrm{O}}^2(x,y) + a_{\mathrm{R}}^2]\delta(\omega_b) \\ &= a_{\mathrm{O}}(x,y)a_{\mathrm{R}}A_1(\omega_b)\exp\{\mathrm{i}[\Delta\phi(x,y) + B_1(\omega_b)]\} \\ &+ a_{\mathrm{O}}(x,y)a_{\mathrm{R}}A_2(\omega_b)\exp\{-\mathrm{i}[\Delta\phi(x,y) + B_2(\omega_b)]\} \end{aligned} \qquad (7)$$

If the angular frequency of the object light is higher than that of the reference light, the +1st order diffraction is obtained in the second term. If the spectrum of each term can be split, the phase difference $\Delta\phi(x, y)$ between the object light and the reference light is easily obtained.

The discrete Fourier transformation of the image recorded by the image sensor of the finite size is obtained as:

$$\begin{aligned} &\mathrm{DFT}[I](x,y,\nu_{b,m}) \\ &= \sum_{n=0}^{N-1} I(x,y,t_n)\exp(-\mathrm{i}2\pi t_n\nu_{b,m}) \quad m = 0,1,2,\ldots,N-1 \end{aligned} \qquad (8)$$

If the +1st order diffraction spectrum of a fixed frequency is extracted from equation (8), the complex amplitude of an object can be calculated very accurately.

3. 3D velocity measurement

Originally, the Doppler phase-shifting was invented to measure the object profile accurately [32]. Yet, as the beat frequency of the Doppler beat is proportional to the velocity difference between the object light and the reference light, the longitudinal velocity of an object can be measured by the beat frequency of the Doppler beat. In order to prove this, Ninomiya *et al* [33] measured the longitudinal velocity of a concave mirror travelling at a constant speed by a Doppler phase-shifting holography.

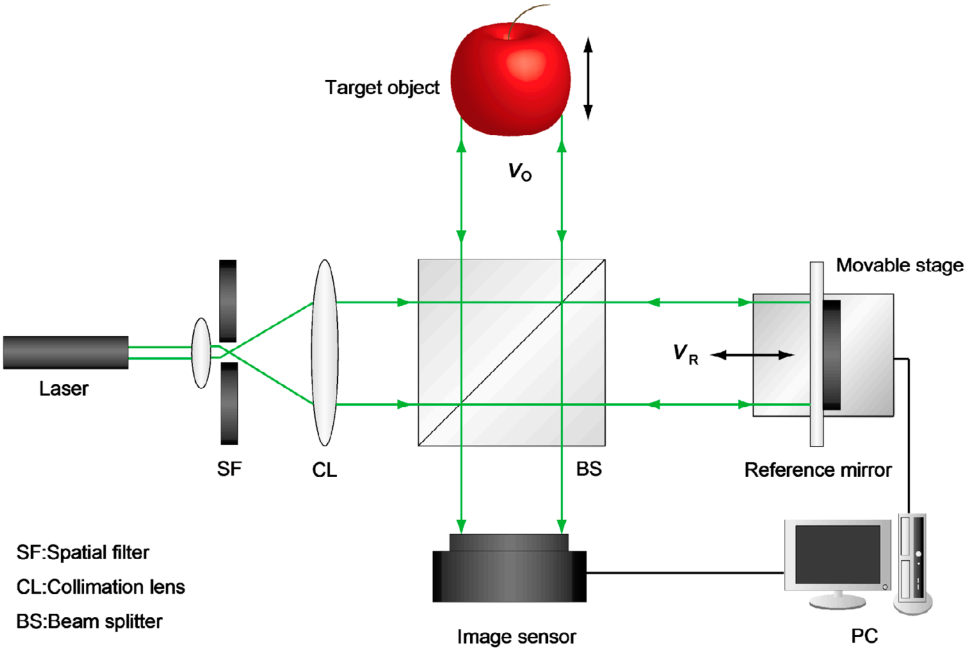


Figure 1. Experimental setup for Doppler phase-shifting digital holography.

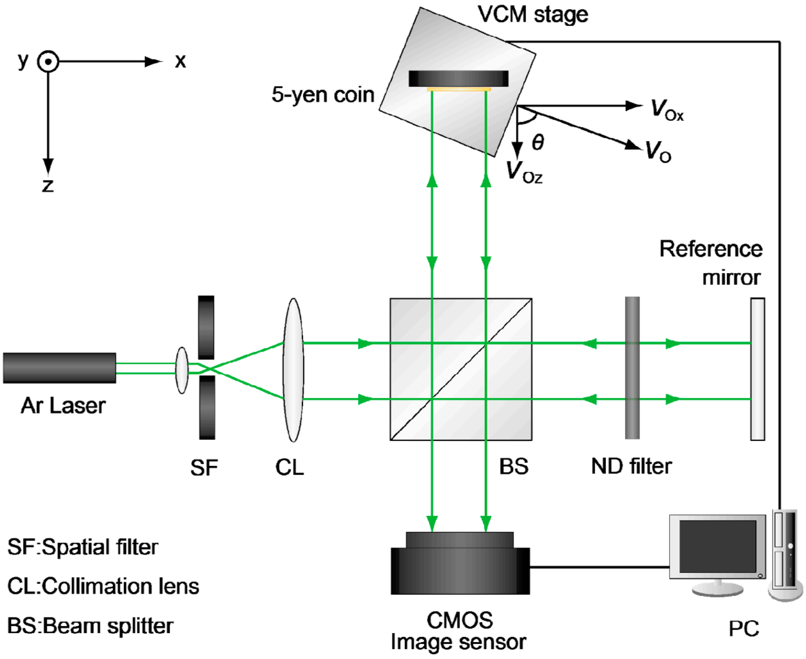


Figure 2. Experimental setup for velocity measurement.

An Ar-ion laser of 514 nm is used as the light source, which is introduced to a pinhole and expanded by the spatial filter of $f = 5$ mm and then made parallel by a collimator lens of $f = 100$ mm. A concave mirror of the radius of curvature $R = 30$ m is used as a target object in figure 1 and traversed at $v_O = 100\ \mu\text{m s}^{-1}$ by the voice coil motor. The images of interference patterns are captured on a high-speed camera of 1024×1024 pixels at frame rate of 2000 fps and shutter speed of 1/70 000 s. The size of each pixel is $10 \times 10\ \mu$m. The time series of intensity fluctuations of the central pixel of 512 consecutive images are transformed into Fourier domain through DFT to obtain its spectrum. It should be noted that as any part of the concave mirror is travelling at the same speed, choice of any pixel may give the similar spectrum. A clear peak of the Doppler beat is found at 386.7 Hz, which corresponds to $v_O = 99.4\ \mu\text{m s}^{-1}$ with the error of 0.6% to the given longitudinal velocity [33]. Thus, it has been proved that a Doppler phase-shifting holography can be used for the measurement of the longitudinal velocity. Moreover, the surface profile of the concave mirror was reproduced from the phase data of the digital holography and the rms error to the $R = 30$ mm profile is only 3.27 nm [33]. This is the evidence that Doppler phase-shifting technique is capable of measuring the 3D position and the longitudinal velocity simultaneously.

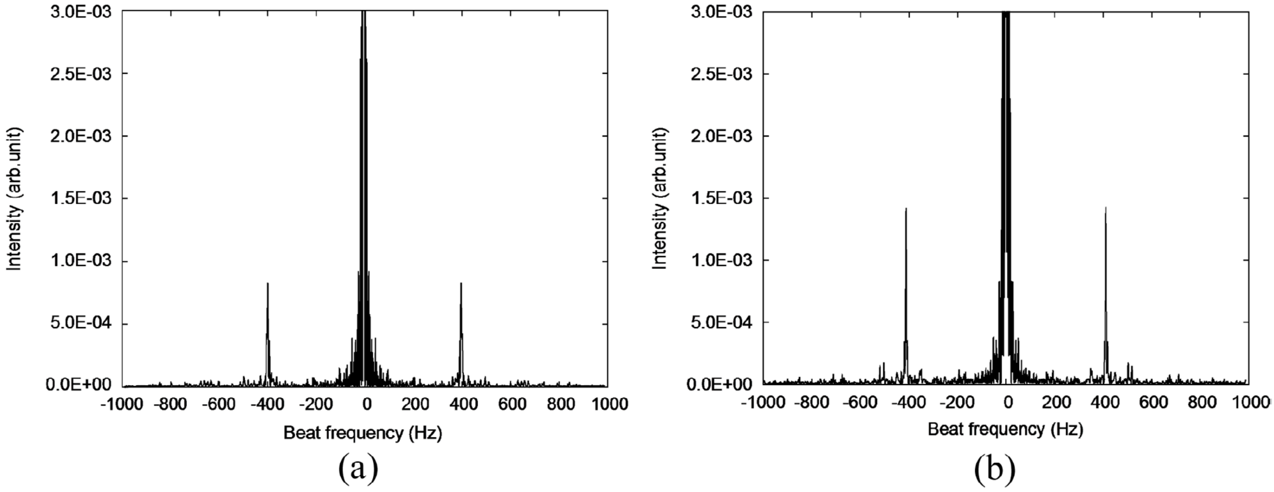
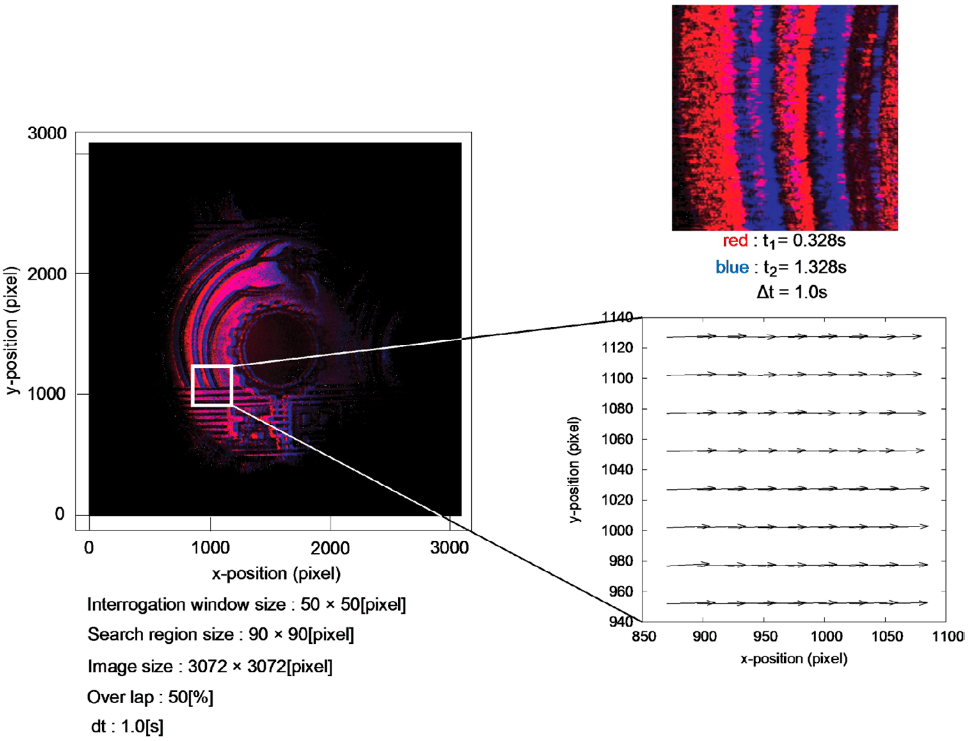


Figure 3. Beat frequency spectrum obtained from 512 images. (a) 400–911 frame. (b) 2400–2911 frame.



Interrogation window size : 50 × 50[pixel]
Search region size : 90 × 90[pixel]
Image size : 3072 × 3072[pixel]
Over lap : 50[%]
dt : 1.0[s]

Figure 4. Displacement of Japanese 5 yen coin measured by 2D PIV. (Left: superimposed image of two sets together with PIV settings, right top: magnified image, right bottom: measured velocity vectors.)

As the fundamental measurement technique has been proved to work in the previous study [33], the actual measurement of the 3D velocity is carried out by the experimental setup shown in figure 2. The Japanese 5 yen coin, whose diameter is about 22 mm, is used as a target object and is traversed at a constant speed at a specific angle. As the reflection from the 5 yen coin is weaker than the reference light, the 70% ND filter is placed in front of the reference mirror in order to match the light intensities.

The images are recorded by a high-speed camera of 1024×1024 pixels at frame rate of 2000 fps. The angle of the moving stage is set at $\theta = 76$ degree and it travels at $v_{\mathrm{O}} = 413.4\ \mu\mathrm{m\ s^{-1}}$, which corresponds to $v_{\mathrm{O}z} = 100.0\ \mu\mathrm{m\ s^{-1}}$ and $v_{\mathrm{O}x} = 400.0\ \mu\mathrm{m\ s^{-1}}$. Figure 3 shows the measured spectrum obtained from 512 frames at two different timings of the traverse. In order to obtain the beat frequency, the time series of intensity fluctuation is needed. Presently, the time trace of the central pixel intensity for 512 frames is used. Moreover, for the later PIV measurement, two sets of 512 frames, i.e. 400–911 frames and 2400–2911 frames, are used whose time interval between sets is 1.000 s. Both of them have strong peaks at (a) 396.2 Hz and (b) 399.7 Hz, which correspond to the longitudinal velocities of (a) $v_{\mathrm{O}z} = 101.8\ \mu\mathrm{m\ s^{-1}}$ and (b) $v_{\mathrm{O}z} = 102.7\ \mu\mathrm{m\ s^{-1}}$ by equation (3), and both agree well

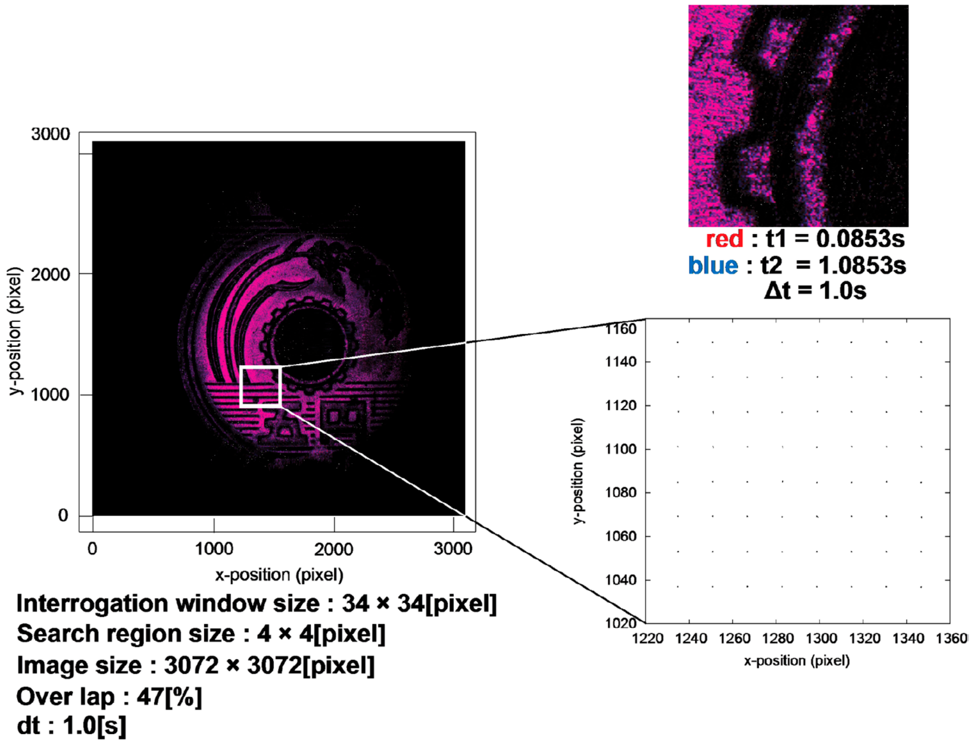


Figure 5. Displacement of Japanese 5 yen coin measured by 2D PIV with shifted images. (Left: superimposed image of two sets together with PIV settings, right top: magnified image, right bottom: measured velocity vectors.)

with the given velocity. It should be noted that the choice of a pixel and a starting frame for the spectrum extraction affect the beat frequency only slightly.

By integrating over these 512 frames, an interference image that contains only the frequency component of this Doppler beat frequency can be extracted. By using this interference image, which is free from the zero order beam, an accurate reconstruction of an object can be done. Figure 4 shows the reconstructed images of the 5 yen coin at two different timings. The reconstruction is done manually by searching the appropriate depth position where the rms intensity takes its maximum. The former image is colored by red and the latter by blue. It is obvious that the 5 yen coin travels in the x direction and its movement is calculated by the correlation method commonly used in the PIV algorithm. The expanded plot of the velocity vectors shows the transverse movement at a fixed speed. By the combination of the longitudinal velocity measurement by the Doppler frequency and the transverse velocity measurement by PIV method, 3D velocity measurement of an object by a single camera has be achieved.

But as the 5 yen coin is also moving in the transverse direction, the time series intensity used to obtain the spectrum shown in figure 3 is not an exact trace of the light emitted from a certain point of the 5 yen coin. Nevertheless, as the transverse movement of the 5 yen coin has been measured by PIV as shown in figure 4, the temporal movement of a fixed point can be interpolated from the results obtained in figure 4. Presently, each frame of the original interference image is shifted back by equation (9) so that it looks as though there is no transverse movement in order to trace the exact time series of the light emitted from a fixed point of the 5 yen coin.

Table 1. Velocities of Japanese 5 yen coin (76 degree).

	v_{Oz}	v_{Ox}
Stage velocity (μm s^{-1})	100.0	400.0
Measured velocity (μm s^{-1})	100.7	401.2

$$f(x-x_0,y-y_0)=\frac{1}{N_xN_y}\sum_{k=0}^{N_x-1}\sum_{l=0}^{N_y-1}F(k,l) \times\exp\left[2\pi i\left(\frac{kx}{N_x}+\frac{ly}{N_y}\right)\right]\cdot\exp\left[2\pi i\left(\frac{kx_0}{N_x}+\frac{ly_0}{N_y}\right)\right] \qquad (9)$$

Then the beat frequencies obtained from the spectrum of the shifted images are (a) 391.2 Hz and (b) 392.6 Hz, which correspond to the longitudinal velocity of (a) $v_{Oz}=100.5\ \mu\text{m s}^{-1}$ and (b) $v_{Oz}=100.9\ \mu\text{m s}^{-1}$. It is quite obvious that the image shifting improves the measurement accuracy of the longitudinal velocity. Figure 5 shows the reproduced images of the 5 yen coin with the image shifting. It can clearly be seen that the shape of the 5 yen coin is more obvious with the use of the shifted images and it is quite a matter of course but the transverse movements are hardly seen in figure 5, which is an evidence that the image shifting has been done properly.

Table 1 summarizes the result of the 3D velocity measurement by a Doppler phase-shifting holography. The voice coil motor used for the moving stage has a positioning accuracy of 0.05 μm and the nominal velocity fluctuation is less than 1%, which has been proved by a high-speed camera to be much smaller. The vertical velocity is almost zero as the traversing stage moves in the horizontal direction. Now it can

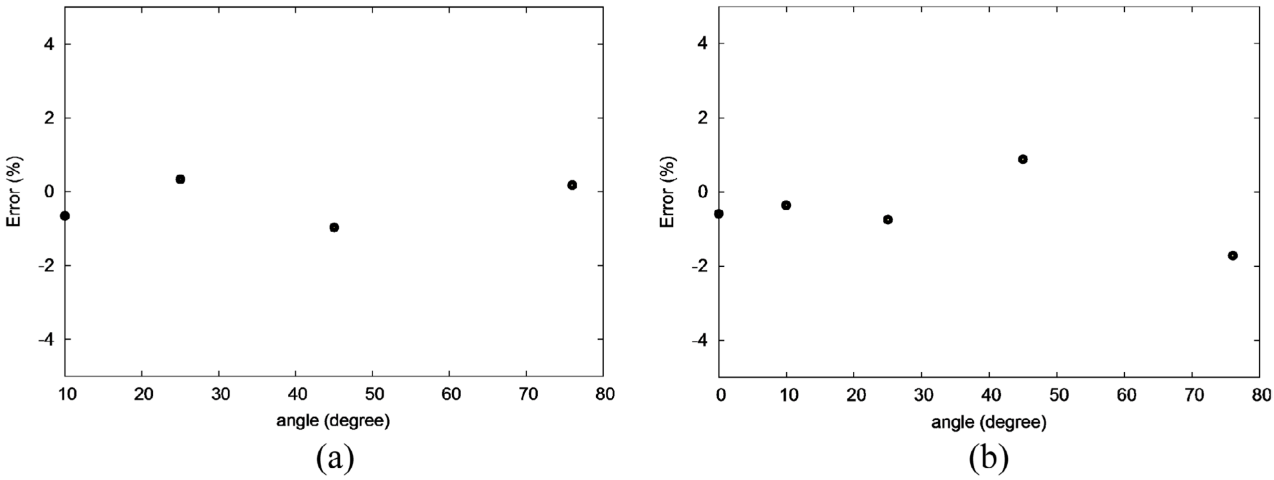


Figure 6. Errors in the velocity measurement in transverse and longitudinal directions. (a) υ_{Ox}. (b) υ_{Oz}.

be concluded that this technique is capable of 3D velocity measurement.

Finally, similar measurements have been repeated with different angles of the traverse. The results are shown in figure 6 and it is quite obvious that this technique is valid for different angles of the traverse with the error less than 2%.

4. Conclusions

This paper presents a newly developed 3D velocity measuring technique based on a Doppler phase-shifting holography. It can measure the 3D velocity of an object by the single camera observation very accurately with the error less than 2% for any angle of traverse.

This method envisions its application to particle motion detection in the micro- or nano-devices and thus the 3D particle velocities can be measured simultaneously by a single camera. As this method does not need the depth-wise tracking, it can easily be coupled with conventional 2D PIV. Nevertheless, the application of this technique to the particle flows, the limit of particle seeding density and the depth of field that this method can be applied remain to be proved by a future study. But, it will contribute to the development of micro- and nano-fluidic devices.

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