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Development of Two-Color Digital Holographic PTV for Dispersed Two-Phase Flow

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Abstract. Bubbly flows have been widely used in various industrial fields such as the drag reduction of ships and the purification of water. It is expected to investigate the three-dimensional mechanism of the two-phases flows which involve bubbles with various sizes. Digital holographic particle tracking velocimetry (DHPTV) is an effectual tool for making the flow structure clear, because DHPTV enables to measure instantaneous three-dimensional time series velocity fields of bubbles without complicated optical systems. In a holographic image, microbubbles are recorded as fringe patterns and a millibubble is recorded as a shadow image. The objective of the present study is to establish the measuring method for the velocity of bubbles with micro- and milli-meter sizes by using two laser beams. Finally, the method was realized by combining stereo holographic technique and stereo shadow imaging technique. A millibubble was measured by stereo shadow imaging technique and microbubbles were measured by stereo holographic technique.

1. INTRODUCTION

Bubbly flows are used in various industrial fields such as the frictional drag reduction for ships (Kitagawa et al., 2005) and the purification of water. For the enhancement of the transport efficiency and the improvement of the industrial water treatment, the mechanism of the bubbly flows which contain bubbles with various sizes should be investigated. Recently, several researchers have developed measurement systems and examined the structures of bubbly flows. Murai et al. (2000) showed that the energy spectrum of liquid phase has a strong relation to the bubble-bubble interval distance by measuring the motions of both liquid phase and rising bubbles with particle tracking velocimetry (PTV). Lindken and Merzkirch (2002) examined the turbulence modification in the liquid phase with bubbles by utilizing digital particle imaging velocimetry (DPIV) system, laser induced fluorescence (LIF) and shadowgraphy. Kitagawa et al. (2005) revealed the effect of bubble deformation on the turbulence modification around microbubbles by utilizing PTV and shadow image technique (SIT). Their efforts have contributed to clarify the mechanism of the bubbly flows. In actual, bubbly flows have three-dimensional structures. The present study focuses on experimental measurement of instantaneous three-dimensional velocity of bubbles.

There are several measuring techniques for three-dimensional velocity fields such as scanning PTV, computed tomography (CT) or DHPTV. Among these systems, DHPTV is an effectual tool for making the bubbly flow structures clear, because DHPTV enables to detect the velocity of bubbles without complicated optical systems, compared with scanning PTV or computed tomography (CT).
The objective of the present study is to establish the measuring method for the velocity of bubbles with micro- and milli-meter sizes. In a recording plane for hologram, microbubbles are recorded as fringe patterns which have three-dimensional information of positions of them and millibubbles are recorded as two-dimensional shadow images. In order to analyze fringe patterns and shadow images in the same system, the method is proposed by combining holographic technique and stereo shadow imaging technique with two laser beams.

2. Experimental procedure

2.1 Principle of holography

The digital holographic technique consists of digital recording and numerical reconstruction procedures. In the recording process, an objective beam and a reference beam are interfered. The objective beam is formed by reflecting, scattering and diffracting from the test volume and the reference beam have the constant phase profile. Images of fringe patterns are obtained in the recording plate as shown in Fig. 1(a). The images are known as holograms which have information of the intensity and phase of light in three-dimensional whole field. The holograms are numerically reconstructed by utilizing fresnel diffraction theory. In numerical simulation, the reconstructed wavefront \( g(X, Y, Z) \) in a certain plane at a distance \( Z \) from the recording plane is obtained by using the Fresnel Kirchhoff equation defined as eq. (1).

\[
g(X, Y, Z) = \frac{-i}{
\lambda Z} \int \int \frac{f(X', Y')}{Z} e^{\frac{2\pi i}{\lambda}(X' X + Y' Y) - i \pi} dx dy
\]

where \((X', Y')\) denote the pixel coordinates in the recording plane, \((X, Y)\) denote the pixel coordinates in the reconstructed plane, \(Z\) is the optical distance from the CCD recording plane to the ambient test volume \(X-Y\) plate, \(f(X', Y')\) is the intensity profile of fringe patterns, \(g(X, Y, Z)\) is the reconstructed wavefront, \(\lambda\) is wavelength, \(k\) is wave number and \(i\) is the square root of \(-1\). Fig. 1(b) shows the reconstructed image of (a) at \(Z = 218\) mm from the CCD recording plane. The images of particles which locate near \(Z = 218\) mm are formed. One of them is marked in a red circle in Fig. 1(b). Those which do not locate near \(Z = 218\) mm are reconstructed as interference fringes in concentric patterns. All of the obtained holograms are analyzed along the following procedures as described in section 2.3. In the present study, \((X, Y, Z)\) are defined as pixel coordinates and \((x, y, z)\) are defined as real space coordinates.

![Fig. 1 (a) Recorded hologram by He-Ne laser (b) Reconstructed image of (a) at Z = 218 mm](image-url)
2.2 Experimental setup

Fig. 2 illustrates the schematic of the experimental setup and Fig. 3 shows the schematic of the test section which locates at the area where two laser beams are crossing. A channel was made of acrylic, whose length, width and depth were 1000 mm, 30 mm and 22 mm, respectively. The test section was only made of glass to keep the coherency of laser beams. The center of test section was located at 800 mm from the upstream of the channel. Working fluid was water and it was circulated by a pump. CW YAG laser (\( \lambda = 532 \, \text{nm} \)) and CW He-Ne laser (\( \lambda = 632.8 \, \text{nm} \)) were used as light sources. Each laser beam was expanded, reflected by mirrors and crossed at the center of test section. Images were recorded by a 12-bit CCD camera (Imperx IPX-2M30H-L, 33 fps) which has 1920 × 1080 resolution with the pixel size of 7.4 μm × 7.4 μm and the exposure time was set to 50 μs. Both two laser beams were vertically introduced to the camera. The left side of CCD array recorded interference fringe patterns by He-Ne laser. The other side of CCD array recorded fringes by YAG laser. For the validation of the developed system, spherical polystyrene particles with diameter of 50 μm were suspended as tracers in the flow. Furthermore, for the applications to the two-phase flows, two kinds of bubbles were prepared that were microbubbles and milibubbles. Microbubble flows were injected at the upstream of the tank. Their diameters were from 50 μm to 80 μm. A milibubble, whose shape was ellipsoidal, was generated by the injector needle at the test section.

![Fig. 2 Schematic of the experimental setup](image)

![Fig. 3 Schematic of the test section which locates at the area where two laser beams are crossing](image)
2.3 Image processing

For the investigation of the three-dimensional bubbly flow structures, the present study captured the holographic images. Fig. 4 shows the flow chart of the method for obtaining the position of a millibubble and velocity-vectors of microbubbles. In a hologram, a millibubble is recorded as a two-dimensional shadow image and microbubbles are recorded as fringe patterns which contain three-dimensional information of them. Firstly, the millibubble is extracted from the holographic image and its position is determined by stereo shadow imaging technique. Secondly, microbubbles are analyzed by stereo holographic technique as described in section 2.1. Details of the procedures are described in section 2.3.1 and 2.3.2, respectively.

Fig. 4 Flow chart of the image processing of the simultaneous measuring technique for (a) the three-dimensional position of a millibubble and (b) velocity-vectors of microbubbles
2.3.1 Detection technique for the velocity-vector of a millibubble

Fig. 4(a) shows the procedures of the measurement of the position of a millibubble. Each procedure is explained below (Step 1(a) - 4(a)).

Step 1(a) Extraction of a millibubble
When black portions of a hologram image occupy over 100 times pixels of a microbubble image, they are regarded as a millibubble. The portions are extracted from the image.

Step 2(a) Detection of a center position in each laser side view
The center position, \((X, Y)\), is calculated from the extracted image in each laser side view.

Step 3(a) Applying stereo shadow imaging technique and detection of a three-dimensional position
The position of a millibubble has the uncertain range in \(x-z\) direction with only one laser as shown in step 2(a). To improve the problem, the present study developed the stereo shadow imaging technique by utilizing two laser beams. In the pixel coordinates, the length of the major axis of the millibubble and that of the minor axis are calculated, and the center position is detected. In the consideration of the refraction between air and water, the pixel coordinates, \((X, Y, Z)\), are translated to the real space coordinates, \((x, y, z)\). After translation, the matched center position of the millibubble, \((x, z)\), is obtained from the function of He-Ne view, \((2)\), and that of YAG view, \((3)\),

\[
\begin{align}
I_{He-Ne} : z &= \frac{1}{\tan \theta_{He-Ne}} x - \frac{\Delta x_{He-Ne}}{\sin \theta_{He-Ne}} \quad (2) \\
I_{YAG} : z &= \frac{1}{\tan \theta_{YAG}} x + \frac{\Delta x_{YAG}}{\sin \theta_{YAG}} \quad (3)
\end{align}
\]

where \(\theta_{He-Ne}\) is crossing angle between \(z\)-axis and He-Ne laser, \(\theta_{YAG}\) is crossing angle between \(z\)-axis and YAG laser, \(\Delta x_{He-Ne}\) is the distance between the center position of \(x\) and original point in the \(x\)-direction in He-Ne view and \(\Delta x_{YAG}\) is the distance in YAG view, respectively. \(\theta_{He-Ne}, \theta_{YAG}, \Delta x_{He-Ne}\) and \(\Delta x_{YAG}\) are described in step 3(a) of Fig. 3. The center position of \(y\) is calculated by multiplying pixel size 0.0074 mm due to laser beam introducing parallel to the \(y\)-axis. In this way, the position of the millibubble is detected.

Step 4(a) Detection of the velocity-vector
The instantaneous velocity-vector is obtained by calculating the difference between the center position at time \(t_1\) and that at \(t_2\).

2.3.2 Detection technique for velocity-vectors of microbubble

Fig. 4(b) shows the procedures of the measurement of the position of the microbubbles. Each procedure is explained below (Step 1(b) to 4(b)).

Step 1(b) Reconstruction in each laser side view
The average brightness value of the image is substituted for the brightness value of the portions of the extracted millibubble. The image with 1mm interval along \(Z\)-axis is reconstructed by utilizing the Fresnel-Kirchhoff equation as described in eq. (1) in each laser side view.

Step 2(b) Detection of three-dimensional position of microbubbles
(Detection of \(X-Y\) position)
In the intensity profile of ambient \(X\) position along \(Y\)-direction, the averaged brightness value, \(a\), and root-mean-square deviation value, \(\delta\), are calculated. The threshold value is defined as \(a - 4\delta\). When
the intensity value at ambient \((X, Y)\) position is less than the threshold value, it is defined as the particle position.

(Detection of \(Z\) position)

By comparing the intensity of the detected \(X-Y\) position along \(Z\)-direction, the position of the lowest value is determined as the optical distance, \(Z\).

**Step 3(b) Applying stereo holographic technique**

\(P_{\text{He-Ne}}\) and \(P_{\text{YAG}}\) which are described in step 3(b) of Fig. 3, are the ranges of position of the microbubble from He-Ne view and from YAG view, respectively. By using only one laser, \(z\)-position of a microbubble has about 1 mm uncertainty due to depth of focus (DOF). However, the stereo shadow holography proposed in the present study yielded the uncertainty of less than 1 mm by matching two laser views.

**Step 4(b) Detection of velocity-vectors**

In this step, in order to detect velocity-vectors of microbubbles, multiple time series PTV is applied to flow fields. For example, the principle of 3 time series PTV is mentioned in the following statements.

Any point in the flow is assumed to be moving in a straight line due to the minuteness of the scale of flow modulation. Fig. 5 illustrates the schematic of 3 time series PTV. Blue circles, red circles and yellow circles are positions detected at \(t_1, t_2\) and \(t_3\), respectively. \(\vec{D}_{12}\) denotes the displacement vector detected between time \(t_1\) and \(t_2\), and \(\vec{D}_{23}\) denotes the displacement vector detected between time \(t_2\) and \(t_3\). Fig. 5(a) illustrates the schematic of the detection of \(\vec{D}_{32}\). At first, \(\vec{D}_{12}\) vectors are obtained from the one position detected at \(t_1\) to several positions detected at \(t_2\). Next, the vectors with the same length and direction as \(\vec{D}_{12}\) vectors are obtained from positions detected at \(t_2\). Due to the above assumption, the position detected at \(t_3\) is expected to be near the termination of the vector. When the error ratio of vector, given as eq. (4), is less than 0.1, \(\vec{D}_{23}\) is determined as the velocity-vector in three-dimensional flow field. In Fig. 5(a), circles surrounded by dotted lines are the ranges of position of yellow circles based on eq. (4) and red vectors are detected vectors. The procedure is applied to all of the positions detected at \(t_1\) and velocity vectors, \(\vec{D}_{12}\) and \(\vec{D}_{23}\), are detected as shown in Fig. 5(b).

\[
|\frac{\vec{D}_{23}}{\vec{D}_{12}} - 1| \leq 0.1
\]  

(4)

Fig. 5 Schematic of 3 time series PTV
(a) Schematic of the detection of \(\vec{D}_{32}\) (b) Velocity-vectors obtained from 3 time series PTV
3 Results and Discussion

3.1 Application to single-phase flow

For the validation of the developed system, it was firstly applied to the laminar single-phase flow whose Reynolds number, $Re$, is 465. The result of the velocity-vectors is shown in Fig. 6. 864 vectors were detected from 150 subsequent images and the number density of tracer particles was $0.09 \text{ mm}^{-3}$. It can be seen that the velocity-vectors were going toward downstream along $x$-axis. The velocity-vectors within the region at $-0.5 < y < 0.5 \text{ mm}$ are compared with the theoretical value as shown in Fig. 7. The experimental value agreed well with the theoretical values. It is indicated that the proposed system is applicable for obtaining three-dimensional and three-components velocity-vectors of single-phase flow.

![Fig. 6 Velocity-vectors in a laminar single-phase flow](image1)

![Fig. 7 u-z plots of the detected velocity within the region between $y = -0.5 \text{ mm}$ and $y = 0.5 \text{ mm}](image2)
3.2 Application to two-phase flows

3.2.1 Measurement of microbubble flows

Fig. 8(a) shows intensity profiles in terms of Z-position of a tracer particle in the reconstructed image. It usually has the peak, which shows the lowest intensity value. Its position is the infection point and has zero value of the differential coefficient. It is determined as the position in Z-direction. On the other hand, Fig. 8(b) and (c) show the intensity profiles of microbubbles. One microbubble has the same intensity over 2 mm interval and the other microbubble has two peaks. Their irregular intensity profiles are marked in red circles. When a microbubble which has irregular intensity profile is detected, its position has uncertainty from 2 mm to 5 mm in the depth direction. With only one laser, it is difficult to detect the accurate position of microbubbles due to the uncertainty in Z-direction. The irregular intensity profiles should be caused by the internal diffraction of microbubbles. In order to break through the problem of the uncertainty of detecting positions of microbubbles, stereo holographic technique is proposed. Developed system was applied to the flow fields with microbubbles and the obtained velocity-vectors are presented in Fig. 9. 157 velocity-vectors are detected from 150 subsequent images and the number density of microbubbles is 0.05 mm\(^{-3}\). It can be seen that stereo holographic technique with two laser beams contributes to detect accurate positions of microbubbles.

Fig. 8. Intensity profiles along the Z-axis
(a) Intensity profile of a tracer particle (b), (c) Intensity profiles of some microbubbles

Fig. 9. Velocity-vectors of microbubbles
3.2.2 Simultaneous measurement of a millibubble and microbubbles

Fig. 10 (a) shows the reconstructed image of a millibubble and microbubbles at He-Ne laser side view, (b) shows the intensity profile of the microbubble which is marked in the red circle along Z-axis. In Fig. 10(b), the microbubble has the intensity peak as described in section 3.2.1. However, in Fig. 10(c), it is found that the image of the millibubble is recognized as a shadow image and its intensity does not have a peak in Z-direction. It can be confirmed that the position of a millibubble cannot be detected by holographic technique.
In the present study, the position of the millibubble was estimated by stereo shadow imaging technique with two laser beams described in section 2.3.1. Three-dimensional velocity-vectors of microbubbles were calculated by PTV with stereo holographic technique. Fig. 11 shows the result of the instantaneous three-dimensional position of the millibubble, which was indicated by the dotted ellipsoid, and velocity-vectors of microbubbles obtained from 10 subsequent images. Fig. 11(a) and (b) show the results from different views based on the same data. The center position of the millibubble was $(x, y, z) = (0.39, 0.36, 2.00)$ where the cross is marked. White circles indicate instantaneous positions of microbubbles and 58 velocity-vectors of microbubbles were detected. The result reveals that the proposed system can be applied to the two-phase flows involving bubbles with micro- and milli-meter sizes.

Fig. 11. Instantaneous position of the millibubble and velocity-vectors of microbubbles (a) and (b), the results from different views based on the same data
4. Conclusion

A new method is proposed in order to measure the three-dimensional positions and velocity-vectors of bubbles with various sizes. The method is realized by combining holographic technique and stereo shadow imaging technique. A millibubble is measured by stereo shadow imaging technique and microbubbles are measured by stereo holographic technique. The important conclusions obtained from this work are summarized below.

1. To validate the proposed system, it was applied to the laminar flow in the rectangular channel. The mainstream velocity component agrees with the theoretical value and the profile of vectors in the stream-wise direction, $u$, and the channel width-direction, $z$, showed parabolic shape.

2. The system was applied to the measurement of the microbubbles whose sizes are from 50 μm to 80 μm. Although many microbubbles have the position uncertainty from 2 mm to 5 mm in Z-axis, accurate positions are detected from two laser beam view. It is revealed that the system can be applied not only to the single-phase flow but also to the two-phase flows.

3. The system was applied to the simultaneous measurement of a millibubble and microbubbles. In the present study, with two laser beams, a millibubble and microbubbles are measured by shadow imaging technique and stereo holographic technique, respectively. The instantaneous position of a millibubble is evaluated and instantaneous three dimensional velocity-vectors of microbubbles are detected. It is revealed that the system can be applied to the two-phase flows which involve bubbles with micro- and milli-meter sizes.

The proposed DHPTV method is a promising technique to measure motions of bubbles with various sizes. In the near future, the measurement system will contribute to investigate the mechanism of bubbly flows.

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NOMENCLATURE

$(X, Y, Z)$ pixel coordinates

$(x, y, z)$ real space coordinates

$i$ the square root of -1  

$k$ wave number  

$a$ averaged brightness value  

$\vec{D}$ displacement vector of the position  

$t$ time  

Greek Letters

$\lambda$ wavelength  

$\theta$ crossing angle between z-axis and the laser beam
\( \Delta x \) distance between center position of \( x \) and original point in the \( x \)-direction [mm]

\( \delta \) root-mean-square deviation value [-]

Subscripts

He-Ne He-Ne side view

YAG YAG side view

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