### Abstract
We construct an in-line digital holographic measurement system to determine 3D fluid structure around a single rising bubble in quiescent water. A feature of our system is using synchronized two digital cameras for overcoming inaccuracy of depth-direction information of holography (depth-of-focus problem). These two cameras are arranged to measure from orthogonal views.

We analyzed the recorded holograms by following steps: 1. Reconstruct the image of tracer particles in time sequence. 2. Detect 3D particle position. 3. Apply PTV method. 4. Match PTV results from each view to obtain precise depth-direction information.

To validate our measurement system, a fluid structure around a solid sphere of 1 cm diameter was measured. We use 532 nm coherent light to illuminate 100 \( \mu \)m tracer particles seeded in liquid phase contained in a non-reflect-coated glass tank. A control volume is 12.0x12.0x12.0 mm. \( Re \) number of solid sphere is 28.0. Comparing with previous experimental results, we found that our system has enough accuracy to measure 3D fluid structure with 1.48 mm spatial resolution.

Then, we measured flow around a spiraling and a zigzagging motion bubble. Tracer particles around spiraling bubble tend to trace bubble spiral trajectory. We think that particles are trapped in double-threaded wake (Mougin G. (2002), deVries A.W.G. (2001)). Particles around zigzagging bubble seems to be affected by the interaction of vortex filaments which is also reported by de Vries A.W.G. (2001)

Though we could obtain information about 3D wake structure, we need more data for quantitative discussion. We have two points to be improved: Failing to detect particles at some time and particle density limitation. The former problem makes it so hard to trace particle trajectories in time sequence. That causes the low resolution of velocity field. We suggest an improved PTV algorithm that if the particle vanished in next step, we continue to search the particle in the area after next time.

About the latter problem, previous studies revealed that density limitation of in-line holography is 2000-3000 particles/cm\(^3\) (Vikram (1992)). We already have density over 2000 particles/cm\(^3\). Therefore, the only way to thick particle dense is to adopt off-axis method whose density limit is 8000-9000 particles/cm\(^3\). We should arrange interval of fringe patterns as wide as possible.

When all these improvements are successfully done, we indicate the possibility to 0.76 mm resolution measurement in 12.0x12.0x12.0 mm.

### 1. Introduction

Bubbly flows are used in various industrial processes such as purification of liquids, chemical reactions and drag reduction of ships. These applications require improved understanding and controlling of the flows.

One of the characters of bubbly flows is its multi-scale structure (Sugiyama K et. al. 2001): Important factors of bubbly flows are not only large scale eddy structures (macro scale) but also a single bubble motion (micro scale) and bubble-bubble interactions (meso scale). From this point of view, it is highly valued to investigate a single bubble motion in quiescent water.

According to previous studies, a single bubble in purified water draws straight or zigzag/spiral trajectory. When a bubble diameter is less than 1 mm, it rises up straightly and its shape is axial
symmetry. Recent numerical and experimental work revealed so many aspects of the axisymmetrical bubble, especially bubble wake structures, surfactant effects and bubble deformations (Duineveld P.C. (1995), Cuenot et al. (1997), Lunde K. et al. (1998)). These three points are regarded as the most important factors in the flow (Magnaudet et al. (2000)).

On the contrary, when a bubble diameter is over 1 mm, it draws zigzag, spiral or transition from zigzag to spiral trajectory (Clift et al. (1978)). There is a dearth of information of these 3D motion bubbles, especially wake structures. One of the main reasons is that we haven’t had appropriate techniques to measure with time sequence.

On the basis of this background, the objective of present study is to investigate 3D wake structure of a single spiraling/zigzagging bubble by developing a 3D measurement system. To be more precise, our main target is little-oscillating zigzagging/spiraling bubble whose diameter is 2.0-2.5 mm because it has little effects of bubble oscillation and there are some valuable numerical results (Mougin G. et al. (2002), Fig.1) and experimental ones (Ellingsen K. et al. (2001)).

Considering 3D measurement systems, there are several methods such as scanning PIV and 3D-PTV. We should note that bubble wake structure analysis requires instantaneous deep depth-direction measurement as well as parallel directions. From this view point, scanning PIV doesn’t provide instantaneous velocity field and the depth-direction of 3D-PTV technique is not enough for obtaining the wake structure.

Given this factor, we focused on holography which can measure instantaneous entire velocity field with deep depth-of-focus (Collier R. (1971), Barnhart DH et al. (1994)). We tried to construct a holographic measurement system because it has a potential to measure entire wake structures.

2. Measurement method

Because of easy set up and necessity of low resolution, we implemented an in-line digital holographic measurement system. (Meng H. et al (2004), Schnars et al. (1994))

When we construct the system, we have to overcome a problem which is unique to holography: Inaccuracy of depth-direction information (depth-of-focus problem). In holography, reconstructed images of particles are stretched toward the depth direction. If we have the diameter \(d \) particle, the depth-of-focus is \(d^2/\lambda \) (\(\lambda \) is wavelength of light source, Vikram (1992)). When we apply 100 \(\mu m\) particles and a laser with wavelength of 532 nm laser, we have an approximately 2 cm stretched particle image. For this reason, it is very hard to obtain exact 3D position of tracer particles in liquid phase by one holography.

One of the solutions is to obtain one more holography from orthogonal view. This idea is previously described by Tao B. et al. (1997), Sheg J. et al. (2003) and Malkiel E. et al. (2003). Malkiel E et al (2003) used a mirror to take two orthogonal views with one digital camera.

Basing on the idea, we use two synchronized cameras with orthogonal views in our system as
shown in Fig. 2.

We analyze recorded holograms as following procedures.

**Step 1. Reconstruct the image of tracer particles in time sequence**

(a) To remove noises and make fringe patterns clear, background noises are subtracted before reconstruction.

(b) We calculate reconstructed images with the Fresnel-Huygens equation as shown below. (Schnars et al. (2005))

\[
h(x, y, z; g(\xi, \eta)) = \frac{\exp(\frac{jkz}{j\lambda})}{j\lambda} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(\xi, \eta) \exp \left[ \frac{jk}{2z} \left( (\xi - x)^2 + (\eta - y)^2 \right) \right] d\xi d\eta
\]

\[
= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(\xi, \eta) g_F(x - \xi, x - \eta) d\xi d\eta
\]

\[
= \mathcal{F}^{-1}[\mathcal{F}(g) \mathcal{F}(g_F)]
\]

Here, \( h \) is reconstructed wave front, \( g \) is transmission of hologram, \((x, y)\) is coordinate system on a reconstructed plane, \((\xi, \eta)\) is coordinate system on a hologram plane, \( z \) is distance between reconstructed plane and hologram plane, \( k \) is wave number, \( j \) is imaginary number, \( \mathcal{F} \) is Fourier transformation and \( \mathcal{F}^{-1} \) is inverse Fourier transformation.

To make calculation faster, we use FFT algorithm.

**Step 2. Detect 3D particle position**

We detect particles in each reconstructed plane by both luminance gradient and brightness. After that, we compare the detected images along depth direction and segment each particle 3D area. The particle positions are represented by particle’s centroids.

**Step 3. Apply PTV method**

PTV method is applied to obtain 3D velocity field. To capture reliable particle trajectories, we trace each particle more than 4 time-series (Four Time Tracking Method).

**Step 4. Match PTV results from each view**

We match each PTV results from two orthogonal views by history of height information.

### 3. Experimental set up

Fig. 2 shows the optical set up for digital holography measurement. Our system consists of coherent light (Nd:YVO4 Laser, 532 nm, CW, Coherent Co.), two digital cameras (Motion Pro 10000, 1280x1024 pixels, 10000 fps, Redlake Co.) and reconstruction software. 100 \( \mu \)m tracer particles made from polystyrene are seeded in a non-reflect-coated glass tank with tap water. A measurement control volume is 12.0x12.0x12.0 mm.

For the validation for this system, we measure flow around a 1 cm solid particle as well known flow. Solid sphere goes at the velocity of 3.0 mm/s. \( Re \) number is 28.0. The measurement condition is 500 frame per second, 1024x1024 pixels, 1/2000 sec exposure time, 0.14 W CW coherent light.

Fig. 3 shows each steps of analyzing recorded holograms. Presented images below are one of recorded holograms (Fig. 3 (a)), their reconstructed image in a certain plane (step 1, Fig. 3 (b)), the distribution of all detected particles (step 2, Fig. 3 (c)).

From Fig. 4 (a), the trajectories of whole particles reveal the 3D fluid structure around a solid sphere. Measured wake length of this flow is 0.10 mm. Fig. 4 (b) shows a previous experimental
result (Clift et al (1978)) in a similar experimental condition. They reported that the wake length is \(0.10 \pm 0.04\) mm. We found that our measurement system has enough accuracy to measure 3D fluid structure. Average spatial resolution is 1.48 mm.

Then, we measured two kinds of fluid structure around a bubble. One is that of spiraling bubble of 2.03 mm diameter at the rising velocity of 334 mm/s in tap water. \(Re\) number is 680. The other is that of zigzagging bubble of 2.08 mm diameter at the velocity of 164 mm/s in 5 ppm tritonX-100 solution. \(Re\) number is 340. The reason why we entrained tritonX-100 (surfactant) is to induce zigzagging motion to compare a spiraling motion bubble of the same diameter. Each bubble’s trajectory and holographic measurement volume are shown in Fig.6. These trajectories are measured with two cameras following up the bubbles as shown in Fig.5. Blue line is bubble trajectory and orange dotted square is measurement volume. Height of measurement volume from bubble generator is 90 mm.

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Fig.2 Experimental set up.

Fig.3 (a) Recorded hologram  
Fig.3 (b) Step 1: Reconstructed image
Fig.3 (c) Step 2: Particle 3D positions

Fig.4 (a) Measurement result around a 1cm solid sphere ($Re=28.0$)
    (b) Flow around solid sphere (Clift et al. (1978), $Re=26.8$, 2D measurement)
Fig. 5 Measurement system of bubble trajectory

Fig. 6 Bubble trajectories (blue line) and holographic control volumes (orange dotted square).

(a) Spiral trajectory  (b) Zigzag trajectory
4. Results and Discussions

Fig. 7 and Fig. 8 are the PTV result from X-view and Y-view of spiraling and zigzagging bubble for 0.12 sec, respectively. Each Orange line is a bubble trajectory. Spatial resolution is 1.2 mm.

Particles around spiraling bubble in a green dotted circle tend to trace bubble spiral trajectory, which are considered to be trapped by double-threaded wake like Fig. 1 (c) (Mougin G. (2001)) which is experimentally reported in detail by de Vries A.W.G. (2001) who visualize bubble wake structures by schlieren method. On the other hand, those around zigzagging bubble don’t trace bubble like particles around spiraling bubble, but seems to be affected by the interaction of vortex filaments of bubble which are also reported by de Vries A.W.G. (2001).

However, there is not enough velocity data to discuss quantitatively. We think about obtaining more data.

Though we detect about 2000 particles every moment, only 990 particles are successively traced more than four time-series. We have two problems to be improved: Missing to detect particles at a certain instance and particle density limitation.

To apply PTV method, we need to detect particles in each time series. But we cannot always detect all particles because tracer particle sizes and shapes are not uniform. In other words, luminance gradient and brightness of each particle is uneven. On present procedures, if a particle cannot be detected at certain time, before or after 3 time traces are wasted. One of the ways to cover this problem is to improve PTV process: If the particle in the next step is vanished, we don’t finish tracing the trajectory but continue to search the particle after the next time step. If there is a particle, the vanished time step can be interpolated. Under existing circumstances, 1200 particles can trace 3 time-series. If these problems are improved, the resolution is expected to improve more than 20%.

Another solution to improve resolution is to thick particle density. Previous study shows that the limit of density of in-line holography with 100 µm particles is 2000-3000 particles/cm³ (Vikarm (1992)). Now we have over 2000 particles. It means that we have saturated density. The only way to thick the density is adopt off-axis method. The density limit of the method is 8000-9000 particles/cm³. In this solution, we should care about the angle between reference beam and object beam that decides the interval of fringe patterns. Because digital cameras don’t have spatial resolution, the angle is preferable to be near zero as possible. By adopting this method, we can obtain 3 times more dense particles. If all these improvement would have been done, the resolution will become about 4 times higher resolution: 0.76 mm.
5. Conclusion

We construct holographic measurement system with two digital cameras to improve reliability of depth-direction information. Our system is able to give accurate 3D velocity field information around a 1cm solid sphere for a given period of time. We also measured fluid structure around spiraling bubble and zigzagging one and obtain 3D velocity information.

For increasing the resolution, we have to improve PTV processing and optical arrangements. These improvements give possibility to upgrade the resolution to 0.76 mm in control volume 12.0x12.0x12.0 mm.

Acknowledgements

We are very grateful to Prof. Katz J., Sheng J., and Malkiel E. for their helping us to construct this holographic system.

References

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