SIZE AND 3D VELOCITY MEASUREMENT TECHNIQUE FOR SPRAY DROPLETS BY USING HYBRID TECHNIQUE OF DIGITAL HOLOGRAPHY AND 3D-PTV.

Yoshibo Zama 1, Tomohiro Uesugi 1, Masaki Kawahashi 2, Hiroyuki Hirahara 2

1 Graduate School of Science and Engineering, Saitama University, dolphin@lamb.mech.saitama-u.ac.jp
2 Mechanical Science Division, Graduate School of Science and Engineering, Saitama University

ABSTRACT Simultaneous measurement method of size and three-components velocity of spray droplet was proposed. In the technique, bright spots are formed from reflection and first order refraction ray scattered by a droplet illuminated with a laser light, and the hologram of the bright spots are recorded on CCD device by using in-line holography. The bright spots and interference fringes are reconstructed from the hologram. Size measurement is evaluated from analysis of fringe order in the interferogram. Three components of velocity are estimated by 3D-PTV based on bright spots images reconstructed from the hologram. Moreover the technique was composed of one CCD camera, and stereo images of the bright spots are reconstructed from the hologram by using property of holography. In the paper, the accuracy tests of sizing and velocity measurement were carried out by measurement of silica particle. The technique was applied to spray issued from swirl nozzle, and the feasibility of the technique for real spray field was verified.

Keywords: In-line holography, 3D-PTV, spray droplet, glare points

1. INTRODUCTION

When a spray droplet is illuminated with a laser light, characteristics of light scattering is formed. And its characteristics depend on diameter of the droplet and wavelength of the light. Some measurement technique of size and velocity by using property of the light scattering have been proposed.

PDA is a method extended from LDV, and it can measure the diameter with high accuracy. But it is a point measurement technique. Recently, light scattered from droplet is captured with CCD camera, and the method that can measure the diameter of droplet from the image processing with high accuracy was proposed. It is called IPI or ILIDS. Glare points generated with reflection and first order reflection are formed on a surface of droplet illuminated with a laser light. Rays from glare points interfere, and interference fringes are generated. In the technique, the interference fringes are captured with CCD camera. The fringe order in interferogram is proportional to a diameter, and the size measurement is evaluated from fringe order with high accuracy. However, the disadvantage of the technique is the dependence of number density of droplets, and there is some difficulty of the measurement in high dense of the droplets. Spray field is the typical example also. Maeda et al. [1] proposed optical compression method and established ILIDS. They applied the improved ILIDS to measurement of size and 2D velocity of individual spray droplets.

Spray field investigated in the paper is generated with a swirl nozzle, and measurement of three components of velocity of droplet is indispensable.

3D-PTV and SPIV are well known as the measurement method of 3D velocity field. Nishino et al. [2] proposed simultaneous measurement technique of size and three-components of velocity based on 3D-PTV. In the technique, size measurement depends on spatial resolution of optical receiver. Palero et al. [3] proposed the method by using SPIV. Diameter of the droplet was estimated by light intensity scattering from the droplet illuminated with a laser light. The method can measure three-components of velocity of droplets cluster, but velocity of individual droplet cannot be obtained. Authors [4] proposed the technique that glare-points and interference fringes are captured with two CCD cameras arranged in stereoscopic configuration. The size measurement was given by interval of glare points and fringe order of interference fringes, and 3D velocity field was provided with application of 3D-PTV to the optical images. However, there was some difficulty in high number density of droplets because of overlapping interferograms.

Burke et al. [5] proposed the method based on digital hologram of glare points. Holography can reconstruct image of object at arbitrary position. Droplet image was extracted by glare-points image reconstructed from the hologram, and size measurement was evaluated from interferogram obtained by the hologram.

Size and 2D velocity measurement method, which was based on the holography of glare points of bubbles, was proposed by Palero et al. [6]. This method can record information of different two planes in the out-of-plane direction by using a CCD camera. Diameter of the bubble was estimated by same procedure reported by Burke et al.[5], and decomposition of information of two planes was carried out from reconstruction distance.

The methods reported by Burke et al. and Palero et al. was based on holography of off-axis configuration, and the optical configuration is intricate regarding angle between object and reference beam. Moreover there is no report related to measurement of three velocity-components by using the holography technique.

In the present report, the simultaneous measurement of size and three velocity-components of spray droplets was proposed. In the technique, hologram of glare points was obtained by a holography based on in-line optical configuration. The optical system composed of two in-line holography, and the digital hologram of glare points was recorded with a CCD camera. Size measurement was estimated by fringe order of interferogram reconstructed.
from the hologram, and three-components of velocity was obtained by 3D-PTV of glare points given from the hologram.

Accuracy of the technique was evaluated with measurement of diameter and 3D displacement by using calibrated silica particles. The technique was applied to real spray ejected from a swirl nozzle, and its feasibility was investigated.

2. PRINCIPLE

2.1 Fundamental Optics

When a transparent spherical droplet is illuminated with a laser light, bright spots generated by reflection and first order refraction rays appear on surface of the droplet. Their bright spots are called glare point. The fundamental optics is illustrated in Figure 1.

The glare points are imaged on a focal plane as a distribution of glare-points pair. On defocused image, interferogram is formed pair because of phase difference between glare points. Intensity of glare point depends on refractive index of medium and scattering angle. In the case of water, intensity of reflection ray coincides with one of first order refraction ray at approximately 70° of scattering angle with incident light of wavelength of 532nm. (Silica particle: approximately 90°) At the scattering angle, the glare point is imaged clearly, and signal of interference fringes can be maximized.

Diameter of droplets is proportional to separation of glare points and fringe order of interferogram. Van de Hulst [7] suggested that the diameter can be measure from the interval of glare points. Authors[8] derived the equation (1) showing the relation between diameter and the interval.

\[
d = 2 \frac{L}{M} \left( \sin \left( \pi \frac{\theta}{2} \right) \right) \left( \frac{\sin \left( \frac{\theta}{2} \right)}{\cos \left( \frac{\theta}{2} \right) - \frac{1}{n}} \right)^{1/2} \tag{1}
\]

Where, \(d\), \(L\), \(M\), \(n\) and \(\theta\) are the diameter of droplet, the interval of glare points, magnification factor, refractive index of medium and scattering angle.

Hesselbacher et al.[8] showed the relation between diameter of droplet and the fringe spacing angle such as equation (2).

\[
\Delta \varphi = \frac{2 \lambda}{d} \cos \left( \frac{\theta}{2} \right) + \frac{n \sin \left( \frac{\theta}{2} \right)}{\sqrt{\frac{\lambda^2}{n^2} + 1 - 2 n \cos \left( \frac{\theta}{2} \right)}} \tag{2}
\]

Where, \(\Delta \varphi\) and \(\lambda\) are the fringe spacing angle and wavelength of a light source. \(\alpha\) is a collecting angle of a lens, then the fringe order \(N\) is shown in equation (3).

\[
N = \frac{\alpha}{\Delta \varphi} \tag{3}
\]

Thus fringe order \(N\) is proportional to diameter \(d\) of droplet.

2.2 Holography

Holography is the method recording a hologram with light wave scattered from an object and a reference wave, and reconstructing the object from the hologram in three dimensional field. In the present technique, glare-points image and interferogram are reconstructed from hologram of glare points by using the property.

Digital reconstruction is shown by multiplying digital hologram \(h(\xi, \eta)\) and numerical reference beam \(r(\xi, \eta)\). Reconstructed image \(b'(x', y')\) is expressed such as equation (4).

\[
b'(x', y') = \frac{1}{i\lambda} \int h(\xi, \eta) r(\xi, \eta) \frac{\exp(ik \rho)}{\rho} d\xi d\eta \tag{4}
\]

Where, \(\rho = \sqrt{(x-x')^2 + (y-y')^2}\) and \(k\) is wave number, \(d'\) is reconstruction distance coinciding with the interval of plane of hologram and object. The integral shown in eq. (4) can be solved with Fresnel approximation or convolution. In the present technique, the digital reconstruction was carried out by using equation (5) changed with the convolution method.

\[
b' = A' F^{-1} \left[ F \left( h \cdot r \right) \cdot F \left( g \right) \right] \tag{5}
\]

2.3 Optical Configuration

Figure 2 shows schematics view of optical configuration proposed. Light source is the Nd:YAG laser (New wave Research) with double-pulsed illumination having wavelength of 532nm. The laser light is separated to reference beam and beam that generates glare point, with a beam splitter. Then the reference beam is divided into two reference beams, and the beams intersect at observation area with 90°. The beam of glare point changes to laser
light sheet with cylindrical lens, and it illuminate the test section. Thus three laser lights cross at the section. After that, two object beams are superposed with a beam splitter, and a CCD camera records hologram of glare point. Pixel size of the CCD camera used (ITD 1400DE) is 1036×1360 pixels², and its camera can capture an 8 or 10 bits image. In the measurements, 10 bits image was recorded.

The technique composes of two optical configurations of in-line holography. The information of position of a droplet observed from two directions is recorded simultaneously, and stereoscopic configuration at stereoscopic viewing angle of 45° coincide with the optical system. In the present technique, the two optical path lengths were different each other. Stereoscopic images of glare point are reconstructed from the hologram, and difference of reconstruction distance is utilized.

The optical system composes of CCD camera and imaging lens. Thus CCD camera records hologram depending on magnification factor.

2.4 3D-PTV and Camera Calibration

In this method, hologram of glare points is recorded, and the 3D position of droplet can be obtained from reconstruction distance of glare-points image. However, spatial resolution of CCD device recording hologram depends on accuracy of the reconstruction of the image. Spatial resolution of CCD device used is also insufficient as hologram, and droplets position to out-of-plane cannot be determined accurately. Thus 3D-PTV was applied to the present technique in order to obtain three-components of velocity.

Perspective relation proposed by Doh et al. [9] was applied to 3D reconstruction. For application of 3D-PTV, camera calibration is needed. In camera calibration, calibrator was utilized and placed at test section, and it was captured with the camera. And the perspective relation was determined by processing of calibrator images captured in the procedure.

In the present technique, it was difficult to apply the conventional calibration procedure. The camera focuses on different position of an object as shown in figure3, and the calibrator cannot be imaged clearly.

Figure 3 Optical condition of the technique

In the technique, camera calibration based on holography was carried out. In the calibration, hologram of the calibrator was recorded, and image of the calibrator was reconstructed from the hologram. Then the calibrator images reconstructed were utilized to camera calibration. In order to record the hologram of the calibrator, the calibrator of a glass plate shown in figure4 was used.

Interval between grids is 1mm, and its accuracy is less that 5µm. In the method of calibration, hologram of grids on the calibrator was generated.

3. VERIFICATION OF ACCURACY OF PRESENT TECHNIQUE

Accuracy of the method was evaluated by using silica particles having refractive index of 2.25.

3.1 Size Measurement

Light intensity of glare points on a silica particle illuminated with a laser of wavelength of 532nm coincides at 90° of scattering angel. Thus hologram of glare points cannot be recorded with the optical configuration shown in fig.2. In this verification, an optical configuration shown in figure5 was applied.

![Figure 5 Schematic view of optical configuration for size measurement](image)

**Table 1** Exact diameter of silica particles

<table>
<thead>
<tr>
<th></th>
<th>Exact diameter [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle 1</td>
<td>58.1</td>
</tr>
<tr>
<td>Particle 2</td>
<td>50.2</td>
</tr>
<tr>
<td>Particle 3</td>
<td>52.5</td>
</tr>
<tr>
<td>Particle 4</td>
<td>60.1</td>
</tr>
</tbody>
</table>

Before the verification, exact diameter of silica particle was measured with a microscope. Result obtained is shown in...
Table 1. The particles were measured with the present technique for the verification.
Interference fringes and hologram of glare points were recorded on an image simultaneously, and diameter of the particle can be evaluated with processing of fringe order such as ILIDS. Moreover, the method by using the property of holography can be utilized for size measurement. Glare points image was reconstructed from the hologram, and the doublet image was extracted. Interference fringes were reconstructed from the doublet image filtered out.
In the verification, two kinds of size measurement method were applied, and these were compared.
Fringe order of interferogram was estimated by FFT analysis, and the fringe order N was obtained by multiplying frequency of the fringes and size of the interferogram. In the method based on holography, the interferogram was reconstructed from glare-points image without condition of aperture shape, and size of interferogram was not reconstructed directly.
Thus diameter of the aperture D projected with reconstruction distance d' onto the image is expressed such as equation (6). Fringe order of interferogram can be obtained from multiplying D and the frequency.

\[ D = \frac{M}{2(1+M)f\#} \]  

(6)

Where, f# is F-number of lens.
The result obtained from size measurement is shown in Table 2.

<table>
<thead>
<tr>
<th></th>
<th>Diameter [um]</th>
<th>Error [%]</th>
<th>Error of propagation [%]</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle 1</td>
<td>54.1</td>
<td>4.1</td>
<td>0.1</td>
<td>5.9</td>
</tr>
<tr>
<td>Particle 2</td>
<td>50.2</td>
<td>4.0</td>
<td>1.2</td>
<td>3.1</td>
</tr>
<tr>
<td>Particle 3</td>
<td>52.5</td>
<td>2.1</td>
<td>2.9</td>
<td>0.2</td>
</tr>
<tr>
<td>Particle 4</td>
<td>60.1</td>
<td>3.8</td>
<td>5.9</td>
<td>1.9</td>
</tr>
</tbody>
</table>

From the result, the method based on the holography is more accurate than ILIDS, and the present technique can measure the diameter with accuracy less than 6%.

3.2 3D Displacement Measurement

The optical configuration shown in Fig. 2 cannot be applied to accuracy test of the displacement measurement using the silica particles, because glare point cannot be generated by the system. The displacement is provided from 3D-PTV of image of the bright spot, and optical system shown in figure 6 can generate glare point.

![Figure 7 Hologram of silica particles](image)

In the configuration, ray of particle was observed from 45° of scattering angle, and hologram of glare point was recorded on a CCD camera. 3D-PTV was applied to stereoscopic images of bright spot reconstructed from the hologram.
In the verification, the glass plate with the particles was moved with a positioning stage. The displacement of the particles was 0.100[mm] in out-of-plane direction. Figure 7 shows the hologram recorded with the optical configuration shown in fig. 6.

<table>
<thead>
<tr>
<th></th>
<th>Displacement[mm]</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle 1</td>
<td>0.095</td>
<td>5</td>
</tr>
<tr>
<td>Particle 2</td>
<td>0.163</td>
<td>63</td>
</tr>
<tr>
<td>Particle 3</td>
<td>0.104</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 3 shows error estimated from exact and measured displacement. Particle 1 and 2 was measured with accuracy less than 5%, but error of Particle 2 was approximately 60%. Its error is cased with quality of image reconstructed from the hologram. The image of Particle 2 was not reconstructed clearly, and position of the image was not extracted exactly. Thus performance of digital reconstruction depends on the accuracy of displacement measurement.

4. APPLICATION OF THE PRESENT TECHNIQUE

The present technique was applied to real spray issued from a swirl nozzle in order to verify the feasibility.
The performance of flow rate for the nozzle used shows in figure 8.
In the experiment, water was ejected from the nozzle at injection pressure of 1.0 MPa continuously. Measurement was carried out with the optical configuration shown in fig. 2. In the measurement, refractive index of water was
configuration, the noise generated from droplets illuminated with reference beam outside test section can be decreased, and 3D-PTV and the separation of interferogram can be evaluated with one camera. The optical configuration will be applied.

![Figure 10 Optical configuration based on off-axis holography](image)

6. CONCLUSIONS

The simultaneous measurement method of size and 3D velocity field was proposed. This method was based on the combined technique of 3D-PTV and in-line holography. The advantage of the method is that the image for 3D-PTV can be recorded with one camera and the separation of interferogram is evaluated with digital reconstruction from hologram of glare points. Size measurement was evaluated by processing of fringe order of interferometric image reconstructed with the hologram, and velocity measurement was given by 3D-PTV of glare-points image reconstructed from the hologram.

Accuracy tests of the technique were carried out by using silica particles. The results of verification for sizing and displacement measurement were within 6%. However, the accuracy of displacement depends on quality of the digital reconstruction.

The feasibility of the technique was verified by applying to simultaneous measurement of droplets size and velocity of a real spray issued from a swirl nozzle. In this measurement, it was clarified that there was a difficulty of the measurement caused by high number density of droplets. It was that the holograms of droplets, which were not glare points, were overlapped with holograms of glare points as optical noise for this technique. And then, in order to remove the optical noise, an improved optical configuration was discussed and proposed.

7. REFERENCES

4. Zama, Y., Kawahashi, M. and Hirahara, H.,


