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# Development and validation of digital holographic particle velocity measurement system for rotational flows

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ABSTRACT

A digital holographic particle velocity measurement system was developed, validated, and applied to the measurement of rotational flows. With the developed system, the 3-Dimensional information of the flow field can be obtained. A validation experiment for the digital holographic particle velocity measurement system by measuring the velocities of glass beads on a rotating disk was conducted to verify the accuracy and feasibility of the system. Uncertainty analysis was performed to identify the sources of all relevant errors and to evaluate their magnitudes. The measurement results of the velocities of glass beads obtained with digital holographic system were compared reasonably well with the known values within acceptable range of errors. Using the developed digital particle holographic system, a rotational flow field was measured and the distribution of 3-D velocities was visualized. The feasibility of this system was verified by the measurement results which were in good agreement with the theoretical predictions.

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## 1. Introduction

The rotational flows encountered in many engineering areas have many complexities as well as being three-dimensional in nature. To investigate the characteristics of such flow fields, various measurement techniques and instruments have been developed and commercialized. Among these, non-intrusive optical instruments such as Laser Doppler Velocimetry (LDV), Particle Image Velocimetry (PIV) have been used to visualize such fluid flows. The conventional system, however, can only measure 2-D velocities in a single plane [1,2]. Various extension systems of 2-D PIV such as Stereoscopic PIV (SPIV) and Holographic PIV (HPIV) have been developed to measure 3-D velocity vectors of flow fields [3,4]. Barnhart and Adrian [5] used two reference beams to record the separate image of particles, and then they adopted a stereoscopic PIV technique to obtain 3-D turbulent flow fields. Zhang et al. [6] developed the hybrid HPIV system, which adopted the advantages of in-line and off-axis holography. Meng et al. [7,8] conducted several significant studies on HPIV, and introduced the in-line recording and off-axis viewing (IROV) system, a multi-beam technique.

Digital holography, which has rapidly taken the place of conventional optical holography, doesn't need a chemical process and it has several benefits such as high efficiency, simplicity, and real time analysis. Therefore, digital holography has been widely used in measurements of flow fields [9–13]. Owing to the rapid development of CCD cameras and computer technologies, the quality of holograms has been improved and the computing speed of image reconstruction has been faster. Thus, digital particle holography has strong potential in measurements of the features of flow fields.

In this study, the digital holographic particle velocity system for measurements of rotational flows was developed and a validation experiment was conducted. The measurement system mainly consisted of a double exposure laser and a CCD. The validation experiment was based on some glass beads on a rotating disk. The velocities of glass beads were measured by digital holographic system and the results were compared with the known values calculated from the rotating disk. The acceptable range of errors of comparison verified the accuracy and feasibility of the digital holographic system. The uncertainty analysis was also performed to identify the sources of all relevant errors and to evaluate their magnitudes. Using the digital particle holographic system, a rotational flow field was measured and the 3-D velocity field was visualized. The results showed that the digital particle holography system could work well in measurements of rotational flows.

## 2. General principles

Digital holography is classified as in-line or off-axis depending on the optical set-up. In-line digital holography is widely used

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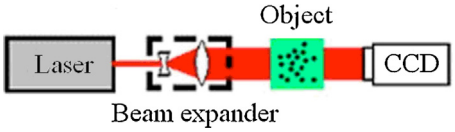



**Fig. 1.** Principle of in-line digital holography.

because it has a simple optical configuration. The concept of in-line digital holography is shown in Fig. 1. An expanded laser beam goes through the object field. The part of the beam diffracted by objects and arriving at the recording surface is called the object beam, and the beam arriving without distortion from objects is called the reference beam. The superposition of two beams creates an interference pattern on a CCD sensor. This diffraction can be described by the Fresnel-Kirchhoff integral [14]:

$$R\left(\xi',\eta'\right)=\frac{i}{\lambda}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}h(x,y)E_R(x,y)\frac{\exp\left(-i\left(2\pi/\lambda\right)\rho\right)}{\rho}\mathrm{d}x\mathrm{d}y \tag{1}$$

with

$$\rho=\sqrt{\left(\xi'-x\right)^2+(\eta'-y)^2+d^2} \tag{2}$$

where $R\left(\xi',\eta'\right)$, $h(x,y)$, $O\left(\xi,\eta\right)$ and $E_R(x,y)$ are functions of the reconstruction image, hologram, object, and reference, respectively. Here, $d$ is the distance between two adjacent planes, $\lambda$ is the wavelength, and $\rho$ is the distance between two corresponding points in two adjacent planes. The coordinates appearing in Eqs. (1) and (2) are shown in Fig. 2.

According to the object distance, holography is also classified as Fresnel (near field) or Fraunhofer (far field) holography. In this paper, Fresnel holography is investigated and the minimum object distance in Fresnel holography is presented by Yang and Kang [15]

$$d\geq\sqrt[3]{\frac{1}{8}\frac{\left[\left(\xi-x\right)^2+(\eta-y)^2\right]^2}{\lambda}}=\sqrt[3]{\frac{1}{8}\frac{\left[N^2\left(\Delta\xi-\Delta x\right)^2+N^2(\Delta\eta-\Delta y)^2\right]^2}{\lambda}} \tag{3}$$

where $\Delta\xi$ and $\Delta\eta$ are the resolutions of the object image.

The reconstruction image $R\left(\xi',\eta'\right)$ can be obtained by the Fresnel method or the convolution method [15]. In our previous analysis [15], the resolution of the reconstruction image by the convolution method was better than that by the Fresnel method. Therefore, the convolution method was used in this study. The mathematical

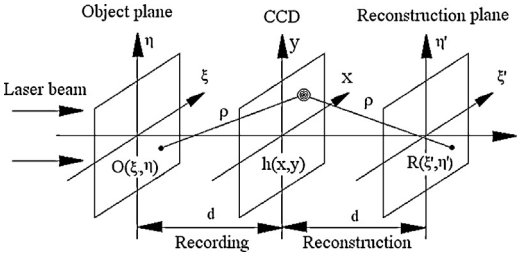



**Fig. 2.** Coordinate system.

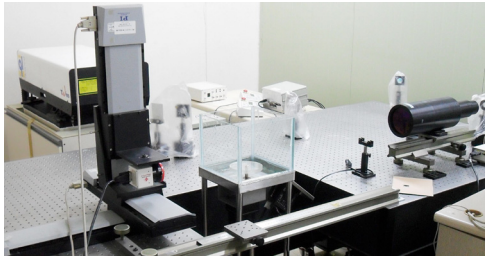


**Fig. 3.** Digital holographic particle velocity measurement system for rotational flows. (a) Schematic diagram, (b) Rotating disk with glass beads

expression of the convolution method is

$$R\left(\xi',\eta'\right)=F^{-1}\left\{F\left[h(x,y)\right]\times F\left[\frac{i}{\lambda}\frac{\exp\left[-i\left(2\pi/\lambda\right)\sqrt{d^2+\left(x-\xi'\right)^2+(y-\eta')^2}\right]}{\sqrt{d^2+\left(x-\xi'\right)^2+(y-\eta')^2}}\right]\right\} \tag{4}$$

where $F[]$ and $F^{-1}\{\}$ are a Fourier transform and an inverse Fourier transform, respectively.

## 3. Experiments

### 3.1. Digital holographic particle velocity measurement system

A digital holographic particle velocity measurement system for capturing the holograms of rotational flows was established as shown in Fig. 3. The laser beam from the double exposure laser system passes through a beam expander and it is extended to a plane beam that generates double exposure holograms on a CCD. After collecting the holograms from the CCD, the hologram image can be reconstructed, and information of flow field can be extracted. The specifications of the system components are as follows:

Laser: Nd-YAG laser (Quantel, wavelength 532 nm).

CCD camera: Megaplus II ES4020 (Kodak, pixel size, $\Delta = 7.4\,\mu$m, pixel number, $N = 2048 \times 2048$).

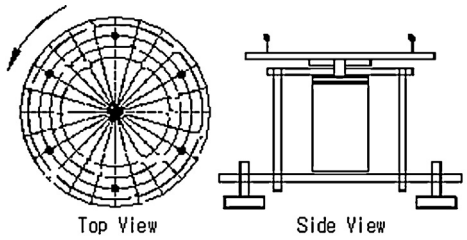
Pulse generator: Model 555 (Berkeley, 4 channels).

Translation system: M-531 (Physik Instrumente, precision: 33 nm).

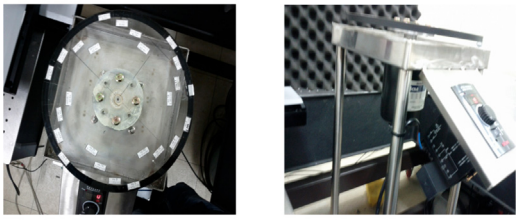
### 3.2. Validation experiment

Once a digital holographic particle velocimetry system has been developed, the results obtained on particle velocities should be verified against some kind of experimental system, in which the particle velocities are already known exactly and easily changed. For this purpose, we used small glass beads on a rotating disk, as shown in Fig. 4. The system consists of a driving motor and a horizontally positioned rotating disk of diameter 300 mm. Glass beads of different sizes were attached to the tips of thin wires of different lengths on the rotating disk. The glass beads were located at radius, $R = 105$ mm. The rotating speed, $\omega$, was each controllable to 756, 1260, and 1524 rpm using a DC power controller, so the actual velocities of glass beads can be calculated easily.

Fig. 5 shows the optical setup for the validation experiment. After setting the rotating disk system in the digital holographic particle velocity measurement system, the double exposure holograms of glass beads can be captured. Fig. 6 shows the typical double exposure holograms and reconstruction images of a glass bead. The




(a) schematic diagram



(b) rotating disk with glass beads

**Fig. 4.** Rotating disk system for validation experiment; (a) schematic diagram, (b) Rotating disk with glass beads.

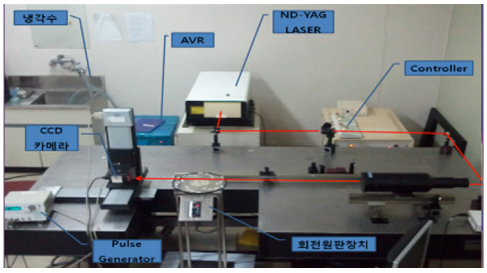
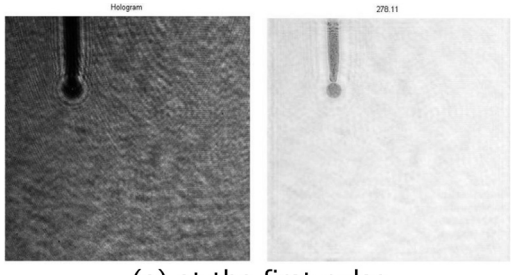
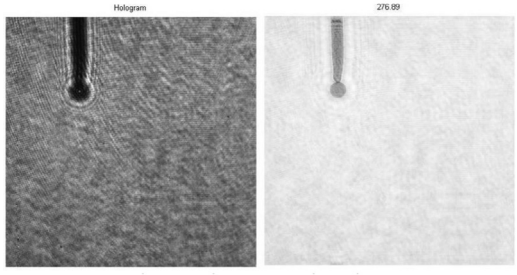



**Fig. 5.** Optical setup for validation experiment. (a) At the first pulse, (b) at the second pulse




(a) at the first pulse




(b) at the second pulse

**Fig. 6.** Typical holograms (left) and reconstruction images (right) of a glass bead at $\omega$ ¯ 756 rpm; (a) at the first pulse, (b) at the second pulse.

measurement results of the velocities of glass beads can be obtained by analysis of reconstruction images. Then, the error can be calculated and the feasibility of the measurement system can be verified. The actual velocities of glass bead can be calculated as 8.31, 13.85, and 16.76 m/s, corresponding to the rotating speed at 756, 1260, and 1524 rpm, respectively.

### 3.3. Uncertainty and error analysis

Before the analysis of the comparison results of measurements and known values, the uncertainty analysis should be performed. The actual velocity of glass bead, $V_a$, can be calculated by

$$V_a = R \times \omega \tag{5}$$

The measurement velocity, $V_m$, can be expressed as,

$$V_m = \sqrt{V_x^2 + V_z^2} \tag{6}$$

where $V_x$ and $V_z$ are the velocities of glass bead at $x$ and $z$ directions in horizontal plane. There is no velocity vector at $y$ direction in vertical plane because the glass beads are fixed on the disk.

The components of particle velocity in each direction are calculated by division of moved distance, $D$, by the time interval of double exposure, $\Delta t$. For $x$, $z$ directions, the distance moved by particle was obtained by multiplying the number of pixels between the center of particles at each exposure, $\Delta N$, by the pixel size of CCD, $\Delta$. They are expressed by

$$V_i = \frac{D_i}{\Delta t} = \Delta N_i \times \frac{\Delta i}{\Delta t} \quad i = x, z \tag{7}$$

The uncertainties of the glass bead velocity are expressed as

$$\begin{aligned} u_{V,a} &= \sqrt{\left(\frac{\partial V_a}{\partial R}u_R\right)^2 + \left(\frac{\partial V_a}{\partial \omega}u_\omega\right)^2} = \sqrt{(\omega u_R)^2 + (R u_\omega)^2} \\ u_{V,m} &= \sqrt{\left(\frac{\partial V}{\partial V_x}u_{V_x}\right)^2 + \left(\frac{\partial V}{\partial V_z}V_z\right)^2} \\ u_{Vi} &= \sqrt{\left(\frac{\partial V_i}{\partial D_i}u_{D_i}\right)^2 + \left(\frac{\partial V_i}{\partial t}u_t\right)^2} = \sqrt{\left(\frac{1}{t}u_{D_i}\right)^2 + \left(\frac{D_i}{t^2}u_t\right)^2} \end{aligned} \tag{8}$$

The comparison of measurement results with actual values is shown in Table 1 including the uncertainties of the velocities of glass beads. As shown in Table 1, the relative error of the velocity measurements by the digital holographic system was within 2.5% of the actual value. The uncertainty of velocity measurement by digital holographic system was lower than 7% of the measured value. The uncertainty of distance measurement in the $z$ direction was much higher than in the $x$ direction due to the difficulty in determining the exact position of particles in the optical axis. All results showed that the digital holographic particle velocity measurement system can work well in measurements of particle velocities.

### 3.4. Measurements of rotational flows

After verifying the feasibility of the digital holographic particle velocity measurement system, we applied the system to the measurement of a rotational flow field which generated by a rotating disk shown in Fig. 7. Using the digital holographic recording system, a series of double exposure holograms of the rotational flow was captured. Typical double exposure holograms are shown in Fig. 8. Recorded holograms were reconstructed and analyzed. The distribution of tracing particles in rotating flow field is shown in Fig. 9 by reconstruction of the hologram one plane by one plane along the optical axis.

**Table 1**
Comparison of measurement results with actual velocities of glass beads.

| Actual velocity (m/s) | | Measured velocity (m/s) | | | Relative error (%) |
|---|---|---|---|---|---|
| RPM | $V_a$ | $V_x$ | $V_z$ | $V_m$ | |
| 756 ± 0.94 | 8.31 ± 0.012 | 1.97 ± 0.049 | 8.13 ± 0.067 | 8.37 ± 0.066 | 0.68 |
| 1260 ± 0.94 | 13.85 ± 0.012 | 1.88 ± 0.049 | 13.87 ± 0.067 | 13.99 ± 0.066 | 0.10 |
| 1524 ± 0.94 | 16.76 ± 0.011 | 2.62 ± 0.049 | 16.13 ± 0.067 | 16.34 ± 0.066 | 2.47 |

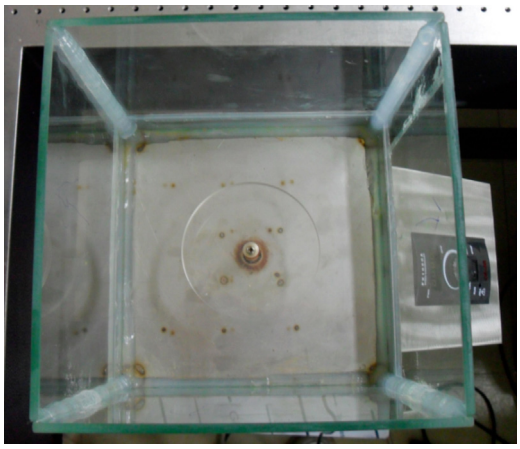


**Fig. 7.** Rotating disk for generating a rotational flow.

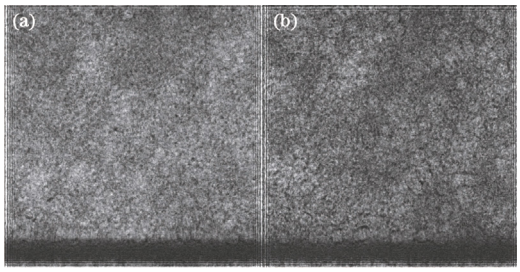



**Fig. 8.** Double exposure holograms of rotating flow field; (a) first exposure, (b) second exposure.

After obtaining the distribution of tracing particles in the first and second exposure holograms, the velocity field of particles can be easily calculated by 3-D Cross Correlation Algorithm [16]. The velocity field of rotating flows is shown in Fig. 10. The velocities of rotating flow field are mainly at $z$ and $x$ directions and the flow toward the rotation disk in the $y$ direction is very weak. In other words, the velocity field is mainly at a plane. This observation also agrees with the theoretical predictions. To verify the accuracy of measurement results, the theoretical predictions of this rotating flow field [17] were calculated. The comparison of theoretical predictions with measurement results is shown in Fig. 11.

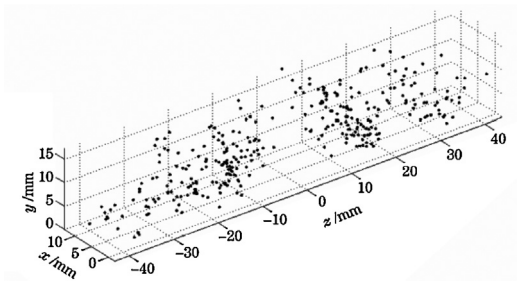



**Fig. 9.** Distribution of tracing particles in rotating flow field.

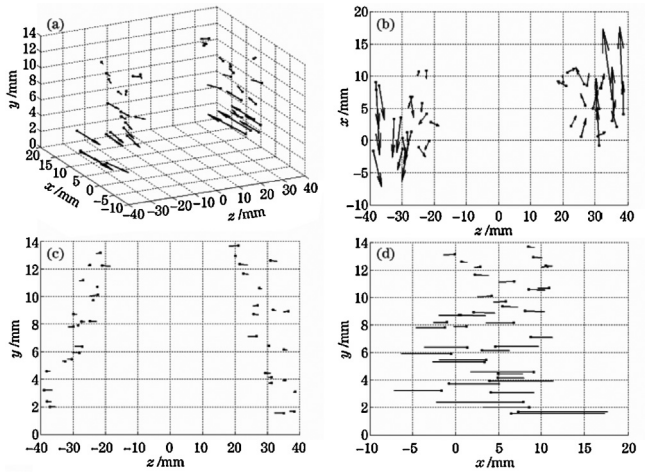



**Fig. 10.** Velocity field of rotating flow; (a) 3D velocity field, (b) projected velocity vectors in $xz$ plane, (c) projected velocity vectors in $yz$ plane, (d) projected velocity vectors in $xy$ plane.

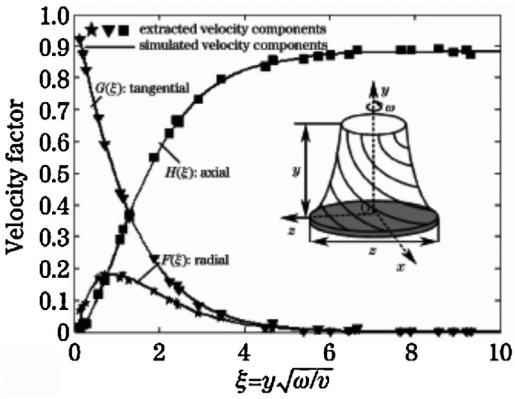



**Fig. 11.** Comparison of measurement results with theoretical predictions.

All experimental results are in good agreement with the theoretical profiles.

## 4. Conclusions

A digital holographic particle velocity system based on double exposure laser system to measure rotational flows was developed, and the 3-D information of the flow field can be obtained. Using the equipment based on the glass beads on a rotating disk, the validation experiments were conducted in order to check the accuracy and feasibility of the digital holographic particle velocity measurement system. After analyzing the uncertainties and all relevant errors, the measurement results of the velocities of glass beads obtained with digital holographic system were compared reasonably well with the known values within acceptable range. Finally, a rotational flow field was measured by the digital particle holographic system, and the 3-D velocity filed of rotational flows was obtained. The feasibility of this system was also verified by the

measurement results which were in good agreement with the theoretical predictions. All experimental results prove that the digital particle holographic system works well in the measurements of rotational flows.

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