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

Y. Yang [a], B.S. Kang [b,*]

[a] Key Laboratory of Advanced Manufacturing Techniques for Automobile Parts (Chongqing University of Technology), Ministry of Education, Chongqing, China

[b] Department of Mechanical Engineering, Chonnam National University, 333 Yongbong-ro, Buk-gu, Gwangju 500-757, Republic of Korea

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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.

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

* Corresponding author. Tel.: +82 625 301 683.
E-mail address: bskang@jnu.ac.kr (B.S. Kang).

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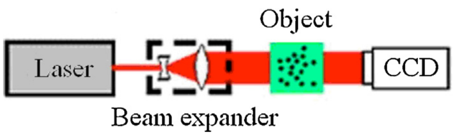

Fig. 1. Principle of in-line digital holography.

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, λ is the wavelength, and ρ 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

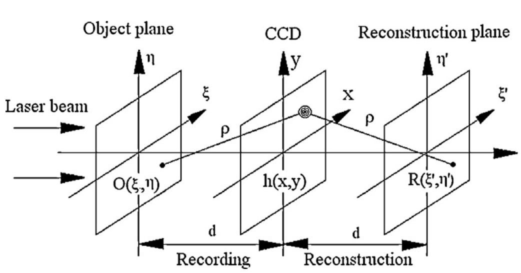

Fig. 2. Coordinate system.

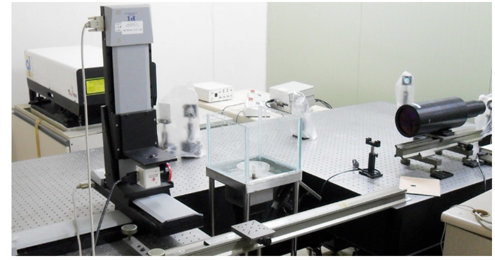

Fig. 3. Digital holographic particle velocity measurement system for rotational flows. (a) Schematic diagram, (b) Rotating disk with glass beads

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, Δ = 7.4 μm, pixel number, N = 2048 × 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, ω, 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