Calibration Plate for Digital Holographic Particle Tracking Velocimetry

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Abstract. A calibration plate for digital holographic particle tracking velocimetry by in-line holography was developed. A quartz plate with a computer-generated hologram pattern is used to determine the distance between an image captured on the plate and a CCD camera to high accuracy. The method allows visual confirmation of the calibration. In addition, the reconstruction of the hologram of a cross marker on plates is demonstrated at distances of 35 mm and 40 mm.

1. Introduction

Holographic particle image velocimetry (PIV) systems using photographic film [1-3] exhibit high quality flow information and allow the recording of instantaneous 3-D velocity fields illuminated by a single beam line. These characteristics are a great advantage over other PIV methods. However, the use of photographic film requires considerable reconstruction process time and makes it difficult to capture the time evolution of a particle image from a single frame recording of instantaneous particles dispersed in a flow field. In contrast, digital holographic techniques using a digital camera can easily capture the time evolution of particles. However, the limitation of digital camera resolution means that they are only used with in-line holograms. Digital holography also requires high-speed computer performance to reconstruct particle locations. Previously, a particle tracking velocimetry (PTV) method for macro flow measurements using digital holograms was developed [4]. Our results are in good agreement with theoretical values. In this paper, a method for calibrating digital PTV systems is presented.

Typically, calibration in PIV or PTV is performed using a metal calibration plate with markers for estimation points [5]. When the image of a marker on the plate is captured by a CCD camera, the exact distance between the object (the plate) and the CCD surface of the camera can be obtained. Hence, an image can be calibrated for camera angle and window size. In addition, the calibration of an image can be confirmed conveniently by eye for fluid experiments. However, calibration methods for PIV using digital holograms have not yet been attempted. A calibration technique for PIV using in-line holograms is particularly needed for penetration material owing
to the fact that the object beam and reference beam are parallel.

For a holographic image, the image of an estimation point marker is seen only as diffraction fringes. Therefore, since it is not possible to read the image by eye, a calibration plate for digital holographic particle tracking velocimetry with visible real estimation points seen by the camera rather than the fringe image was developed. Using the method presented here, the calibration plate is made of quartz with a calibration hologram pattern drawn on the surface by an electron beam (EB) and chemical etching. The hologram pattern includes estimation points that represent distances determined by a computer-generated hologram. This hologram pattern is then used to determine the exact distance between the object and the CCD camera surface.

2. Digital holography

Figure 1 illustrates the technique of image reconstruction by digital holography. The reconstruction of the maker positions (x,y coordinates) from the fringe images in Fig. 1 is performed by an FFT technique using the Fresnel diffraction equation [6,7]. The FFT technique employs the following relationship:

\[
\Phi(I,J) = \int_{-N1/2}^{N1/2} \int_{-N2/2}^{N2/2} H(x,y)G(I,J) \exp[-2\pi i(Ix + Jy)] \, dx \, dy = \hat{H}(I,J)G(I,J).
\] (1)

Here, \(\Phi(I,J), H(x,y)\) and \(\hat{H}(I,J)\) are the reconstructed image in Fourier space, the hologram image, and the hologram image in Fourier space, respectively. \(I\) and \(J\) are the pixel points in the x-direction and y-direction. \(N1\) and \(N2\) are the pixel number in the x-direction and y-direction. \(G(I,J)\) is a transform function using the Fresnel approximation, as detailed in Refs. [6,7].

In Eq.(1), \(H(x,y)\) is realized in real space. Therefore, the translation from Eq. (1) to get the real maker image \(H(x,y)\) is considered. The two-dimensional image of \(H(x,y) = \mathcal{F}^{-1}[\Phi(I,J)/G(I,J)]\) is drawn on a material with a penetration. \(G(I,J)\) contains the reconstruction information for distance \(d\), the distance between the original object and the hologram image. When the hologram pattern is created by a computer-generated hologram, the distance between the camera and object can be determined highly accurately.

![Figure 1. Theory of hologram reconstruction.](image-url)
3. Fabrication of hologram plate

Figure 2 shows a target marker in the shape of a cross. Figure 3(a) shows the computer-generated hologram of the cross and Fig. 3(b) shows the reconstructed image of the cross obtained from a computer-generated hologram.

![Figure 2. Original cross marker.](image)

![Figure 3. Cross marker for image; (a) Computer-generated hologram of a cross marker (b) Reconstruction of the cross marker from the computer-generated hologram.](image)

The hologram in Fig. 3(a) is reproduced on a quartz plate, as shown in Fig. 4. Quartz is used for the holographic plate, because it is transparent to the laser wavelength of 527 nm used in this study.

![Figure 4. Cross marker from computer-generated hologram is drawn on quartz plate.](image)

The holographic patterns must be precise, and therefore electron beam (EB) lithography is used for their fabrication. However, as quartz is an electrical insulator, charging during the EB writing distorts the resist patterns on the quartz. To prevent charging, a 5-nm conductive polymer ESPACER (Showa Denko K.K.) layer is spin-coated over a 300-nm positive polymethylmethacrylate (PMMA) resist layer.

This sample is exposed using an EB at an acceleration voltage of 10 kV. The exposed resist
is developed in a 1:3 mixture of methyl isobutyl ketone (MIBK) and isopropyl alcohol (IPA). A 100-nm thick Cr layer is deposited using an EB evaporation process, and then lifted off in acetone. At the completion of the process the residual Cr patterns form the holographic image.

The computer-generated hologram in Fig. 3(a) was made binary by four gradation steps. It was then numerical reconstructed as shown in Fig. 3(b), confirming that the original image of a cross was restored. A photograph of the image in Fig. 3(a) transcribed using EB lithography on the quartz plate is shown in Fig. 4. In the photograph the smallest division shown on the scale accompanying the hologram is 10 μm.

4. Experimental setup

Figure 5 shows the experimental setup for reconstructing an image, including a laser, beam expander, traverse facility for holographic plate, and CCD camera. A Nd:YLF laser (Photonic Industries DS20-527, λ = 527 nm) is used, which outputs a pair of laser pulses at a repetition rate of 1 kHz. When the light strikes a marker, it creates hologram fringes that are captured by the high-resolution digital CCD camera (Redlake, MotionPro X3) with a resolution of 1280 pixel × 1024 pixel (12 μm/pixel).

5. Result and discussion

In the setup of Fig. 5, the plate can be traversed (moved forward or backward along the optical axis of the setup) by a micro-meter with a resolution of 10 μm. Two plates were designed by the method presented in section 4: plate A (Fig. 6) is designed for focusing at \( d^0 = 35 \) mm and plate B (Fig. 7) for focusing at \( d^0 = 40 \) mm.

![Figure 5. Experimental setup.](image)

![Figure 6. Reconstruction images on quartz plate A in each z-distance.](image)

Figures 6 and 7 show optically reconstructed images of the holograms, along with an enlargement of the center, for the two plates at various distances \( d' \) between the plate and
CCD surface of 30, 35, 40, and 45 mm, recorded by the CCD camera, from a series of images taken between 30 to 45 mm in 1-mm steps.

In Fig. 6, the image of the cross is best resolved in (b) \((d' = 35\, \text{mm})\). In Fig. 7, (c) \((d' = 40\, \text{mm})\) is the best resolved. This is in good agreement with the theoretical distances. To more accurately examine the focusing, the brightest points detected for plates A and B are shown in Fig. 8.

The maximum brightness value represents the maximum value measured for \(2 \times 2\) pixels at four points at the top, bottom, left, and right of the cross. The peak points in Fig. 8 correspond precisely with the theoretical focusing points, namely 35 mm for plate A and 40 mm for plate B.
6. Conclusion
A calibration plate with a pattern for calibration designed by a computer-generated hologram was developed and reconstruction of the hologram pattern at 35 mm and 40 mm was demonstrated.

The object-camera distance in the reconstructions is highly accurate. It is evident that the plate can be used for calibration for digital holographic particle tracking velocimetry.

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