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Tilt Aberration Compensation Using Interference Patterns in Digital Holography

Hyungjun Cho, Doocheol Kim, and Younghun Yu*

Department of Physics, Cheju National University, Jeju 690-756, Korea

Sanghoon Shin

AP & Tec, Suseo-dong, Gangnam-gu, Seoul 135-539, Korea

Wongi Jung

School of Electrical Engineering, Jeonju University, Jeonju 560-759, Korea

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We present a numerical procedure that compensates for tilt phase aberration in in-line digital holography by computing the period of interference patterns in the reconstructed phase image. This method enables the reconstruction of correct and accurate phase information, even if strong tilt aberrations exist. Example applications of tilt aberration compensation are shown for a tilted plate, a micro-lens array, and a thin film transistor. This method is convenient because it uses only one hologram and no hardware to minimize the tilt aberration.

Keywords : Holography, Image reconstruction, Diffractive optics
OCIS codes : (090.0090) Holography; (100.3010) Image reconstruction techniques; (050.1970) Diffractive optics

I. INTRODUCTION

Holography is a way of recording phase modulation by using the light reflected or transmitted from a projected object onto a photo-plate in the form of interference patterns. Object and reference beams are required for the recording, and an interference pattern is generated from the combination of the two beams. In the past, the interference patterns were recorded on film plates, but now charge-coupled devices (CCDs) or complementary metal-oxide semiconductor cameras are normally applied, and a computer is used to reconstruct the hologram.

Yaroslavskii and colleagues proposed a method of numerical hologram reconstruction in the 1970s, and Onural and Scott used numerical reconstruction to measure the size of a particle after improving on the reconstruction algorithm [1-6]. This method of digitally recording and reconstructing a numerical hologram is known as digital holography (DH) [7-10], which has many advantages. For example, it requires no chemical processing because the reconstructed image can be observed easily on a computer monitor, and experts can obtain numerical data for three-dimensional (3-D) objects [11, 12].

Two types of DH exist, off-axis and in-line. In off-axis DH, tilt aberration occurs if the sample plane is not parallel to the CCD. To achieve a good image, one must remove this aberration. In off-axis DH, the tilt aberration is unavoidable because the reference wave is not parallel to the object wave. Many studies have reported on tilt aberration removal in off-axis DH, e.g., through numerical parametric lenses or reference conjugated holograms [13-15]. However, few studies have addressed tilt aberration removal in in-line DH, in which hardware is used to remove the tilt aberration. This method is also applied in normal image acquisition systems, e.g., confocal and normal microscopes. The method, however, depends on the environment and is inconvenient.

We studied the elimination of tilt aberrations in in-line DH using a numerical technique. This method used only one hologram. The reconstructed phase image contains the tilt aberration information, and extraction of this information allows a corrected hologram free of tilt aberration.

*Corresponding author: yyhyoung@cheju.ac.kr

II. THEORETICAL MODEL

1. Digital Holography

In the hologram recording process, a plane reference wave R and a diffusively reflected object wave O interfere at the CCD. The hologram intensity is given by

$$I_H(x,y) = |R|^2 + |O|^2 + R^*O + RO^*, \tag{1}$$

where R^* and O^* are the complex conjugates of the reference and object waves, respectively [1, 2]. The digital holographic image can be recorded using a black-and-white CCD camera. The digital hologram $I_H(k,l)$ is an $N \times X$ array resulting from the two-dimensional (2-D) sampling of $I_H(k,l)$ by the CCD camera. It is given by

$$I_H(k,l) = I_H(x,y)\mathrm{rect}(\frac{x}{L},\frac{y}{L}) \times \Sigma_{k=-N/2}^{N/2} \Sigma_{1=-N/2}^{N/2} \delta(x-k\Delta x, y-l\Delta y), \tag{2}$$

where Kandl are integers, $L \times L$ is the area of the CCD chip, and Δx and Δy are the pixel sizes of the CCD.

If a screen is placed at a distance d behind the hologram, a real image is formed on it. Mathematically, the amplitude and phase distributions in the plane of the real image can be found using the Fresnel–Kirchhoff integral [1, 2]. If a plane wave illuminates the hologram with an amplitude transmittance $I_H(x,y)$, the Fresnel–Kirchhoff integral yields a complex amplitude $\psi(\xi,\eta)$ in the real image plane,

$$\Psi(\xi,\eta) = \frac{\exp(\frac{iz\pi d}{\lambda})}{i\lambda d} \iint (R(x,y)I_H(x,y)\exp\left\{\frac{i\pi}{\lambda d}[(x-\xi)^2+(y-\eta)^2]\right\}dxdy, \tag{3}$$

where λ is the wavelength, R(x,y) is the reference wave and d is the reconstruction distance. Because $\psi(\xi,\eta)$ is an array of complex numbers, one can obtain an amplitude- contrast image using the intensity

$$I(\xi,\eta) = \mathrm{Re}[\Psi(\xi,\eta)]^2 + \mathrm{Im}[\Psi(\xi,\eta)]^2, \tag{4}$$

The phase image is obtained by calculating the argument

$$\Psi(\xi,\eta) = \tan^{-1}\left\{\frac{\mathrm{Im}[\Psi(\xi,\eta)]}{\mathrm{Re}[\Psi(\xi,\eta)]}\right\}, \tag{5}$$

The real 3-D information is acquired by phase unwrapping this image.

2. Elimination of Tilt Aberration

Generally, the object wave contains tilt aberrations when the object plane is not parallel to the CCD plane. This aberration $\exp\left[i\frac{2\pi}{\lambda}(k_x x + k_y y)\right]\exp(i\phi(t))$ is included in Eq. (3). k_x and k_y define the propagation direction and $\phi(t)$ is the phase difference between the reference and object wave with time. $\phi(t)$ depends on the environment, and is not considered here. If no tilt aberration exists, $\exp\left[i\frac{2\pi}{\lambda}(k_x x + k_y y)\right]$ will be equal to 1.

To eliminate the aberration, this information should be extracted from the reconstructed image. We used the modulation properties of a 2-D Fresnel transform to acquire the tilt information from the phase image. The Fresnel transform (ft) is defined as

$$ft[f(x,y)](\xi,\eta) = \frac{1}{\lambda d}\iint f(x,y)\exp\left\{\frac{i\pi}{\lambda d}[(x-\xi)^2+(y-\eta)^2]\right\}dxdy, \tag{6}$$

which has the modulation property [16]

$$ft[\exp(i2\pi\nu x)f(x)](\xi,\eta) = \exp(i2\pi\nu x\xi)\exp(-i\pi\nu^2(\lambda d)^2)^* \; ft[f(x)](\xi-\nu_x(\lambda d)^2, \eta-\nu_{yx}(\lambda d)^2), \tag{7}$$

where $\mathbf{x} = (x,y)$, $\xi = (\xi,\eta)$, and $\nu = (\nu_x, \nu_y)$. $V_x = k_x/\lambda$ and $V_y = k_y/\lambda$ are the spatial frequencies. With this definition, the complex wave including the tilt aberration can be written as

$$\Psi(\xi,\eta) = -i\exp(\frac{i2\pi d}{\lambda})\, ft[RI_H](\xi,\eta) = -i\exp(\frac{i2\pi d}{\lambda}) ft\left\{R * \exp\left[i\frac{2\pi}{\lambda}(k_x x + k_y y)\right]\exp[i\phi(x,y)]I_H\right\}(\xi,\eta). \tag{8}$$

Eq. (8) becomes

$$\Psi(\xi,\eta) = -i\exp(\frac{i2\pi d}{\lambda}) * \exp\left[i\frac{2\pi}{\lambda}(k_x\xi + k_y\eta) + i\phi(x,y)\right]^* \exp\left\{-i\pi\lambda d\left[(\frac{k_x}{\lambda})^2 + (\frac{k_y}{\lambda})^2\right]\right\} ft[I_H](\xi + k_x d, \eta + k_y d) \tag{9}$$

From Eq. (9), the tilt aberration information $\exp\left[i\frac{2\pi}{\lambda}(k_x x + k_y y)\right]$ is outside of the Fresnel integration. This means that the tilt aberration does not affect the phase information of the sample. This tilt can be compensated for by multiplying the reconstructed wave front using a correcting term that is calculated from the mathematical model of a plane wave. The tilt aberration information (the interference pattern) exists in the phase reconstruction image. The tilt aberration is therefore removed by the following steps:

(i) Reconstruction of the phase image using the recorded hologram.
(ii) Extraction of the tilt information (k_x and k_y) from the interference pattern in the phase image.
(iii) Correction of the hologram and the reconstruction phase image.

III. EXPERIMENTAL SETUP AND RESULTS

Figure 1 shows a schematic of a transmission holographic microscope. The basic experimental setup is similar to that of a Mach–Zehnder-type interferometer. A 10-mW He–Ne laser served as the light source, and the objective lens of a microscope (ML) was used to expand the beam passing through the sample. We used neutral-density filters to obtain the interference patterns for maximum contrast, a beam expander for the reference beam in the TEM_{00} mode, and a CCD camera (Sony IPX4M15L) to record the holograms. The pixel size and number of pixels were 7.4 μm × 7.4 μm and 1024 × 1024, respectively. The CCD was placed 10 cm from the ML, and the overlapping angle between the reference and objective rays was maintained at 0°, resulting in in-line holography.

Figure 2 presents the experimental results for the tilt plate. Figure 2(a) shows the hologram and (b) the reconstructed phase image, while (c) shows the phase-unwrapped, 3-D grayscale image. Figure 2(b) clearly indicates that the interference pattern is as expected from Eq. (9). This pattern includes the tilt information. The period of the pattern depends on the tilt angle and distance between the reconstruction and CCD planes. As expected from Eq. (9), we can acquire the tilt information by measuring the period of the interference pattern. We calculated the correction phase, $k_x\hat{x}+k_y\hat{y}=0.001169\hat{x}+0.000369\hat{y}$, from the periods of the interference patterns. We then corrected the hologram using the correction term and reconstructed phase image (Figure 2(d)). Clearly, this removed the interference patterns caused by the tilting. Figure 2(e) shows the phase unwrapped image reconstructed from the corrected hologram. The insets in Figures 2(c) and (e) indicate the incline of the sample plane with the white dotted line. These results demonstrate the feasibility of removing the tilt aberration numerically.

Figure 3 shows experimental results for a thin film transistor (TFT) on glass. The pattern was fabricated by a photo-resistor. Figure 3(a) presents the digital hologram of the TFT and (c) shows the grayscale phase-unwrapped image. We corrected the hologram using $k_x\hat{x}+k_y\hat{y}=0.00195\hat{x}$. The reconstructed phase image with corrected hologram is given in Figure 3(d). Figure 3(e) presents the phase-unwrapped image with corrected phase image, with the tilt aberration removed. Figure 4 shows experimental results from a micro-lens array; the height and diameter of the micro-lens were 50 μm and 30 μm, respectively. We used index-matching oil to remove 2π ambiguities. Figures 4(a) and (d) show the phase images without and with correction, respectively. Figures 4(b) and (e) present the phase unwrapped image, while Figures 4(c) and (d) show the lens profile of the phase- unwrapped images. The profile of the lens is clearly asymmetrical in Figure 4(c). This asymmetry, which is caused by the tilt aberration, is removed by the tilt correction [Figure 4(f)]. These experimental results demonstrate that the tilt aberration is corrected using the periods of an interference pattern in the reconstructed

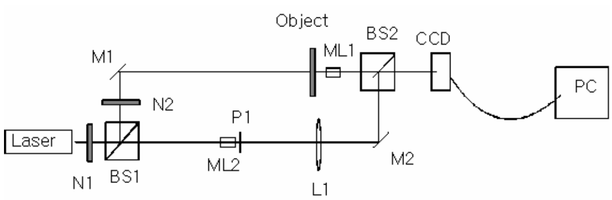

FIG. 1. Transmission-type digital holographic microscope. BS: beam splitter; M: mirror; ML: microscope objective lens; CCD: charge-coupled device.

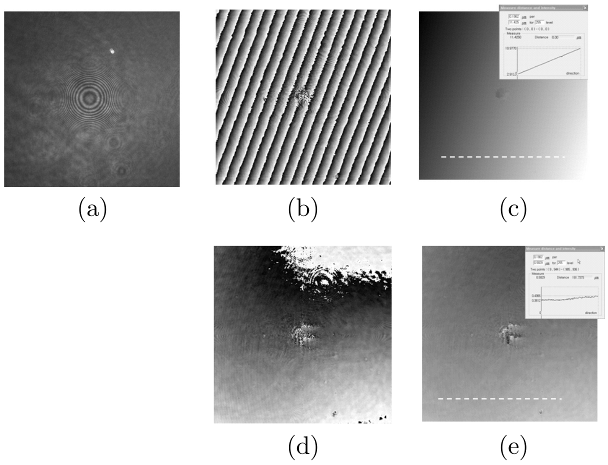

FIG. 2. Tilt aberration removal. (a) Digital hologram of the tilt plate, (b) reconstructed phase image of the digital hologram, (c) phase unwrapped grayscale image, (d) phase image with corrected hologram, and (e) phase unwrapped grayscale image with corrected hologram.

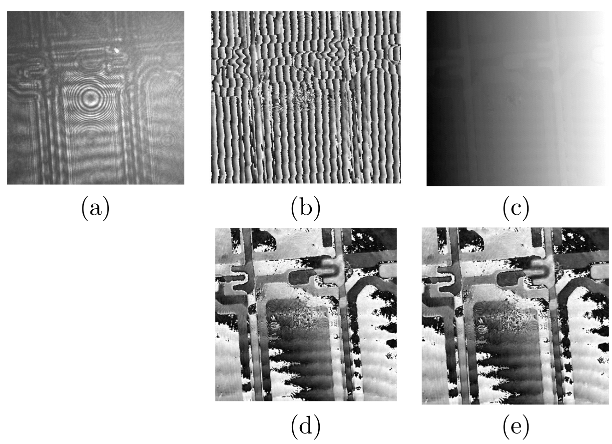

FIG. 3. Tilt aberration removal for a TFT. (a) Digital hologram of the tilt TFT, (b) reconstructed phase image of the digital hologram, (c) phase unwrapped grayscale image, (d) phase image with corrected hologram, and (e) phase unwrapped grayscale image with corrected hologram.

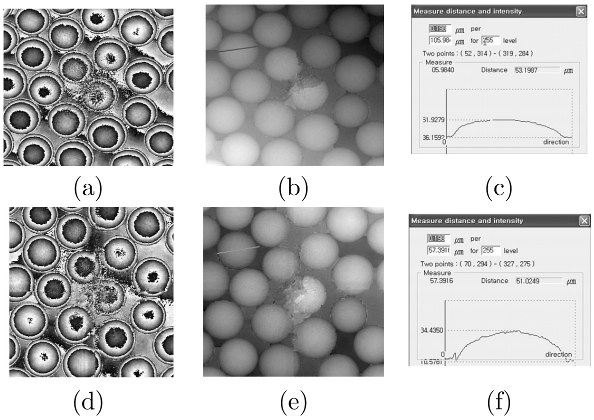

FIG. 4. Tilt aberration removal for a micro-lens array. (a) Reconstructed phase image with recorded digital hologram, (b) phase unwrapped image of (a), (c) lens 3-D profile of (b), (d) reconstructed phase image with corrected digital hologram, (e) phase unwrapped image of (d), and (f) lens 3-D profile of (e).

phase image.

Normally, it is very hard to separate the phase image in a reconstructed image because object image is composed of phase and contrast. In this paper, we propose the method of separating the phase image from a reconstructed phase image manually. However it is necessary to separate the tilting phase information automatically to apply to scientific areas. For a specimen with a flat surface, it is possible to separate the tilting information automatically as shown in figure 2. But for an arbitrarily shaped specimen without flat surface, it is hard to separate the tilting information from a reconstructed phase image automatically. We will study how to separate the tilt information from a reconstructed phase image automatically and how to correct the method systematically in future work.

IV. CONCLUSIONS

Digital holographic microscopy can be used to measure optical path differences with a high degree of accuracy, which allows the storage of 3-D information. To retrieve this information, phase images without aberrations are necessary. Many possible anomalies such as spherical and tilt aberrations exist, and if the phase image includes them, the acquired 3-D information is not the same as the sample morphology. Tilt aberrations are caused by nonparallel sample and image acquisition sensor (CCD) planes. We presented numerical methods that compensate for tilt aberrations in in-line digital holography. Generally, tilt aberrations are minimized by the use of a well designed optical system and by mechanical adjustment. Our system has the advantages of using only the hologram. To eliminate the tilt aberration in in-line digital holography, we used a corrected hologram. The tilt aberration information exists in the reconstructed phase image, and the hologram, which includes the tilt aberration, could be adjusted by correction terms that were extracted from the reconstructed phase image. We showed that tilt aberration could be removed by the corrected hologram. This method is convenient because it does not use hardware to minimize the tilt aberration. However it is necessary to separate the tilting phase information automatically to apply scientific areas. We will study how to separate the tilt information from a reconstructed phase image automatically and how to correct the method systematically in future work.

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