Complex amplitude reconstruction and phase aberrations compensation in phase-shifting in-line image digital holographic microscopy

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When an image digital holographic microscopy (DHM) layout is employed, the Fresnel integral cannot be used in separating the reconstructed image from its conjugate image and background. However, combining image plane DHM with the phase-shifting in-line technique, the complex amplitude of reconstructed image can be obtained without using Fresnel integral, moreover the approximate error of reconstruction calculation is easily eliminated and the signal-to-noise ratio of reconstructed image is significantly improved. Since a normal incidence plane wave is used as the reference wave, the difficulty and complexity of phase aberration and phase unwrapping of DHM are remarkably decreased.

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Digital holographic microscopy (DHM)[1] is a powerful optical metrology for simultaneously obtaining amplitude and phase of a sample, and has been widely used in a variety of technical fields such as profile of three-dimensional (3D) objects[2,3], concentration change distribution[4], measurement of particles flow field[5], structures of biological specimens[6], micro-electro-mechanical system (MEMS)[7], etc.

In conventional DHMs, a microscope objective (MO) and off-axis geometry are usually used in recording, and an image sensor named charge-coupled device (CCD) array is placed between MO and the image plane. In general cases, the reconstruction of digital hologram is performed through Fresnel integral, followed by the phase aberrations compensation of curvature and tilt for phase recovering. Some compensation methods of phase aberrations of DHM have been reported[6,8−10]. The basic phase compensation method is to search for a digital reference wave for compensation of tilt aberration and a digital phase mask for compensation of quadratic-phase curvature[8]. An ameliorated method is to make the adjustment implement as a semi-automated procedure[9]. For another, by performing a two-dimensional (2D) fitting with Zernike polynomials, the reconstructed unwrapped phase curvature and tilting can be compensated[6]. Furthermore, by directly calculating a polynomial phase mask from the hologram, phase aberrations of DHM can also be compensated[10]. However, these compensation methods are complicated and time-consuming for their reconstruction being performed through Fresnel integral or complex iterative calculation.

In this letter, we present a new phase aberration compensation method based on the combination of image plane DHM with phase-shifting in-line technique to record and reconstruct digital hologram directly without using Fresnel integral, and then a digital phase mask is employed to perform phase aberration compensation.

Figure 1 depicts the optical configuration of phase-shifting in-line geometry to record DHM of transparent objects. The basic architecture is a Mach-Zehnder interferometer (MZI). A magnified image of object imaged by MO is used as an object wave $O(x_{\rm H}, y_{\rm H})$. A plane wave, which is perpendicular to the CCD surface, is used as reference wave $R(x_{\rm H}, y_{\rm H})$ in another branch. The phase of $R(x_{\rm H}, y_{\rm H})$ can be shifted by a movable mirror driven by a piezoelectric ceramics. By shifting the reference wave phase sequentially by 0, $\pi/2$, π, and $3\pi/2$, four corresponding phase shifting in-line holograms $I_n(x_{\rm H}, y_{\rm H})$ (n = 1, 2, 3, 4) are recorded, and a four-step phase-shifting digital hologram is obtained as[2,11]

$$\begin{aligned} I_{\rm PS}(x_{\rm H}, y_{\rm H}) = &\ O(x_{\rm H}, y_{\rm H})R^*(x_{\rm H}, y_{\rm H}) \\ &= [(I_1 - I_3) + {\rm j}(I_2 - I_4)]/4. \end{aligned} \tag{1}$$

From Eq. (1), we can see that the background $| O |^2 + | R |^2$ and the virtual image RO^* have been eliminated by using phase-shifting technique.

Figure 2 is the configuration for a DHM. In the figure, f is the focus of MO, $d_{\rm o}$ and $d_{\rm i}$ are the object and image distances from MO, respectively, then the image on the

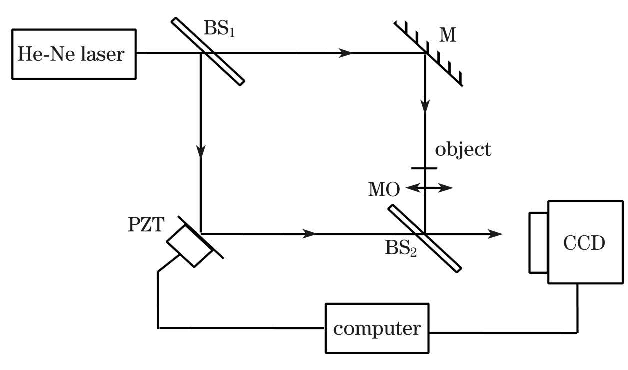

Fig. 1. Experimental setup for recording phase-shifting in-line DHM. BS_1, BS_2:beam splitters; PZT: piezoelectric transducer actuator.

CCD array plane can be expressed as[8]

$$O(x_{\rm H}, y_{\rm H}) = |O(x_{\rm H}, y_{\rm H})|$$
$$\exp[\frac{{\rm j}\pi}{\lambda D}(x_{\rm H}^2 + y_{\rm H}^2) + \varphi_{\rm O}(x_{\rm H}, y_{\rm H})], \quad (2)$$

where $\varphi_{\rm o}(x_{\rm H},\ y_{\rm H})$ denotes the object phase, and D is a parameter used to compensate the wavefront curvature, which is denoted as[8]

$$\frac{1}{D} = \frac{1}{d_{\rm i}}(1 + \frac{d_{\rm o}}{d_{\rm i}}). \quad (3)$$

The wavefront curvature in Eq. (2) can be compensated by the following digital phase mask[8]:

$$\Phi(x_{\rm H}, y_{\rm H}) = \exp[-\frac{{\rm j}\pi}{\lambda D}(x_{\rm H}^2 + y_{\rm H}^2)]. \quad (4)$$

While a digital hologram is reconstructed, a digital reference wave[8−10] $R_{\rm D}(x_{\rm H},\ y_{\rm H})$, which should be replica of the reference wave $R(x_{\rm H},\ y_{\rm H})$, is multiplied with the digital hologram[8,9]. In our case, it can be written as

$$R_{\rm D}(x_{\rm H}, y_{\rm H}) = A_{\rm R}\exp[\frac{{\rm j}2\pi}{\lambda}(k_x x_{\rm H} + k_y y_{\rm H})]. \quad (5)$$

In our study, the CCD is exactly located at the image plane, thus the image digital hologram of object is recorded. In this situation, Fresnel integral cannot be used any more. However, the combination of image plane digital holographic microscopy with phase-shifting in-line technique induces not only the calculating process to be simplified, but also high quality reconstructed image to be obtained. The complex amplitude of reconstructed image can be directly described as

$$U_{\rm r}(x_{\rm H}, y_{\rm H}) = \Phi(x_{\rm H}, y_{\rm H}) I_{\rm PS}(x_{\rm H}, y_{\rm H}) R_{\rm D}(x_{\rm H}, y_{\rm H}). \quad (6)$$

Therefore the complex amplitude is directly reconstructed in the image plane.

The amplitude image and the phase-contrast image can be respectively calculated as

$$I(x_{\rm H}, y_{\rm H}) = U_{\rm r}(x_{\rm H}, y_{\rm H}) U_{\rm r}^*(x_{\rm H}, y_{\rm H}), \quad (7)$$
$$\varphi_{\rm O}(x_{\rm H}, y_{\rm H}) = \arctan\{\frac{[{\rm Im}(U_{\rm r}(x_{\rm H}, y_{\rm H}))]}{[{\rm Re}(U_{\rm r}(x_{\rm H}, y_{\rm H}))]}\}. \quad (8)$$

The experimental result is presented in Fig. 3. The sample is the 25th element in Chinese standard No. 3 resolution test pattern, which consists of four groups of gratings with grating constant $d = 20\ \mu$m. Firstly, the sample is imaged on the CCD array surface by a 4 × MO, and interferes with the plane reference wave which is perpendicularly incident to the image plane, then shifting reference wave phase sequentially by 0, $\pi/2$, π, and $3\pi/2$, respectively. Thus four phase shifting in-line holograms are recorded, and one of them is shown in Fig. 3(a). Figure 3(b) is the reconstructed amplitude image which is actually obtained by directly calculating the modulus square of the four-step phase-shifting hologram, as shown in Eq. (1). Figure 3(c) shows the reconstructed phase of the marked white rectangle in Fig. 3(a), and Fig. 3(d) is the corresponding 3D presentation of Fig. 3(c), which is calculated by Eq. (8). It can be clearly seen that the wavefront curvature has been compensated by the digital phase mask in Eq. (4). Moreover, because a normal incidence plane wave is used as the reference wave, the difficulty and complexity of phase unwrapping and reconstruction are obviously decreased.

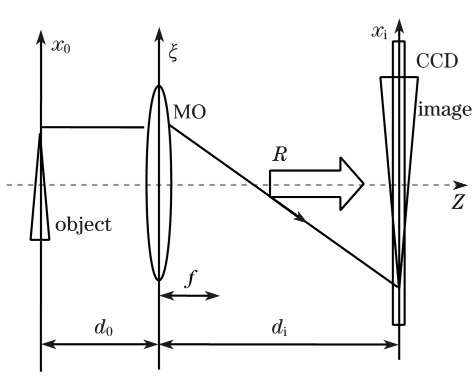

Fig. 2. Coordinate system for image formation.

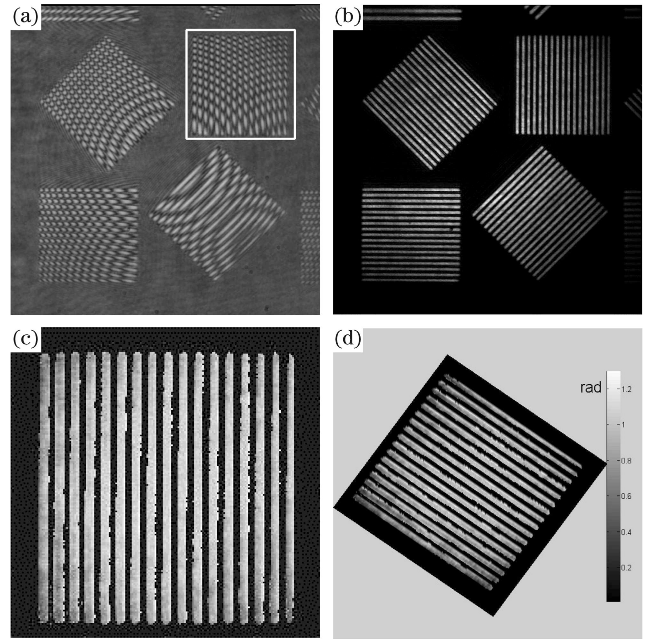

Fig. 3. Reconstructed amplitude and phase of a Chinese standard No. 3 resolution test pattern. (a) One of four digital holograms; (b) amplitude-contrast image reconstructed form (a); (c) phase-contrast image reconstructed from the marked rectangle of (a); (d) 3D presentation of (c).

From above analysis and experimental results, we can conclude some advantages about the combination of the image plane DHM with the phase-shifting in-line technique for the reconstruction of complex amplitude and the compensation of phase aberrations. Firstly, the reconstructed image can be quickly obtained without calculating Fresnel integral since the sample is exactly imaged on the CCD target plane. Secondly, the separation of reconstructed image from its conjugate and background can be performed easily, and the signal-to-noise ratio of reconstructed image is significantly improved because the phase-shifting technique is employed. Thirdly, since the in-line geometry is used, instead of conventional off-axis geometry, the tilt phase aberrations are easily eliminated and the phase unwrapping is simplified. Furthermore, a digital phase mask is useful to perform the compensation of phase aberrations. Therefore the combination of image plane DHM with phase-shifting in-line technique should be a good candidate to perform complex amplitude reconstruction and phase aberration compensation of DHM.

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