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Imaging on the surfaces of an uneven thickness medium based on hybrid phase retrieval with the assistance of off-axis digital holography

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ABSTRACT

A hybrid phase retrieval method with the assistance of off-axis digital holography is proposed for imaging objects on the surfaces of a transparent medium with uneven thickness. The approximate phase distribution is obtained by a constrained optimization approach from the off-axis hologram, and it is used in an iterative procedure for retrieving the complex field of the object from the Gabor hologram. Furthermore, principal component analysis is introduced for compensating for phase aberrations caused by the medium. Numerical simulations and optical experiments were carried out to validate the proposed method. The quality of the reconstructed image is improved remarkably compared to only off-axis digital holography.

1. Introduction

Digital holography (DH) refers to the acquisition of holograms with a digital image sensor, typically a CCD or CMOS camera, and the reconstruction of object by numerical calculation from the digitized holograms [1]. With DH, the intensity and phase of the object wave can be measured, stored, transmitted, applied to simulations and manipulated with the computer [2]. In recent years, DH has been improved by various techniques for enhancing the resolution [3–8], suppressing the speckle noise [9,10], eliminating the zero-order and twin images [11–14], and so on. It is increasingly applied in 3-D measurement [15–17], biological detection [18–20], particle tracing and sizing [21,22], etc. However, almost all the previous studies of DH were based on a prerequisite that the objects must be in a homogeneous medium or on the flat surface of the medium.

Actually, in some practical applications, objects may be on the surface of a transparent medium with uneven thickness or in its interior. In these cases, the diffracted pattern of the object is deformed or destroyed by the refracted light of the medium. In our previous research, we proposed a method to image on the irregular surfaces by dual-plane on-axis DH with stochastic illumination [23]. However, the resolution of the system is low because of the speckle noise caused by the random phase of stochastic illumination, and the phase image of the object cannot be obtained. As we discussed in [23], when a plane light wave passes through a transparent medium with uneven thickness, the longer the propagation distance, the greater the intensity difference, which is the difference between the maximum intensity of the glare spot and the minimum intensity of the dark area in the recording plane; the distribution of the light is also more dispersed. Owing to the limitation of the dynamic range of the digital sensor array, and in order to record more information of the object wave, the image sensor is required to be as close as possible to the object plane.

In traditional off-axis DH, in order to separate the +1, 0 and −1 spectra of the hologram, the distance between the object plane and the recording plane should conform to [24]

$$z > \frac{4\delta(L + M\delta)}{\lambda}, \tag{1}$$

where λ is the wavelength of light, δ is the size of a pixel of the image sensor, M is the number of pixels in the x or y directions of the image sensor and L is the size of the object target. Therefore, traditional off-axis DH is not suitable for imaging on the surface of a transparent medium with uneven thickness. Khare et al. [12,25] suggested a constrained optimization approach for the demodulation of a hologram. An averaging filter is used as the smoothness constraint to suppress the carrier-frequency component and its second harmonic. This approach can provide a reconstruction with a single hologram, even when the

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DC and the cross terms overlap in the frequency domain. Therefore, it is not limited by Eq. (1). However, the resolution of the system decreases because the high-frequency components of the image are inevitably suppressed in the average filtering. Phase-shifting technique was proposed to eliminate the twin image in on-axis or slightly-off-axis DH [26,27]. However, it requires a precise phase-shifting device. Gabor DH can recording a hologram at a very short distance for high resolution, such as on-chip microscopy [28]. Phase retrieval algorithms [11,14,29] are used frequently to eliminate the twin image; however, they are only suitable for sparse objects or transparent objects with a small phase fluctuation.

Some studies have reported that the high-frequency information of objects can be obtained more effectively by in-line DH, and off-axis DH is more favorable for the reconstruction of low-frequency information [30–32]. Therefore, hybridization approaches [33,34] have been proposed for improving the quality of the reconstructed image. In the method presented in the reference [34], a rough support estimation and the spectrum of object term obtained from off-axis hologram are employed to assist the phase retrieval of an in-line hologram. However, this method is not suitable for imaging objects on the surface of a transparent medium with uneven thickness.

In this paper, we present a new hybrid phase retrieval method with the assistance of the approximate phase distributions in the recording plane and object plane obtained from the off-axis hologram. After reconstructing the precise phase, automatic aberration compensation, such as presented in Refs. [35] and [36], can be used to eliminate the influence of the uneven thickness medium. Here, we choose the principal component analysis (PCA) method. The remainder of the paper is organized as follows. In Section 2, the principles and hybrid phase retrieval algorithms are described. The compensation method of the medium phase is described in Section 3. The simulations are presented in Section 4. The proposed method is verified by experiments in Section 5. Finally, Section 6 is a brief conclusion.

2. Hybrid phase retrieval with the assistance of off-axis digital holography

As shown in Fig. 1, a monochromatic plane wave with unit amplitude is incident on the object plane (x_0, y_0) along the positive z direction. We assume that the amplitude and the phase distribution of the wave immediately behind the object plane are $t(x_0, y_0)$ and $\phi_0(x_0, y_0)$, respectively. Then, the complex amplitude distribution immediately behind the object plane is

$$O_0(x_0, y_0) = t(x_0, y_0)\exp\{j\phi_0(x_0, y_0)\}. \tag{2}$$

According to the angular spectrum approach, the complex field of the object wave in (x, y) plane can be written as

$$O(x, y) = \mathrm{FT}^{-1}\{\mathrm{FT}\{O_0(x_0, y_0)\}H(f_x, f_y, z)\}, \tag{3}$$

where FT and FT^{-1} denote the Fourier Transform and inverse Fourier Transform respectively, and $H(f_x, f_y, z) = \exp\left[j\frac{2\pi}{\lambda}z\sqrt{1-\lambda^2(f_x^2+f_y^2)}\right]$ is the transfer function with the wavelength λ, the recording distance z, and the spatial frequency components f_x and f_y. Then, the Gabor hologram in the (x, y) plane is expressed as

$$I_G = |O(x, y)|^2. \tag{4}$$

Due to the effect of the medium having uneven thickness, there is no direct transmit light saver as the plane reference wave. Therefore, the image cannot be reconstructed from I_G by traditional algorithms of reconstruction.

Another plane reference wave $R(x, y)$ interferes with the object wave $O(x, y)$ in the recording plane, as shown in Fig. 1. Then, the off-axis hologram can be expressed as

$$I_{off} = |O|^2 + |R|^2 + OR^* + O^*R, \tag{5}$$

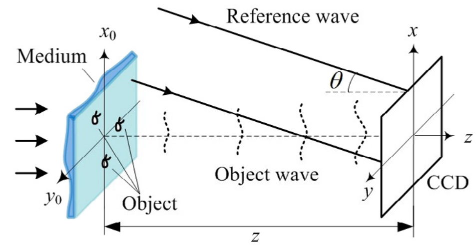

Fig. 1. Schematic of digital holography.

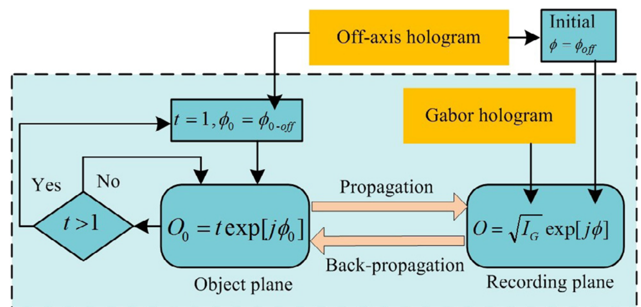

Fig. 2. Schematic of hybrid phase retrieval algorithm.

where the superscript * represents the complex conjugate. For simplicity, we omit the coordinates (x, y) in Eq. (5) and in the following formulae. Assuming that the propagation vector of the reference wave is in the x–z plane, the reference wave can be expressed as

$$R = R_0 \exp\left(j\frac{2\pi}{\lambda}x\sin\theta\right), \tag{6}$$

where R_0 is the amplitude and θ is the offset angle with respect to the normal of the recording plane, which can be measured from the intensity of the reference beam and the spectrum of the hologram [37].

For a digitally recorded hologram I_{off} and a known reference beam R, the complex object function O in the recording plane can be recovered by using the constrained optimization algorithm [12]. This is processed by the iteration as

$$O^{(n+1)} = G \otimes \left\{ O^{(n)} + \alpha\left[I_{off} - \left(\left|O^{(n)}\right|^2 + |R|^2 + O^{(n)}R^* + O^{(n)*}R \right)\right]\left(O^{(n)} + R\right)\right\}, \tag{7}$$

where G denotes the averaging filter that is used to suppress the carrier-frequency component, $\otimes$ is the correlation symbol, α is a positive constant representing the step size, selected using line search during each iteration as 0.001–0.01, and $O^{(0)}$ is usually set to zero. Then, the complex field in the object plane can be reconstructed by back-propagation according to the angular spectrum approach.

In the phase retrieval, the initial value and the constraints are important factors to determine whether the iterative algorithm is effective. Although the high-frequency information of the object is suppressed by the averaging filter in the reconstruction of the off-axis hologram, the low-frequency information can be used as an initial value and constraints in the reconstruction of the Gabor hologram, to obtain the high-resolution images. An iterative procedure shown in the dashed rectangle in Fig. 2 is employed to retrieve the complex field of the object wave. The hybrid algorithm is implemented with the following procedures:

(1) The phases in the recording plane and in the object plane, expressed by ϕ_{off} and $\phi_{0\text{-}off}$ respectively, are extracted from the off-axis hologram according to the constrained optimization algorithm.