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Fast and accurate carrier and aberration removal in phase retrieval for off-axis holography

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ABSTRACT

An efficient method to remove carrier and aberration during phase processing from off-axis holography is proposed using a specimen-free hologram (SFH). One modulated carrier hologram (MCH) and one SFH are firstly encoded into a synthetic hologram. The synthetic hologram is then Fourier transformed, and the two cross-correlation orders can be obtained from its spectrum using two band pass filters. After implementing inverse Fourier transform, we can achieve the results containing phase distribution, carrier information, and aberration phase both of MCH and SFH. Through a division operation, the expected phase distribution can be retrieved without the information of carrier error and aberration. Simulations and experiments are carried out to demonstrate the validity of the method. Both results demonstrate that the new method can provide an accurate reconstruction with a superior retrieval speed.

1. Introduction

Off-axis digital holography (DH) has been widely used in application of quantitative phase imaging because it can allow phase processing just using one shot [1–4]. Since off-axis DH can separate the DC and two cross-correlation terms in the Fourier spectrum from the recorded hologram [5], one of the widely used phase processing method is Fourier transform method (FTM). For traditional FTM, it is critical to determine the peak position of one cross-correlation term, and then shift its surrounding Fourier space to the zero frequency location to remove the carrier. However, some challenging problems are required to be solved for FTM. The first one is to ensure the peak position, but it is not practical to ensure it located at an integral pixel position, which then causes carrier removal error. Much work has been done to suppress the carrier removal error. For example, Bone et al. [6] applied least-squares fitting to an information-free region of the MCH to construct a carrier phase plane, and the specimen phase can then be obtained by subtracting the estimated carrier phase. However, the accuracy of the method is limited by the information-free region which cannot usually be fulfilled in the practical measurement. Along with least-squares-fit technique, Gu et al. [7] introduced an iterative process to improve the estimation accuracy of the carrier phase. To achieve sub-pixel accuracy estimation, Fan et al. [8] realized it using spectrum centroid method (SCM), and Du et al. [9] performed it using zero padding method (ZPM). The second problem is to remove the aberration phase which is introduced by aberrations and distortions of the optical system. Much work has also been done in this aspect, including multiwavelength interferometric method [10], background fitting method [11], and self-referencing method [12], and so on. However, all these methods to remove carrier and aberration presented above are complex with multiple processes and

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high computation cost. To some extent, the estimation accuracy comes at the cost of the real-time ability from a single shot. To avoid the requirement of computationally intensive phase unwrapping for thin objects (<2π radians) and then speed up, Pham et al. [13] acquired the final phase by the division of the two complex results of MCH and SFH using Hilbert transform. However, spectrum shifting is still required to remove the carrier in the method. Moreover, carrier removal errors and phase aberrations are not taken into consideration during their analysis process.

In this paper, we present a fast and accurate method to remove carrier and aberration using a SFH in off-axis DH. By encoding the MCH and SFH into a synthetic hologram, we can retrieve the information of MCH and SFH at one time to demodulate the final phase distribution. We also perform some simulations and experiments to demonstrate the validity of the method.

2. Theory

In off-axis DH, a hologram with carrier frequency in both x direction and y direction has the intensity distribution as following:

$$I_{MCH} = a(x, y) + b(x, y)\cos\left[2\pi f_x x + 2\pi f_y y + \varphi_s(x, y)\right], \tag{1}$$

where, $a(x, y)$ denotes the DC term, $b(x, y)$ denotes the local contrast of fringe, f_x and f_y are the carrier frequencies in the x and y directions, and φ_s is the specimen phase. In practice, however, the carrier frequency peak position may be at a small of an integral pixel in the frequency domain, and beam aberrations and curvatures inevitably exist. Thus, a further form of Eq. (1) can be expressed as:

$$I_{MCH} = a(x, y) + b(x, y)\cos\left[2\pi f_x x + 2\pi f_y y + \varphi_s(x, y) + \varphi_p(x, y) + \varphi_a(x, y)\right], \tag{2}$$

where, φ_p is the phase error due to the carrier peak at a decimal position in the Fourier domain [9], and φ_a is the aberration phase introduce by the test wavefront which contains aberrations or is aspheric [14–16]. Then, the intensity distribution of a SFH can be expressed as:

$$I_{SFH} = a(x, y) + b(x, y)\cos\left[2\pi f_x x + 2\pi f_y y + \varphi_p(x, y) + \varphi_a(x, y)\right], \tag{3}$$

For previous work [13], I_{MCH} and I_{SFH} are firstly Fourier transformed to obtain their spectra, respectively. After spectrum selecting (include shifting) and inverse Fourier transform (IFT), the expected phase can be achieved through a division between the two results. However, the method have its drawbacks. First, the same retrieval processes including forward and inverse Fourier transform (FT), and spectrum shifting have to be implemented twice. Second, only one of the cross-correlations of the spectrum participates in the phase reconstruction, so the FT operation is inefficient. Here, we employ the imaginary part to encode a synthetic hologram from MCH and SFH to simplify the retrieval process [17]. The intensity of the synthetic hologram can be expressed as:

$$I_{CE} = I_{MCH} + i \cdot I_{SFH}, \tag{4}$$

After applying FT operation to Eq. (4), the DC term and the cross-correlation terms can be separated in the frequency domain. Due to the complex encoding, the two cross-correlation terms both contain information of φ_s, φ_p, φ_a, and carrier frequencies. The two cross-correlation terms can be selected out using band pass filters (BPFs), and then transferred to two complex results through IFT operation, which reads

$$c_1(x, y) = \mathrm{IFT}\left\{\mathrm{FT}\left\{I_{CE}\right\} \cdot \mathrm{BPF}_1\right\} = b(x, y)\left\{\begin{array}{l}\exp\left[i\left(2\pi f_x x + 2\pi f_y y + \varphi_s + \varphi_p + \varphi_a\right)\right] \\ +\exp\left[i\left(2\pi f_x x + 2\pi f_y y + \varphi_p + \varphi_a + \frac{\pi}{2}\right)\right]\end{array}\right\}, \tag{5}$$

$$c_2(x, y) = \mathrm{IFT}\left\{\mathrm{FT}\left\{I_{CE}\right\} \cdot \mathrm{BPF}_2\right\} = b(x, y)\left\{\begin{array}{l}\exp\left[-i\left(2\pi f_x x + 2\pi f_y y + \varphi_s + \varphi_p + \varphi_a\right)\right] \\ +\exp\left[-i\left(2\pi f_x x + 2\pi f_y y + \varphi_p + \varphi_a - \frac{\pi}{2}\right)\right]\end{array}\right\}. \tag{6}$$

The key point here is that we do not require to shift both the cross-correlation terms to center, which can save run time. In fact, according to the shift theorem of FT, a frequency shift in the frequency domain can be interpreted as a phase shift in the spatial domain. Fortunately, the phase shift caused by the carrier and aberration can be eliminated by a further division step.

To obtain the final results, we further applied conjugate operation to Eq. (6) as:

$$c_2^*(x, y) = \mathrm{IFT}\left\{\mathrm{FT}\left\{I_{CE}\right\} \cdot \mathrm{BPF}_2\right\} = b(x, y)\left\{\begin{array}{l}\exp\left[i\left(2\pi f_x x + 2\pi f_y y + \varphi_s + \varphi_p + \varphi_a\right)\right] \\ +\exp\left[i\left(2\pi f_x x + 2\pi f_y y + \varphi_p + \varphi_a - \frac{\pi}{2}\right)\right]\end{array}\right\}. \tag{7}$$