Optics Communications 393 (2017) 40–44

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Phase-shift extraction algorithm for blind phase-shifting holography based on the quotient of inner products

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ARTICLE INFO

Keywords:
Digital holography
Phase retrieval
Phase shift
Interferometry

ABSTRACT

This paper presents a phase-shift extraction method for blind phase-shifting holography applications based on the quotient of inner products. The method only requires acquiring three-frame holograms with arbitrary unequal phase-shift values and the intensity of the reference wave, without requiring the object wave intensity. Two phase shift values can be extracted precisely using the algorithm, which can remove the background noise and DC component effects. Both simulated and experimental results have demonstrated the phase step retrieval accuracy and the feasibility of reconstructing the complex amplitude of the object wave.

1. Introduction

Holography is an important tool that has been widely used in many applications [1–5], including industrial metrology, cell biology, ultra-fast dynamic detection and materials topography measurements. However, the existence of the zero-order image and the conjugate image will disturb the quality of the reconstructed original object wave front. To eliminate the zero-order term and the conjugate term have been to be a key issue to reconstruct the object wave front. Many numerical iterative methods in frequency domain have been proposed [6,7]. Although these only need one hologram, these cannot eliminate the zero-order term and the conjugate term completely and only be used in off-line holography. Phase-shifting holography (PSH) has captured extensive attention, which can eliminate DC and conjugate components and enable effective retrieval of original object wave. Standard PSH requires four phase-shifting holograms with specific phase shifts $\frac{\pi}{2}$ [8]. However, this requirement is very difficult to achieve, because of restrictions based on practical factors, such as vibration, the error of phase shifter. To solve these practical issues, phase-shifting methods using arbitrary phase steps have been discussed widely, and ways to accurately retrieve the phase step have become a major research focus. Iterative methods [9,10] can produce accurate phase values; however, they can be very time-consuming, depending on the number of iterative steps required. Therefore, non-iterative methods have also been developed [11–16]. In [11], Guo et al. proposed a zero difference algorithm for phase-shift extraction in blind PSH, according to the fact that there exist some points whose intensity in two adjacent phase-shifting holograms are equal. In [12], they also proposed a non-iterative blind phase-shifting algorithm for two-step phase-shifting interferometry based on an analytical formula. But both methods require acquiring the object wave intensity. In most real conditions, the object wave intensity cannot be obtained precisely. In [13], Masatoshi et al. proposed a single-exposure method to reconstruct complex object wave amplitude. However, the information of the reference wave needed to be obtained by some techniques in advance. In [14–16], some phase shift extraction algorithms are proposed, in which the phase shift is calculated a formula through the average operator. Those effective are likely to be sensitive to background noise, DC components, and random noise.

In this paper, we derive a phase-shift extraction method for blind phase-shifting holography that is based on the quotient of inner products method. Moreover, the proposed method only requires acquiring three-frame holograms with arbitrary and unequal phase shifts and the intensity of the reference wave. Both background noise and DC components, including laser noise, stray light, and speckle effect interference, can be eliminated thoroughly by subtracting one hologram from another. We propose an algorithm for calculating two phase-shift values, and the complex amplitude of the object wave can then be reconstructed. The proposed method shows strong robustness and is helpful in many practical applications. This method can be applicable with in-line and off-axis phase-shifting holography. Because the proposed method can reconstruct the amplitude and the phase of object wave at the same time, therefore it also has the high application prospect in quantitative phase imaging [17]. In the rest of this paper, we will provide the theoretical analysis and verify the effectiveness of the method using numerical simulations and experimental results.

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http://dx.doi.org/10.1016/j.optcom.2017.02.011
Received 24 October 2016; Received in revised form 2 February 2017; Accepted 4 February 2017
Available online 16 February 2017

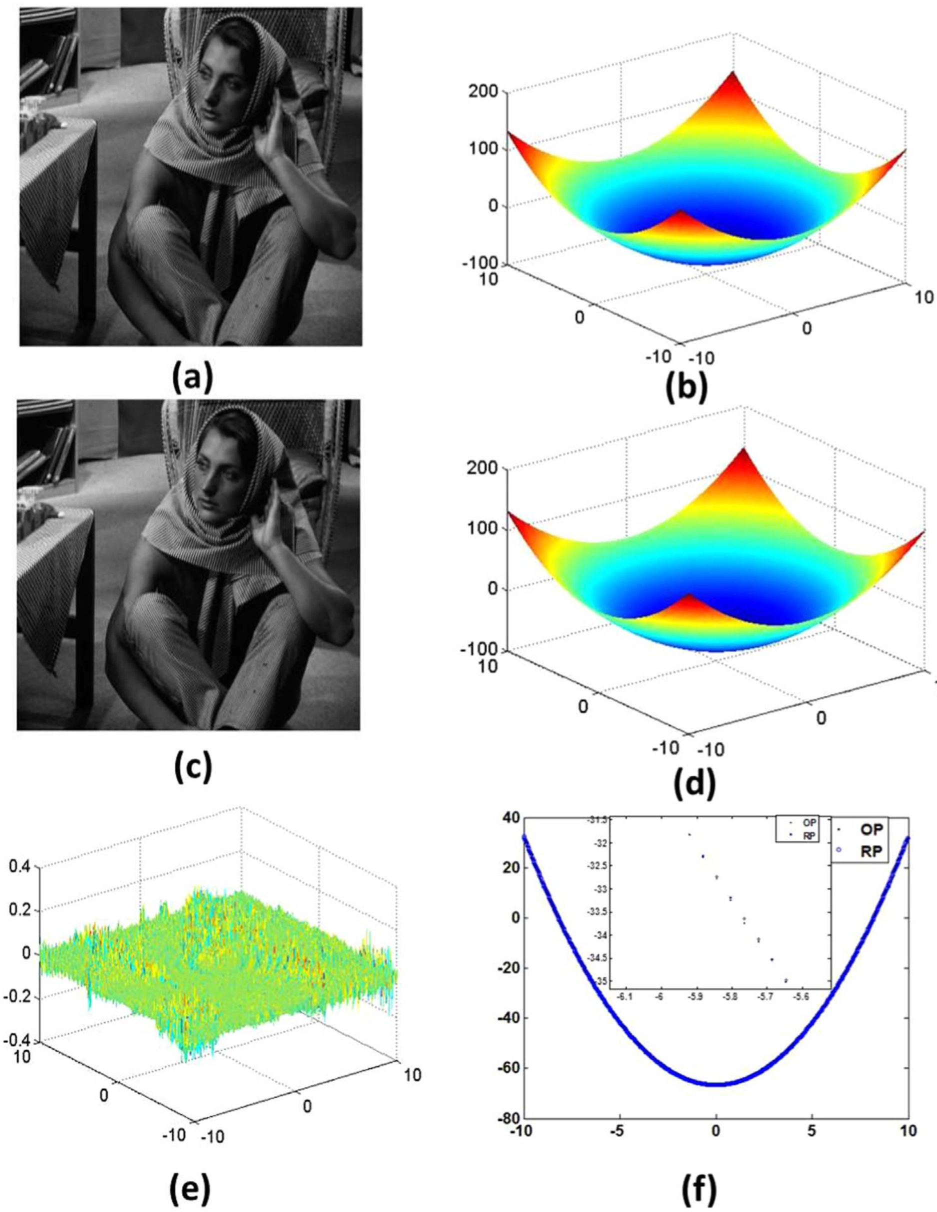

Fig. 1. Simulation of the proposed method. (a), (b) Simulated amplitude and phase distribution of the object wave, respectively (i.e.). (c), (d) The amplitude and phase of the object wave reconstructed using our algorithm, respectively. (e), (f) the difference between the original phase (OP) and reconstructed phase (RP): (e) 3D phase difference; (f) 2D phase difference.

2. Theoretical analysis

In PSH, we denote the complex amplitude of the object wave and the reference wave as $u_o = (\sqrt{I_o})\exp(i\varphi_o)$ and $u_r = (\sqrt{I_r})\exp(i\varphi_r)$ respectively. Therefore, the intensity distributions of three holograms with unequal phase shifts can be described as:

$$I_1 = I_o + I_r + 2\sqrt{I_o I_r}\cos(\varphi) = a_k + b_k\cos(\varphi_k) \quad (1)$$

$$I_2 = I_o + I_r + 2\sqrt{I_o I_r}\cos(\varphi + \theta_1) = a_k + b_k\cos(\varphi_k + \theta_1) \quad (2)$$

$$I_3 = I_o + I_r + 2\sqrt{I_o I_r}\cos(\varphi + \theta_2) = a_k + b_k\cos(\varphi_k + \theta_2) \quad (3)$$

Here, θ_1 and θ_2 are the phase step between the holograms, I_O and I_r are the intensity of the object wave and the reference wave, respectively.$\varphi = \varphi_o - \varphi_r$ is usually regarded as the object phase, because the reference wave, such as a plane wave or a spherical wave, is often known. We also can express I_1, I_2 and I_3 as their respective rightmost formulas, where, k (k=1,2...K) represents each pixel position in a single hologram, and K is the total number of pixels in each hologram. $a_k = I_{ok} + I_{rk}$, $b_k = 2(I_{ok}I_{rk})^{1/2}$ represent the background intensity and the modulation intensity, respectively. Using Eqs. (1), (2) and (3), the complex amplitude of the object wave can easily be expressed as [18]:

$$U_o = \frac{1}{4\sqrt{I_r}\sin[(\theta_2 - \theta_1)/2]}\left[(I_1 - I_3)\frac{\exp(i\theta_1/2)}{\sin(\theta_2/2)} - (I_1 - I_2)\frac{\exp(i\theta_2/2)}{\sin(\theta_1/2)}\right] \quad (4)$$

Based on the above equation, accurate determination of the phase steps θ_1 and θ_2 is thus crucial to reconstructing the complex amplitude of the object wave. By subtracting one hologram from another, three new holograms can be obtained. We denote these holograms as follows:

$$s_1 = I_1 - I_2 = 2b_k\sin\left(\frac{\theta_1}{2}\right)\sin(\Phi_k) \quad (5)$$

$$s_2 = I_1 - I_3 = 2b_k\sin\left(\frac{\theta_2}{2}\right)\sin(\Phi_k + \Delta) \quad (6)$$

$$s_3 = I_2 - I_3 = 2b_k\sin(\Delta)\sin\left(\Phi_k + \frac{\theta_2}{2}\right) \quad (7)$$