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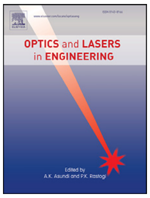

Fast phase retrieval in slightly off-axis digital holography

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ABSTRACT

In this study, three efficient algorithms are proposed for fast phase retrieval in slightly off-axis digital holography using spectrum cropping, spatial multiplexing, and complex encoding. In the first algorithm, the real spectral order of the subtracted hologram is filtered and cropped, and the number of pixels is decreased in the subsequent retrieval operations. In the second algorithm, two sequential subtracted holograms are digitally phase shifted and spatial multiplexed into one synthetic hologram, and thus only one inverse Fourier transformation is then required. In the third algorithm, two sequential subtracted holograms are encoded separately into the real part and the imaginary part of a complex hologram. Two cross-correlations can be used to reconstruct the phase, thereby improving the utilization of the spectrum. The three new algorithms speed up our previously proposed retrieval method with the assistance of specimen-free holograms. Our experiments demonstrated the validity and improved time requirements of the proposed methods.

1. Introduction

Digital holography (DH) has emerged as an important tool for achieving quantitative phase analyses of biological specimens, surface measurements, and micro-structures [1–4]. Due to the reliance of DH on interference, three types of methods in DH are usually used: on-axis, off-axis and slightly off-axis. The on-axis methods can fully utilize the space–bandwidth product of the DH system. However, to achieve high phase retrieval accuracy, phase-shifting methods must record several holograms (typically ≥ 3) in time sequence or in a single shot [5–8]. Unlike phase-shifting methods, the off-axis methods just need one hologram in a single shot, which make them suitable for faster imaging by fully exploiting the field of view (FOV) of the camera. However, these benefits come at the cost of the *space–bandwidth product* [9–13]. By integrating off-axis and phase-shifting to record two phase-shifted slightly off-axis holograms, the slightly off-axis methods provide an intermediate solution between the on-axis and off-axis methods [14–19]. After applying a subtraction operation to the two slightly off-axis holograms to eliminate the DC term, digital phase reconstruction can also be performed using a Fourier transform algorithm with the slightly off-axis DHs. However, similar to the off-axis DHs, digital processing requires large amounts of computations so it must be conducted offline. An improved phase retrieval method was proposed by our group based on the offline prior acquisition of specimen-free holograms [18,19], but it is still necessary to speed up the phase retrieval process for slightly off-axis DHs.

The retrieval operations are usually the same for different pixels in one hologram. Parallel computing techniques using graphic processing units (GPUs) are then introduced to achieve higher retrieval efficiency [20,21]. However, special graphic units and programming skills are required. Considering that Fourier transform operation is the main time-consuming process, Girshovitz and Shaked retained only the real spectral order and omit all the other redundant data during the retrieval process [11]. They then achieved real time phase reconstruction with 1 megapixel. To further speed up this process, Sha et al. spatially multiplexed four holograms into one synthetic hologram [12], while Girshovitz and Shaked encoded four sequential holograms into one complex hologram, and then used both the real and twin image parts [13]. However, all of these methods are only suitable for off-axis DHs.

In this study, we present three more efficient algorithms for phase retrieval in slightly off-axis DHs. Those algorithms combine spectrum cropping, spatial multiplexing, and complex encoding with our previously proposed method. They speed up phase retrieval in slightly off-axis DHs, as well as compensating for the disturbing phase caused by the phase shift α, carrier frequency, and background phase. Finally, we demonstrated the improved performance of our proposed approaches based on simulations, and by processing phase maps of a phase plate and water drops.

2. Reconstruction algorithms

In slightly off-axis DH, two measured holograms with a phase shift α have the forms:

$$H_1(x,y) = a(x,y) + 0.5b(x,y)\exp\left[i\left(\varphi_t + \varphi_{bg} + 2\pi f_x x\right)\right] + 0.5b(x,y)\exp\left[-i\left(\varphi_t + \varphi_{bg} + 2\pi f_x x\right)\right], \quad (1)$$

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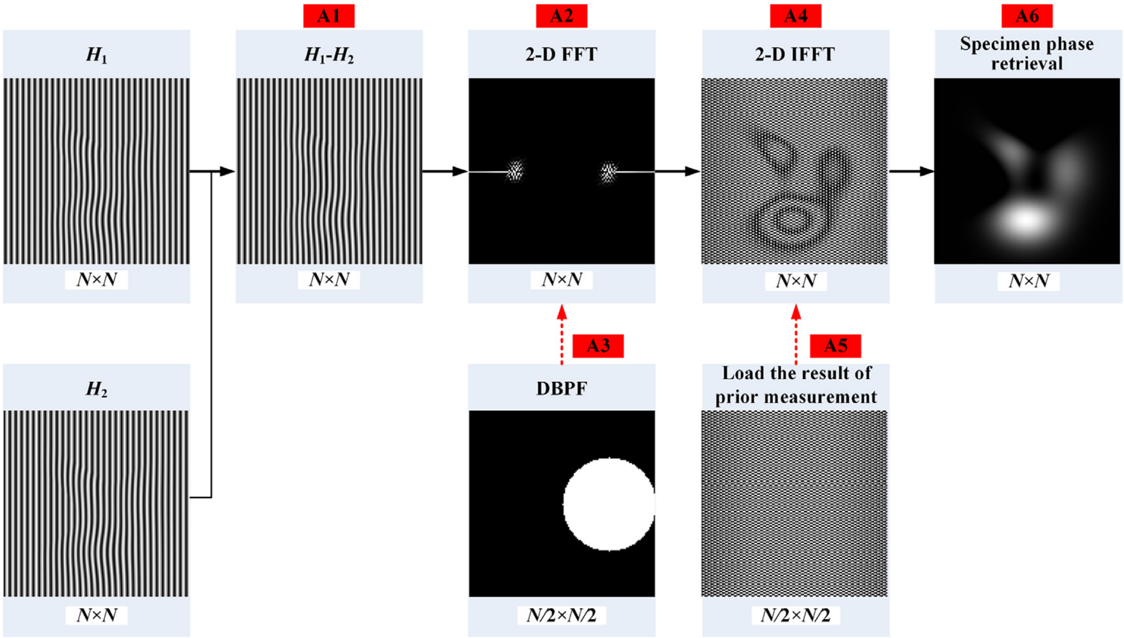

Fig. 1. Algorithm A: the algorithm based on an offline prior acquisition of specimen-free holograms.

$$H_2(x,y) = a(x,y) + 0.5b(x,y)\exp\left[i\left(\varphi_t+\varphi_{bg}+2\pi f_x x\right)\right]\exp(i\alpha) + 0.5b(x,y)\exp\left[-i\left(\varphi_t+\varphi_{bg}+2\pi f_x x\right)\right]\exp(-i\alpha), \qquad (2)$$

where $a(x, y)$ is the DC term, $b(x, y)$ is the modulation term, φ_t is the phase distribution of specimen at time t, φ_{bg} is the background phase caused by the aberration and the noise of the system, f_x is carrier frequency in the x direction and $2\pi f_x x$ is its corresponding phase tilt. After applying subtraction, we can eliminate the DC term and obtain:

$$S = H_1 - H_2 = 0.5b(x,y)\left\{\begin{array}{l}\left[1-\exp(i\alpha)\right]\exp\left[i\left(\varphi_t+\varphi_{bg}+2\pi f_x x\right)\right]\\ +\left[1-\exp(-i\alpha)\right]\exp\left[-i\left(\varphi_t+\varphi_{bg}+2\pi f_x x\right)\right]\end{array}\right\}. \qquad (3)$$

The phase distribution φ_t of a specimen can be retrieved from the subtracted hologram using Fourier transform algorithm [17]. To increase the retrieval speed, we suggested a faster retrieval algorithm based on the offline prior acquisition of specimen-free subtracted holograms [18,19]. The faster algorithm can also compensate for the disturbing phase caused by the phase shift α, carrier frequency, and background phase. In the following, we first review the algorithm, and then propose three more efficient algorithms.

2.1. Algorithm A: algorithm based on the offline prior acquisition of specimen-free holograms

When the phase variance of a specimen is less than 2π, we previously proposed a simple retrieval algorithm assisted by a prior measurement without any specimen [18,19]. This algorithm can achieve a fast phase retrieval speed and it comprises the following steps, as shown in Fig. 1.

A1: Holograms subtraction: Subtract the two phase-shifted holograms containing $N \times N$ real pixels to eliminate the DC term and obtain a subtracted hologram.

A2: Two-dimensional fast Fourier transform (2-D FFT): Convert the subtracted hologram into the spatial-frequency domain using a 2-D FFT, thereby obtaining a matrix containing $N \times N$ complex pixels.

A3: Digital band pass filtering (DBPF): Use a band pass filter (BPF) with a size of $N \times N$ pixels and digitally filter out the twin spectral order, but retain the real spectral order. In slightly off-axis DH, the DC order is subtracted out, so the maximum circle in the BPF can reach the zero-frequency point [14]. Thus, for a spectral matrix containing $N \times N$ pixels, the maximum diameter of the circle in the BPF can be selected as $N/2$.

A4: Two-dimensional inverse FFT (2-D IFFT): Convert the result obtained in step A3 back to the image domain by using a 2-D IFFT to product an $N \times N$ complex matrix containing the phase distribution of the specimen and disturbance. The disturbing phase includes phase shift, carrier information and background phase.

A5: Load the result of prior measurement: To compensate for the disturbing phase, obtain two phase shifted holograms without a specimen before the experiment and then process them according to steps A1–A4, as described above. The result containing $N \times N$ pixels is actually stored before the measurement and it is only loaded to help retrieving phase during the reconstruction process.

A6: Specimen phase retrieval: Divide the result obtained from step A4 by that from step A5 to eliminate the disturbing phase. Finally, implement an arc tangent operation to obtain the phase distribution of the specimen.

2.2. Algorithm B: spectrum cropping algorithm

Shaked et al. noted that when selecting the real spectral order, there is no need to use a BPF matrix with the same size as the original images ($N \times N$). The filtering operation can be performed by decreasing the number of pixels and the 2-D FFT operation can be followed by using a cropped matrix with the same size. For slightly off-axis DH, we can crop the real spectral order using a BPF with $N/2 \times N/2$ pixels and continue processing with a matrix that is four times smaller. Fig. 2 shows the digital process, which is described in Algorithm B. The algorithm comprises the following step.

B1: Holograms subtraction: This is the same as step A1.

B2: 2-D FFT: This is the same as step A2.

B3: DBPF and cropping: Apply a BPF containing $N/2 \times N/2$ pixels to the area $(N/2+1{:}N,\ N/4+1{:}3N/4)$ of the spectrum and crop the real spectral order.

B4: 2-D IFFT: Convert the result obtained from step B3 back into the image domain by using a 2-D IFFT to produce an $N/2 \times N/2$ complex matrix containing the phase distribution of the specimen and disturbance.