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An effective approach to removing zero-order term overlap and controlling image distortion in digital off-axis holography

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ABSTRACT

In this paper, we propose and describe a novel nonlinear numerical filtering approach to remove the zero-order term which overlaps the image, and meanwhile, to effectively control the image distortion in digital off-axis holography. To reach this goal, a special numerical filter is constructed by extracting and improving a modulation function from the G-channel sampling-gained hologram in Fourier frequency domain based on a color CCD detector. The quantitative analysis on the zero-order term suppression and image distortion control in both amplitude and phase for the filter optimization are presented in detail. The experimental result agrees with theoretical prediction well and proves the effectiveness of this method.

1. Introduction

In digital holography, the reconstructed object wave-field is generally accompanied by two additional components of zero-order diffraction and conjugate term of the object [1]. If all terms overlap one another in the hologram reconstruction, the image quality will be much affected. In order to remove the influences from the zero-order diffraction and the conjugate term in the hologram reconstruction, the digital off-axis holography was proposed and developed in the past, in which all terms could be completely separated from one another so that the zero-order diffraction and the conjugate term were easily removed in Fourier frequency domain or in spatial domain using a simple mask [2]. However, such an off-axis arrangement will lead to considerable loss of the space bandwidth available for the object image due to limited pixel numbers in a detector. As a result, the image resolution will decrease in the reconstruction. This means that to increase the space bandwidth in the off-axis holography, the zero-order term will inevitably overlap the object image so that it becomes difficult to remove the zero-order term from the image reconstruction.

Now, the problem is focused on how to remove the zero-order term overlap and obtain the distortion-free image. Regarding the previous techniques which may remove the zero-order term in the digital holography [3–15], the typical phase-shifting processing requires a perturbation-free condition and is difficult in recording dynamic targets due to multiple holograms required [4]. Although the parallel phase-shifting and space-shifting approaches can be used for dynamic holography, they sacrifice the space bandwidth, i.e. the pixels available for the object image due to the monochromatic channel sampling of the hologram [5–7]. The iterative computation requires some rigor conditions and approximations for an acceptable result so that its applicability is limited [8,9].

The previous filtering approaches to using different masks in the frequency domain are not satisfactory for removing the zero-order term overlap [10–13], as those methods failed to find a really proper solution which matches the zero-order term spectrum well. This is because the zero-order term actually contains different frequencies which form a certain distribution rather than only low frequencies going full to a small spot in the frequency domain due to inhomogeneous object wave and unexpected light modulations induced by optical elements in digital holography. Thus, it is impossible to completely remove the zero-order term by using a simple high-pass filter. In addition, most of the previous techniques neglected possible image distortion which may be induced from the process of zero-order term suppression.

Thus, here we propose and describe a novel numerical filtering approach in order to search for a satisfactory solution which can remove the zero-order term overlap with perfect image distortion control in the digital off-axis holography. The detail of this method is illustrated as follows.

2. Filter construction and optimization

In digital off-axis holography, the zero-order term spectrum may be separated from the object spectrum in the frequency

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domain for the tilt of the reference wave introduces a carrier frequency, even if the zero-order term partly covers the object image in the spatial domain. This enables removal of the zero-order term overlap through a spectral filtering process. The discrete hologram function from the G-channel sampling with a Bayer filter in a color CCD detector can be written as [16]

$$h_1(k,l) = h(k,l) \times \frac{1}{2}\left[1 + (-1)^{k+l}\right] + h_b(k,l) \times \frac{1}{2}\left[1 - (-1)^{k+l}\right] \quad (1)$$

$$h_b(k,l) = [h(k+1,l) + h(k-1,l) + h(k,l+1) + h(k,l-1)]/4 \quad (2)$$

where $h(k, l)$ denotes the hologram array recorded without the Bayer filter, which can be obtained from a black and white CCD detector. (k, l) are the discrete coordinates in the hologram plane, where $k=1,2,3\ldots M$, $l=1,2,3\ldots N$. M and N represent the horizontal and vertical pixel numbers in the detector, respectively. $h_b(k, l)$ is the bilinear interpolation function used for reconstructing a full hologram array in the G-channel sampling [17]. Thus, the hologram in the Fourier frequency domain can be obtained as follows by applying the Fourier transform to Eq. (1).

$$\begin{aligned} H_1(m,n) &= \mathcal{F}\left[h_1(k,l)\right] \\ &= \frac{1}{4}[2 + \cos(\omega_m) + \cos(\omega_n)] \times \\ &\quad [H(m,n) + H(m - M/2, n - N/2)] \end{aligned} \quad (3)$$

where (ω_m, ω_n) are the spatial frequency variables and (m, n) are the discrete coordinates in the image plane, where $m=1,2,3\ldots M$, $n=1,2,3\ldots N$ is the spatial variables. Eq. (3) is actual a product of two terms of $[2+\cos(\omega_m)+\cos(\omega_n)]/4$ and $[H(m, n)+H(m-M/2, n-N/2)]$. It reveals a unique feature of the G-channel sampling-gained hologram, i.e. the first term in Eq. (3) acts as a modulation function of the second term in the frequency domain, and the second term contains dual holograms and will result in two images corresponding to $H(m, n)$ and $H(m-M/2, n-N/2)$, respectively, in the hologram reconstruction.

By applying the inverse Fourier transform to Eq. (3) in the image plane, we find that there is only one zero-order term to occur, which overlaps the object image at the central location in the image plane due to the role of the specific modulation function. This feature is illustrated in Fig.1, where the modulation function is plotted in Fig. 1(a) and the reconstructed images from the in-plane Fresnel hologram reconstruction of a USAF-1951 pattern using Eq. (3) is obtained in Fig. 1(b).

This result can be interpreted by the spectral configuration of the modulation function in Fig. 1(a), with which the low frequencies at four corners are suppressed. Thus, it shows a sort of filtering performance for low frequency signals distributing in a specific region in the frequency domain. This provides a fabulous chance to remove the zero-order term, if this original modulation function can be properly improved to avoid possible image distortion induced by the filtering process. Unfortunately, to the best of our knowledge, no one has investigated and reported how to utilize and improve such a modulation function given in Eq. (3) to construct an effective numerical filter for the removal of the zero-order term overlap in the digital off-axis holography from existing literatures so far.

In the numerical filter construction, we firstly extract and normalize the modulation term in Eq. (3) as a fundamental filtering function. Then, it is converted by a spatial displacement of $(M/2, N/2)$ in the frequency domain to produce a normalized filtering function (NFF) for removing the zero-order term at the central location. The modified filtering function is expressed as Eq. (4) and plotted in Fig. 2(a).

$$filter(\omega_m, \omega_n) = \frac{1}{4}\left[2 + \cos(\omega_m - \pi) + \cos(\omega_n - \pi)\right] \quad (4)$$

Thus, the hologram with the zero-order term removed can be obtained following the mathematical operation below.

$$h_{filtered}(x,y) = \mathcal{F}^{-1}\{filter(\omega_x, \omega_y) \times \mathcal{F}[h_{original}(x,y)]\} \quad (5)$$

The object wave-field reconstruction with the filtering process is expressed as follows using the Fresnel transformation processing [18].

$$u(x', y') = \frac{e^{ikd}}{i\lambda d} \times e^{\frac{ik}{2d}[(x'\Delta x')^2 + (y'\Delta y')^2]} \times \mathcal{F}\{e^{\frac{ik}{2d}[(x\Delta x)^2 + (y\Delta y)^2]} \times R'(x,y) \times h_{filtered}(x,y)\} \quad (6)$$

where $h_{filtered}(x,y)$ is the hologram function after the zero-order term is removed, and $h_{original}(x,y)$ is the original hologram which can be recorded with any sampling mode of a CCD detector. $\mathcal{F}$ and $\mathcal{F}^{-1}$ represent the Fourier transform and the inverse Fourier transform, respectively. (x, y) and (x', y') denote the coordinates of the hologram plane and the image plane respectively. $(\Delta x, \Delta y)$ and $(\Delta x', \Delta y')$ represent the pixel sizes in the hologram plane and in the image plane respectively and $\Delta x = \lambda/M\Delta x'$, $\Delta y = \lambda/M\Delta y'$. $R'(x, y)$ is the illumination wave for the hologram reconstruction, which is taken as a plane wave with a wavelength of λ here. k is the wave number and d is the reconstruction distance.

An example of Fresnel digital off-axis holography based on Eqs. (4)–(6) is demonstrated in Fig. 3. In Fig. 3(a), the hologram is

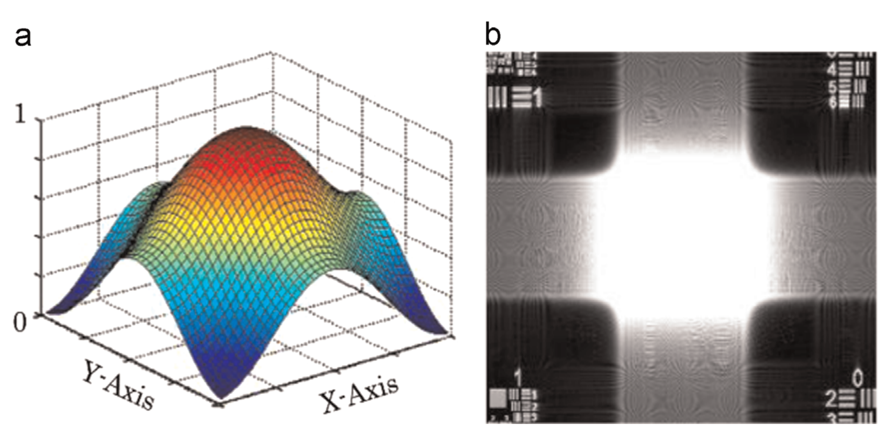

Fig. 1. Feature of G-channel sampling digital holography, (a) normalized modulation function in frequency domain; (b) the in-line Fresnel hologram reconstruction of a USAF-1951 pattern, where the zero-order term covers the object image at the central location, and the conjugate term is pre-removed using the phase-shifting technique.