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Method for eliminating zero-order image in digital holography

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Abstract: For eliminating the zero-order image in digital holography, a new method using the differential of the hologram intensity instead of the hologram itself for numerical reconstruction is proposed. This method is based on digital image processing. By analyzing the spatial spectrum of the off-axis digital hologram, it theoretically proves that the zero-order image can be effectively eliminated by differential before reconstruction. Then, the detected hologram is processed in the program with differential and reconstruction. Both the theoretical analysis and digital reconstruction results show that it can effectively eliminate the large bright spot in the center of the reconstructed image caused by the zero-order image, improve the image quality significantly, and render a better contrast of the reconstructed image. This method is very simple and convenient due to no superfluous optical elements and requiring only one time record.

Key words: digital holography; zero-order image; digital image processing; Fresnel integral

Digital holography, which uses a charged-coupled device (CCD) camera to record holograms, and then employs a computer to perform the reconstruction of the digitized holograms based on Fourier optics theory[1-4] without chemical and physical developing, has been widely used in many areas. However, due to the spatial resolution of CCD sensors, the allowable angles between the object and reference beams has to be reduced by a few degrees, so that the reconstruction image unavoidably contains the conjugate image and the zero-order image. The zero-order image includes most of the energy; thus a large bright spot is generated in the center of the image, which causes a decrease in contrast.

To overcome this problem, many methods have been proposed to eliminate or weaken the zero-order image and the conjugate image, including improving the diffraction efficiency of the hologram called the gray linear transformation method[5-6]; subtracting the average intensity from the actual intensity called the average intensity subtraction method[7]; adding phase-shifting techniques in the digital holographic record process method[8]; applying Fourier transform to the digital hologram according to the separation conditions in off-axis holography; removing the zero-order and conjugate image spectrums called the spectrum filter method[9-10], and so on. However, these methods are inadequate. The former two methods do not have obvious effects on eliminating the zero-order diffraction. The phase-shifting method requires at least four holograms to record each phase of the vertical reference light. Thus both the complexity of the device and the requirements of the stability of the environment increase. More importantly, this method cannot be applied to biological cells and other non-static objects, and the application is limited. The spectrum filtering method is a very effective and convenient means, but the reconstruction speed is slow due to the time consumption of the Fourier transform and spectrum filter.

To overcome these limitations, a new method is presented in this paper for eliminating the zero-order image in off-axis digital holography. Instead of the hologram itself, we use the differential of the hologram for reconstruction by calculating the discrete Fresnel integral. This method can simultaneously suppress the zero-order diffraction and keep the twin images intact. So, it can not only improve the image quality but also give a better contrast of the reconstructed image. Furthermore, due to its simple experimental setup and its rapid process, this method has better resistance to environmental disturbances than other methods.

1 Hologram Acquisition and Reconstruction

Consider the optical path of off-axis digital holography as shown in Fig. 1. A plane reference wave and a diffusely reflected object wave are made to interfere at the x-y plane, where the CCD is used to record the hologram. Under the condition of the Fresnel approximation, the object wave can be reconstructed at the ξ-η plane by computing the Fresnel integral[11] of the digitized hologram intensity $I_{\mathrm{H}}(x, y)$,

$$\Psi(\xi,\eta) = \frac{\mathrm{i}a}{\lambda d}\exp\left[\frac{\mathrm{i}\pi}{\lambda d}(\xi^2+\eta^2)\right]\iint R_{\mathrm{D}}(x,y)I_{\mathrm{H}}(x,y)\cdot \exp\left[\frac{\mathrm{i}\pi}{\lambda d}(x^2+y^2)\right]\exp\left[-\frac{\pi}{\lambda d}(x\xi+y\eta)\right]\mathrm{d}x\mathrm{d}y \tag{1}$$

where a is the amplitude of the incident wave; d is the reconstruction distance, which is usually equal to the distance of object and hologram recording planes; λ is the wavelength; $R_{\mathrm{D}}(x, y)$ is the reconstruction reference light. The function $\Psi(\xi, \eta)$ can be digitized if the hologram transmission $I_{\mathrm{H}}(x, y)$ is sampled on a rectangle raster of $M \times N$ matrix points, with steps Δx and Δy along the coordinates. Then ξ and η are replaced by $m\Delta\xi$ and $n\Delta\eta$, where m, n are

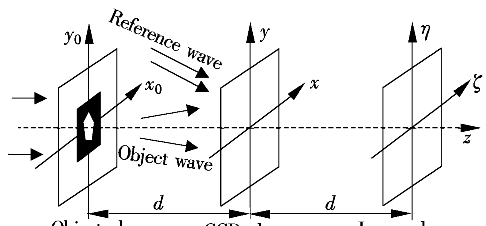

Fig. 1 Principle of digital off-axis holography

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integers. In this case, the discrete representation of Eq. (1) is given by the following equation[12]:

$$\Psi(m,n) = \frac{\mathrm{i}a}{\lambda d}\exp\left[\frac{\mathrm{i}\pi}{\lambda d}(m^2\Delta\xi^2 + n^2\Delta\eta^2)\right]\cdot$$
$$\mathrm{FFT}\left\{R_{\mathrm{D}}(x,y)I_{\mathrm{H}}(x,y)\exp\left[\frac{\mathrm{i}\pi}{\lambda d}(k^2\Delta x^2 + l^2\Delta y^2)\right]\right\} \quad (2)$$

where k, l, m, n are integers; FFT is the fast-Fourier-transform operator; and Δx and Δy are the sampling intervals (the pixel size of the CCD target) in the hologram plane. The sampling intervals on the reconstructed image plane ($\Delta\xi$ and $\Delta\eta$) are related to the size of the CCD(L) and to the distance d by the relation of $\Delta\xi = \Delta\eta = \lambda d/L$. Eq. (2) is an array of complex numbers, so the amplitude-contrast image and phase-contrast image can be obtained by calculating the intensity $[\mathrm{Re}(\Psi)^2 + \mathrm{Im}(\Psi)^2]$ and the phase $\{a\tan[\mathrm{Re}(\Psi)/\mathrm{Im}(\Psi)]\}$ of $\Psi(m,n)$, respectively.

2 Spatial Spectrum of Off-Axis Digital Hologram

In the hologram plane x-y, the interference between the object wave O and the plane reference wave R produces a distribution of intensity, which is generally written as a sum of four terms,

$$I_{\mathrm{H}}(x,y) = I_{\mathrm{R}} + I_{\mathrm{O}}(x,y) + R^*O + RO^* \quad (3)$$

where I_{R} is the intensity of the reference wave and $I_{\mathrm{O}}(x,y)$ is the intensity of the object wave, R^*O and RO^* are the interference terms, and R^* and O^* are the complex conjugates of the two waves. Let us assume that the hologram is reconstructed by a plane wave U. Then, the reconstructed wave front in the hologram plane is given by

$$\Psi(x,y) = UI_{\mathrm{R}} + UI_{\mathrm{O}}(x,y) + UR^*O + URO^* \quad (4)$$

The first two terms of Eq. (4) form the zero-order diffraction. The third and the fourth term generate the twin images of the specimen. The third term UR^*O produces a virtual image located at the position initially occupied by the specimen, and the fourth term URO^* produces a real image located on the other side of the hologram. In off-axis holography, the object wave O and the reference wave R arrive in the hologram plane with separated directions. If we assume that a reference wave with the obliquity of θ is in the form of $R(x,y) = \sqrt{I_{\mathrm{R}}}\exp(\mathrm{i}k_0x)$, where $k_0 = 2\pi\sin\theta/\lambda$, the hologram intensity becomes

$$I_{\mathrm{H}}(x,y) = I_{\mathrm{R}} + I_{\mathrm{O}}(x,y) + \sqrt{I_{\mathrm{R}}}\exp(-\mathrm{i}k_0x)O + \sqrt{I_{\mathrm{R}}}\exp(\mathrm{i}k_0x)O^* \quad (5)$$

Performing a Fourier transformation on both sides of Eq. (5), we have

$$\tilde{I}_{\mathrm{H}}(f_x,f_y) = \tilde{I}_R + \tilde{I}_{\mathrm{O}}(f_x,f_y) + \sqrt{I_{\mathrm{R}}}\tilde{O}(f_x - k_0, f_y) + \sqrt{I_{\mathrm{R}}}\tilde{O}^*(f_x + k_0, f_y) \quad (6)$$

Digital hologram after FFT transform is shown in Fig. 2(a). We can see clearly that there are three parts in the picture. The spatial frequencies corresponding to the zero-order image are located in its center, and the other two parts are the spatial frequencies corresponding to the conjugate image and the real image. Its one-dimensional condition is shown in Fig. 2(b). The first term is a δ function located at the origin of the spatial-frequency plane. The second term, being proportional to the autocorrelation function of $\tilde{Q}(f_{x,}\ f_y)$, is also centered on the origin, with twice the extent of the object wave spectrum. The third term is the object wave spectrum shifted upwards a distance k_0, while the fourth term is the conjugate of the object wave spectrum, shifted downwards the same distance k_0.

Since it is necessary to have at least two sampled points for each fringe in a holographic recording, the maximum spatial frequency of a hologram is $f_{\max} = 1/(2\Delta)$ when a CCD with sensors spaced by Δ is used for hologram recording.

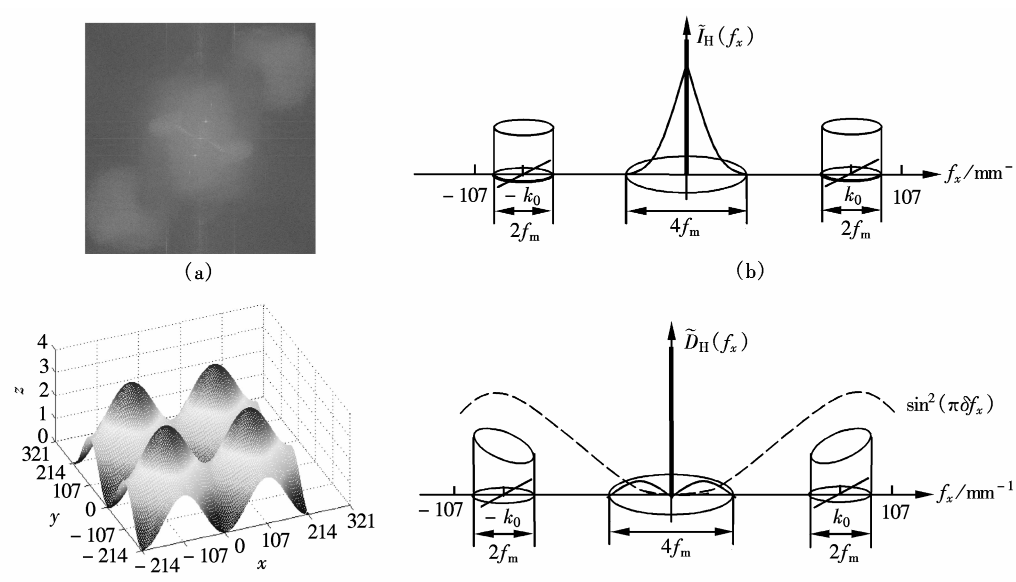

Fig. 2 Schematic diagrams of differentially disposed hologram intensities. (a) Digital hologram after FFT transform; (b) Schematic of the spatial spectrum of the digital hologram; (c) 3-dimensional schematic diagram of $K(f_x, f_y)$; (d) One-dimensional schematic diagram of the spatial spectrum of the disposed digital hologram intensity

For $\Delta = 4.65$ μm (the actual spacing for the CCD sensors used in this work), $f_{\max}$ is about 107 mm^{-1}. It can be seen from Fig. 2(b) that the maximum spectral width of the object wave spectrum is only 53 mm^{-1}.

3 Differential of Off-Axis Digital Hologram

The differential of the hologram intensity is defined as

$$D_H(x, y) = \frac{\partial I_H(x, y)}{\partial x} + \frac{\partial I_H(x, y)}{\partial y} = \frac{I_H(x + \delta, y) + I_H(x, y + \delta) - 2I_H(x, y)}{\delta} \quad (7)$$

where δ is the distance between neighboring pixels.

Performing a Fourier transformation on both sides of Eq. (7) to consider the spectrum of a digitally processed hologram, we have

$$\mathrm{DFT}[D_H(x, y)] = \frac{\tilde{I}_H(f_x, f_y)[\exp(i2\pi\delta f_x) + \exp(i2\pi\delta f_y) - 2]}{\delta} \quad (8)$$

where $\hat{I}_H(f_x, f_y)$ is the Fourier transform of $I_H(x, y)$. Considering the real part of Eq. (8), we have

$$\mathrm{DFT}[D_H(x, y)]_{\mathrm{real}} = \tilde{D}_H(f_x, f_y)_{\mathrm{real}} = \frac{\tilde{I}_H(f_x, f_y)[\cos(2\pi\delta f_x) + \cos(2\pi\delta f_y) - 2]}{\delta} = \frac{\tilde{I}_H(f_x, f_y)[2\sin^2(\pi\delta f_x) + 2\sin^2(\pi\delta f_y)]}{\delta} \doteq \tilde{I}_H(f_x, f_y)K(f_x, f_y) \quad (9)$$

Fig. 2(c) presents the 3-dimensional schematic diagram of $K(f_x, f_y)$. Due to the separability of this equation, we need only investigate the one-dimensional spectrum $\check{D}_H(f_x)_{\mathrm{real}}$, which is shown schematically in Fig. 2(d). We can see that the spectrum of the zero-order diffraction is efficiently suppressed by the $\sin^2(\pi\delta f_x)$ function, which is figured by a broken line, and the spectra of the twin images are almost intact except for a small change in intensity. Therefore, the zero-order diffraction will almost disappear from the reconstructed image, and the quality of the reconstructed twin images will be significantly improved when the differential of the detected hologram is used for reconstruction instead of the hologram itself.

It can be seen in Fig. 2(d) that the suppression of the spectrum of zero-order diffraction is accompanied by a modification in the spectrum of two twin images. This means that the reconstructed twin images will be modified to some extent when this method is used. However, as mentioned above, the maximum spectral width of the twin images is only 53 mm^{-1}, which is much smaller than the period of the function $\sin^2(\pi\delta f_x)$. The spectra of the twin images undergo no substantial changes when multiplied by the function $\sin^2(\pi\delta f_x)$, except for a small change in their intensity. On the other hand, $\sin^2(\pi\delta f_x)$ only slightly changes the magnitude of the spectra of the twin images by simultaneously weakening their lower frequency components and strengthening their higher frequency components. According to Fourier imaging principles, this kind of modification only results in an alteration of the image contrast. So, when we reconstruct a hologram by this method, we slightly alter the image quality of the twin images. But in comparison with the significant improvement in image quality due to the elimination of the zero-order diffraction, this alteration is practically imperceptible.

4 Experimental Results

To verify the efficiency of this method, a hologram is reconstructed with and without the elimination of the zero-order diffraction.

The experimental setup is shown in Fig. 3, with a dice as specimen. A He-Ne laser is used as the light source, with wavelength of 632.8 nm. The linearly polarized plane wave fronts are produced by a beam expander including a pinhole for spatial filtering. After passing through a beam splitter, the wave fronts become two beams; one illuminates the specimen to be tested, and the other illuminates the reference plane. Then the two beams come back to the beam splitter respectively after reflecting and interfere at the target of a CCD camera to form the hologram, which is shown in Fig. 4(a).

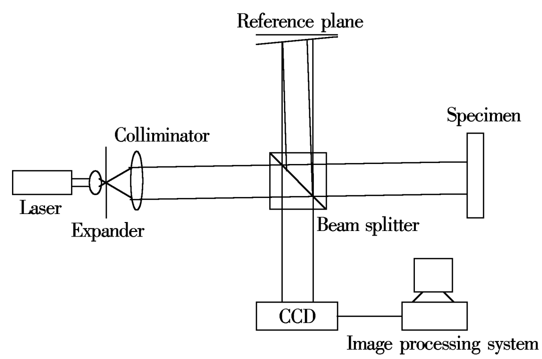

Fig. 3 Experimental setup

The distance between the CCD camera and the specimen is 40 cm. The image in Fig. 4(a) contains 1 024 × 1 024 pixels, and the area of the sensitive chip of the CCD is 4.65 μm × 4.65 μm. The interference fringes characterizing the off-axis geometry are clearly observable in this image. Fig. 4(b) shows the amplitude-contrast image obtained by the numerical reconstruction of the original hologram shown in Fig. 4(a). Fig. 4(c) shows the differential of the original hologram. Fig. 4(d) presents the amplitude-contrast image obtained by the numerical reconstruction of the differential of the hologram. It is obvious that the zero-order diffraction has been efficiently eliminated especially in the first quadrant where the real image is located, and the contrast of the reconstructed image is significantly improved.

Because only one frame of the digitized hologram is required in this method and the experimental process involves no complex processing, the data acquisition is very fast in this experiment. Furthermore, the differential is a classic tool for digital image processing, and there are many standard computer programs for its computation. So eliminating the zero-order diffraction by this method is much more convenient and faster than that by other methods.

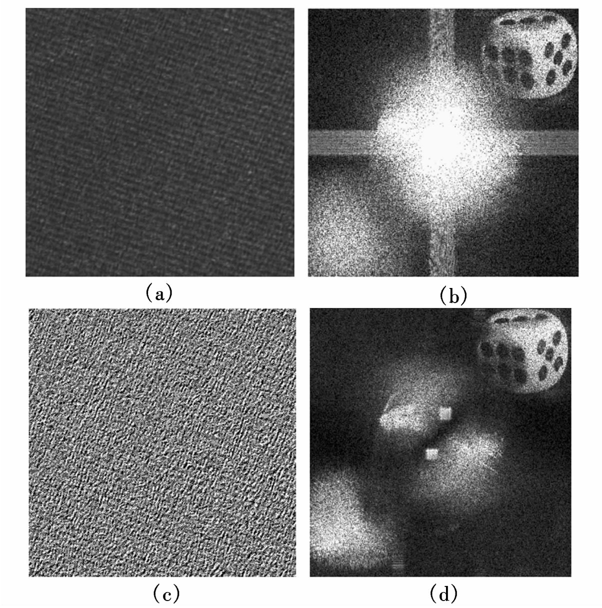

Fig. 4 Elimination of the zero order of diffraction in digital holography. (a) Original off-axis hologram; (b) Amplitude-contrast image obtained by numerical reconstruction of the original hologram; (c) The disposed hologram; (d) Amplitude-contrast image obtained by numerical reconstruction of the differential of the original hologram

5 Conclusion

A simple method is developed for eliminating the zero-order diffraction in digital holography. With this method, the differential of the hologram is used instead of the detected hologram itself for reconstruction by computing the Fresnel integral. By theoretical and experimental analysis, it is proved that the zero-order diffraction can be efficiently eliminated, especially in the first quadrant where the real image is located. This method is based on digital image processing which is free of any superfluous optical elements. The application of this method not only results in an improvement in the image quality but also produces better contrast in the reconstructed twin images.

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一种去除数字全息零级像的新方法

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摘要:为了去除数字全息零级像,提出了用离散全息图的微分强度替代全息图本身用于数字重建的新方法. 该方法基于数字图像处理技术,通过对离轴数字全息图的空间频谱分析,首先理论上证明数字全息图的强度经过微分后再重建,可有效去除零级像;然后将实验采集到的全息图在程序中先微分再重建. 理论分析和数字重建结果都表明,该方法可以有效地去除数字全息零级像在重建图像中心产生的大亮斑,从而显著提高重建图像的质量,使得重建像具有良好的对比度,且不需要其他辅助设备或多次全息记录,实验操作简单,方便快捷.

关键词:数字全息;零级像;数字图像处理;菲涅尔积分
中图分类号:O438. 1