A New Method for Eliminating Zero-Order and Conjugate Image in Digital Holography

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ABSTRACT

A new experiment method for recording the hologram by CCD with less distortion and reconstructing the original image with high quality is described in this paper. The feature of this developed method is that conjugate and zero-order image can be eliminated simultaneously by setting their spectrum zero in spatial domain. The results have demonstrated that it is an efficient method of image acquisition and the reconstruction with high quality in digital holography.

Key words: digital holography, distortion, zero-order image, conjugate image, spatial domain

1. INTRODUCTION

Digital holography, which uses a charge-coupled device (CCD) to record holograms, and then employs a computer to perform the reconstruction of the digitized holograms based on Fourier optics theory1,2 without chemical and physical developing, has been widely used in 3D imaging, interferometry and metrology. However, due to the lower resolution of CCD sensors compared with the traditional recording medium, such as silver halide, the allowable angle between the object and reference beams has to be reduced to a few degrees only, so that the reconstruction image unavoidably contains the conjugate image and the zero-order beam transmitted directly, resulting in the low resolution.

Several methods for eliminating the conjugate image and the zero-order diffraction image have been developed 3-5, such as phase-shift technique, the CCD image pretreatment in spatial domain, and eliminating mean value etc. In the phase-shift technique many pieces of holographs are recorded by adjusting the phase of the reference beam, it requires to setup a rigorous experiment environment with extra phase-shift equipment to collect the holographs time after time3. The method of CCD image pretreatment in spatial domain preprocesses the recorded image in the spatial domain using Laplacian transform and convolution to wipe off zero-order image and the conjugate image respectively4. It reduces the complexity in measurement, but it takes longer time to perform the computation of the Laplacian transform and convolution than phase-shift method. The method of eliminating mean value can wipe zero-order image simple, and fast but it can not the zero-frequency component of the image.

In this paper, we use off-axis holography to capture the image and to separate the spectrums of the conjugate and

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zero-order image, and wipe them off simultaneously in spatial domain. The mechanism and the analysis of the new method will be discussed in detail below.

2. MECHANISM OF SPATIAL SMOOTHING IN DIGITAL HOLOGRAPHY

2.1 Experiment condition analysis

In our experimental system, a holographic dry plate is replaced by CCD to record the hologram. According to the principle of digital image processing, the spatial resolution of the CCD and the hologram match the Nyquist’s theorem as follows

\[ f_{	ext{ccd}} \geq 2f_{\text{hologram}} \]  

(1)

where, \( f_{\text{ccd}} \) is the spatial frequency of CCD, which is determined by the size and array number of the CCD, and \( f_{\text{hologram}} \) is the spatial frequency of hologram.

Assume that the transverse width of CCD is \( W_{\text{ccd}} \), the number of array is \( N \), so the spatial resolution of CCD in this direction is:

\[ f_{\text{ccd}} = \frac{N}{W_{\text{ccd}}} \]  

(2)

Based on the holography theory, \( f_{\text{hologram}} \) is related to the angle between the object beam and the reference beam. The schematic diagram for making an off-axis digital holography is shown in Figure 1, where \( x_0-y_0 \) is the object plane, \( x-y \) is the image plane, \( \alpha \) is the angle between the reference beam and the object beam, and \( \theta \) is the angle between the reference beam and the normal line of the image plane. In \( x \) direction, the equicohesive plane of peak value is formed by the object beam and the reference beam on the \( x-y \) plane, that is the interference fringe of these two beams, and it demonstrates the spatial distribution of the holograph. So the spatial frequency of hologram is:

\[ f_{\text{hologram}} = \frac{2\sin(\alpha/2)}{\lambda} \]  

(3)

From Eqn. (1), (2) and (3), we can obtain:

\[ \alpha \leq 2\arcsin(\sqrt{\frac{N\lambda}{4W_{\text{ccd}}}}) = \frac{N\lambda}{2W_{\text{ccd}}} \]  

(4)

Equation (4) shows the condition of the angle between the object beam and reference beam has to satisfy in order to make the spatial frequency of the CCD and hologram match the Nyquist’s theorem, and it is determined by the spatial frequency of CCD and the wavelength of the light.
Based on the theory of the holographic optics, the original image, the conjugate image of the object and the direct light can be obtained from the reconstructed holograph. In order to require the clear reconstructed image in the digital holography, the three images must be separated and the separation condition is:

\[ \xi_r \geq 3 \xi_{o,\text{max}} \]  \hspace{1cm} (5)

The resolution of the record medium is:

\[ f_{\text{ccd}} \geq 4 \xi_{o,\text{max}} \]  \hspace{1cm} (6)

where, \( \xi_r = \sin(\theta) / \lambda \) is the spatial frequency of the reference beam on the surface of CCD. The max spatial frequency recorded by CCD is \( \xi_{o,\text{max}} \). So from Eqn. (6), the max spatial frequency of object which can be collected by CCD is \( f_{\text{ccd}} / 4 \), and from Eqn.(5), we can get:

\[ \sin(\theta) = \theta \geq 3N\lambda / 4W_{\text{ccd}} \]  \hspace{1cm} (7)

In order to separate the three images, the incident angle of the reference beam should satisfy Eqn. (7), the angle is also determined by the spatial frequency of CCD and the wavelength of the incident light.

Supposing that the distance between the sample plane and the image plane is \( L \), the width of the object is \( d \), as shown in Figure 1, then based on geometrical relationship, we have:

\[ d = 2L\alpha \]  \hspace{1cm} (8)

It shows that the max object size in digital holography is codetermined by the distance between object and the surface of CCD, and the angle between the object beam and the reference beam.

2.2 Spatial filtering theory

In figure 1, suppose that the beam is plane wave, the reference and object wave can be expressed as \( R(x, y) \exp(2\pi \xi_r x) \) and \( O(x_0, y_0) \) only in \( x \) direction. After traveling \( L \) distance, the object beam is expressed as \( O(x, y) \) then the complex amplitude of the holograph which collected by CCD is obtained:

\[ I(x, y) = |O(x, y)|^2 + R(x, y)^2 + R^\ast(x, y)O(x, y) \exp(-2\pi \xi_r x) + R(x, y)O^\ast(x, y) \exp(2\pi \xi_r x) \]  \hspace{1cm} (9)

In Eqn. (9), the former two parts are direct current component, the third part contains the information of the object and can be reconstructed to the original image of the object, and the last part is the conjugate component of the reconstructed image.

The frequency spectrum of holography can be got as equation (10) by Fourier transformation and is shown in figure 2:

\[ \tilde{I}(\xi, \eta) = \text{FFT}[I(x, y)] = \tilde{O}(\xi, \eta) \otimes \tilde{R}(\xi, \eta) + \delta(\xi, \eta) + \tilde{O}(\xi + \xi_r, \eta) + \tilde{O}^\ast(\xi - \xi_r, \eta) \]  \hspace{1cm} (10)

The first part is the autocorrelation component and the frequency range is \([-2\xi_{o,\text{max}}, 2\xi_{o,\text{max}}]\). The second part is the impulse function. The third part is the spectrum of the original image as shown in the left rectangle in Fig.2 and the last part is the spectrum of the conjugate image, shown in the right rectangle in Fig.2. The spectrum width of the two rectangles is \( 2\xi_{o,\text{max}} \). The spectrum of the zero image, conjugate image and original image can be separated when the beam path content the Eqn. (7). When the zero-order and conjugate image in the spectrum holograph are eliminated from
Eqn. (9), the information of original image is not destroyed. and the original image of object can be reconstructed by inverse Fourier transformation of.

3. ANALYSIS OF EXPERIMENT RESULT

3.1 Digital holography record system

The experimental setup in this study is shown in figure 3. He-Ne laser is the laser source and the wavelength is 632.8nm. The size of the CCD is 7×6.6mm and the number of pixel is 768×576, thus the resolution of CCD is about 200 lines per mm. Since the experiment condition must match equation (4) and (7), so the angle between object beam and reference beam and the incident angle of reference beam should be:

$$\alpha \leq \frac{N \lambda}{2W_{cd}} \approx 1.98^\circ$$

$$\theta \geq \frac{3N \lambda}{4W_{cd}} = 2.98^\circ$$

If the distance from object to CCD is 1m, the size of the object is from Eqn. (8):

$$d \leq 2L \alpha = 6.9cm$$

The object (size of 2.5×6.5cm) in this study is from a part of a power amplifier. The angle between reference wave and the normal line of CCD is 30.

![Fig.2 Spectrum of hologram](image)

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![Fig.3 The experimental setup](image)

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![Fig.4 Hologram recorded by CCD](image)

Fig.4 Hologram recorded by CCD

![Fig.5 The flow chart of digital holography](image)

Fig.5 The flow chart of digital holography
3.2 Process of spatial frequency filtering

The digital holograph recorded by CCD is shown in figure 4, in which the gray level indicates the complex amplitude of the light wave. The procedure diagram of spatial frequency filtering and reconstruction of image is given in Fig.5. In order to describe the procedure conveniently, only one dimension data and results are shown from Figure 7 to 10.

Figure 6 shows the spectrum including large direct current component expressed by bold line. It is the source of zero light in reconstructed image. Figure 7 is the frequency spectrum of digital holography. The component in zero frequency
is very sharp, and its left and right spectrums are correspond to the original and conjugate image, respectively. Deleting the zero frequency and conjugate spectrum in Figure 7, we can get figure 8 which only include information of original image. Figure 9 is the inverse FFT of figure 8. Compared to figure 6, the direct current has been removed and the component of high frequency is clearly shown in figure 9, so the articulation of the reconstructed image can be improved.

Figure 10 (a) and (b) show the reconstructed images with and without spatial frequency filtering, respectively. Since the zero and conjugate image are mixed with the original one in figure 10(a), the reconstructed image is very indistinctness comparing to 10(b) in which the zero and conjugate image are removed.

For comparison, Figure 11 is the reconstructed image when the system doesn’t match Eqn. (7). The zero-order image is at the center of the reconstructed image and the conjugate image is mixed with the original image. The object can not be distinguished clearly in Fig. 11.

![Fig.11 Reconstructed image is unmeet the Eqn (7)](image)

4. CONCLUSIONS

The holography recorded by CCD can distinguish the measured object clearly by transforming the holography to spatial domain, removing the component of zero-order and conjugate spectrum and reconstruct the object image without losing information of original image, when and only when the spatial frequency of the CCD and holograph match the Nyquist’s theorem, and it is determined by the spatial frequency of CCD and the wavelength of the light. The results in this paper have demonstrated that it is an efficient method of image acquisition and the reconstruction with high quality in digital holography.

REFERENCES