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The elimination of zero-order diffraction of 10.6 μm infrared digital holography

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HIGHLIGHTS

- Novel zero-order diffraction elimination method for infrared digital holography.
- No degradation of reconstruction contrast.
- Easy calculation.

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ABSTRACT

A new method of eliminating the zero-order diffraction in infrared digital holography has been raised in this paper. Usually in the reconstruction of digital holography, the spatial frequency of the infrared thermal imager, such as microbolometer, cannot be compared to the common visible CCD or CMOS devices. The infrared imager suffers the problems of large pixel size and low spatial resolution, which cause the zero-order diffraction a severe influence of the reconstruction process of digital holograms. The zero-order diffraction has very large energy and occupies the central region in the spectrum domain. In this paper, we design a new filtering strategy to overcome this problem. This filtering strategy contains two kinds of filtering process which are the Gaussian low-frequency filter and the high-pass phase averaging filter. With the correct set of the calculating parameters, these filtering strategies can work effectively on the holograms and fully eliminate the zero-order diffraction, as well as the two crossover bars shown in the spectrum domain. Detailed explanation and discussion about the new method have been proposed in this paper, and the experiment results are also demonstrated to prove the performance of this method.

1. Introduction

Digital holography technology was invented by Goodman and Lawrence [1] in 1967. The basic theory of digital holography is to record a hologram using the electronic device instead of normal photo plate, and re-display the recorded object with digital computation. It has been greatly improved and applied in many scientific researches, such as small scale three dimensional measurement [2,3,16], microscopy inspection [4], monitoring [12,13], and particle measurements [14,15]. In recent years, an Italian team focused on the infrared digital holography which widen the usage of digital holography [9]. Like the normal digital holography, the infrared digital holography encountered the same situation of the zero-order diffraction effect, which degraded the detail of the reconstruction of the recorded object. The zero-order diffraction is appeared to be a big and bright spot located in the center of the reconstructed hologram. According to Ref. [5], when the amplitude ratio of the object wave and the reference wave was closed to 1:1, the recorded hologram had the best contrast. Under this circumstances, the energy of the reconstructed real image took up to only 1/6 of the total diffraction energy, the conjugate image took up to 1/6 of the total diffraction energy, and the zero-order diffraction took up to 4/6 of the total diffraction [5]. So, the elimination of the zero-order diffraction is crucial to the improvement of the contrast of the reconstructed holograms.

Nowadays, many researchers are working on how to eliminate the zero-order diffraction, and progresses have been made. The common ways of doing this can be identified into several categories: 1. The phase-shifting methods. These kinds of method recorded one or more holograms by shifting the recording phase, however, these methods needed particular experiment setup and

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took too much time in adjusting the setup, they performed well in static measurements but not dynamic measurements [6]. 2. The spatial filtering methods. These methods conducted the fast Fourier transform (FFT) onto the hologram and got the spatial frequency distribution of it, and then specific filtering window was used to spot out the conjugate image and the zero-order diffraction at the same time, then finally reconstructed the object with the filtered spectrum. These methods were by far the most popular ways in eliminating the zero-order diffractions, but they still had some limitations. For example, different objects had different spectrum distributions, the size and shape of the filtered window must be chosen properly to adapt the spectrum of the objects, otherwise, it will degrade the quality of the reconstruction process. The filter window has to be maximally containing all the information of the object. It is hard to find a common filtering window to apply for all recorded holograms, if the filtered window is not proper enough, the zero-order diffraction will not be eliminated [7]. 3. The averaging methods. These methods tempted to eliminate the zero-order diffraction by directly subtracting the DC (direct-current) component of the hologram by calculating the averaging value of every pixel of the capturing device. However, these methods can only be effective when the amplitude distribution of the reference wave was uniformed. And furthermore, the subtraction will cause the degradation of the amplitude of the reconstruction of the real image, which will lower the contrast of it [8].

Usually in infrared digital holography, the zero-order diffraction causes more problem then in the common digital holography. For example, the thermal imager or microbolometer has lower pixel resolution than the common CCD or CMOS devices. Meanwhile, since the laser source has a much longer wavelength of infrared digital holography, the recorded objects are chosen much bigger than the ones used in common digital holography. That is to say, the spatial-bandwidth product of the infrared holograms is not sufficient enough to be fully filtered out, the zero-order diffraction are often overlapped with the real image and the conjugate image. We have done some research in the field of infrared digital holography in order to improve the reconstruction quality before [17,18]. In this paper, we propose a novel method to eliminate the zero-order diffraction. This method focuses on pre-processing the hologram in the spatial domain with single-shot capture, no specific experimental setup is used in the optical path. According to the strategy of this method, it is much easier than the common methods mentioned above. It can greatly lower the complexity of the calculation, and achieve high quality reconstruction of the hologram.

This paper is organized as follows: in Section 2, the basic concept of digital holography and the mechanism of our experiment have been explained; in Section 3, the main strategy of our newly raised method has been discussed; in Section 4, the experimental results of our method has been demonstrated; and in Section 5, we give conclusion of our method.

2. The setup of our experiment and the basic concept of digital holography

2.1. The optical setup of the experiment

The aim of our experiment is to design a new algorithm which can easily eliminate the zero-order diffraction in a single-shot digital holographic capture with no specific optical components added. The whole optical setup is based on simple Mach-Zender interferometry and the scheme is shown below:

We give a brief discussion of our experimental setup. The laser source we use is a power tunable 10.6 μm CO_2 laser which works under the continuous mode. The output power has been set to 25w. The optical mirrors we use are made by II-VI infrared co. Ltd. BS represents Beam Splitter with the efficiency of 80–20. M1, M2, M3 and M4 are reflective mirrors. VA is an attenuator with the extinction ratio of 500:1. L1 and L2 form a beam expander. L3 is a focal lens with the focal length of 1 in. The object is a Caser statue with the dimension of 60 cm × 35 cm, which is made of gesso. The microbolometer we use is a 384 × 288 A-Si uncooled thermal imager with the pixel pitch of 25 μm, the imaging lens has been removed from the microbolometer.

2.2. The basic concept of digital holography

Fig. 2 gives the basic illustration of off-axis digital holographic recording and reconstructing process.According to Fig. 2, the x_0y_0 plane is the object plane, XY is the hologram plane and the $x'y'$ is the image plane. Let us assume the complex amplitude distribution of object wave on x_0y_0 is $O(x_0, y_0)$, the propagating distance between the object plane and the hologram plane is d, the wave distribution on the XY plane can be calculated as Eq. (1) according to the Fresnel diffraction:

$$\begin{aligned} O(x,y) &= \frac{\exp(jkd)}{j\lambda d}\exp\frac{jk(x^2+y^2)}{2d}\cdot F\left\{O(x_0,y_0)\exp\left[\frac{jk(x_0^2+y_0^2)}{2d}\right]\right\} \\ &= |O(x,y)|\cdot\exp[j\phi(x,y)] \end{aligned} \tag{1}$$

In Eq. (1), k represents the wave number, $|O(x,y)|$ and $\exp[j\phi(x,y)]$ represent the amplitude and the phase of the object wave respectively. As we can see from Fig. 1, unlike Ref. [9], we use the plane wave as the reference wave, and its complex amplitude distribution can be written as:

$$R(x,y) = A\exp[jk(x\cos\theta_x + y\cos\theta_y)] \tag{2}$$

where A represents the intensity, θ_x and θ_y represent the angle between the reference wave and the x, y direction respectively.

When the interferometry between the object wave and the reference wave happens, the intensity distribution on the hologram plane can be written as:

$$\begin{aligned} I(x,y) = A^2 + |O(x,y)|^2 + 2A|O(x,y)|\cdot\cos[\phi(x,y) - kx\cos\theta_x \\ - ky\cos\theta_y] \end{aligned} \tag{3}$$

We can see from Eq. (6) that, it contains three parts. The first and second terms represent the zero-order diffraction, the third part represents the real image and the conjugate image. We use the microbolometer to digitally record the hologram, let us set the size of the infrared plane array to $L_x \times L_y$, the pixel number to $N_x \times N_y$, and Δx, Δy are the pixel dimensions. If we ignore the pixel distances, after the spatial sampling, the discrete intensity distribution of an infrared digital hologram can be calculated as:

$$I(m,n) = I(x,y)comb\left(\frac{x}{\Delta x}, \frac{y}{\Delta y}\right)rect\left(\frac{x}{L_x}, \frac{y}{L_y}\right) \tag{4}$$

where m and n are integers, and follow the rule of $-\frac{N_x}{2} \leqslant m \leqslant \frac{N_x}{2}, -\frac{N_y}{2} \leqslant n \leqslant \frac{N_y}{2}$. We use the unit complex amplitude plane wave as the reconstructing wave to illuminate the hologram, and to reconstruct the object, the complex amplitude distribution on the image place can be written as:

$$\begin{aligned} U(x',y') = \frac{\exp(jkd')}{j\lambda d'}\exp\left[j\frac{k}{2d'}(x'^2+y'^2)\right] \\ \cdot F\left\{I(x,y)\exp\left[j\frac{k}{2d'}(x^2+y^2)\right]\right\} \end{aligned} \tag{5}$$

where d' represents the reconstruction distance. When the reconstruction distance is equal to the recording distance, the object