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

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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.

Keywords: infrared digital holography; zero-order diffraction elimination; Gaussian filtering; phase averaging filtering.

1 Introduction

Digital holography technology was invented by J. W. Goodman [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], particle measurements [14,15], and so on. 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 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 than 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 II, the basic concept of digital holography and the mechanism of our experiment have been explained; in section III, the main strategy of our newly raised method has been discussed; in section IV, the experimental results of our method has been demonstrated; and in section V, 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:

Fig.1 the optical setup of our experiment

We give a brief discussion of our experimental setup. The laser source we use is a power tunable 10.6 μm CO₂ 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 inch. The object is a Caser statue with the dimension of 60cm×35cm, which is made of gesso. The microbolometer we use is a 384×288 A-Si uncooled thermal imager with the pixel pitch of 25μm, 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.

Fig.2 the scheme of off-axis digital holographic recording and reconstructing

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:

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

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:

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

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:

$$I(x, y) = A^2 + |O(x, y)|^2 + 2A|O(x, y)| \cdot \cos[\phi(x, y) - kx \cos \theta_x - ky \cos \theta_y] \quad (3)$$

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 $\Delta x, \Delta y$ 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:

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

Where m and n are integers, and follow the rule of $-\frac{N_x}{2} \leq m \leq \frac{N_x}{2}, -\frac{N_y}{2} \leq n \leq \frac{N_y}{2}$. 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:

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

Where d' represents the reconstruction distance. When the reconstruction distance is equal to the recording distance, the object can be clearly reconstructed. When we rewrite the eq.5 into its discrete form to eq.6, the sampling interval $\Delta x'$ and $\Delta y'$ can be calculated as eq.7 as follows:

$$U(m', n') = \frac{\exp(jkd')}{j\lambda d'} \exp\left[j \frac{k}{2d'} (m'^2 \Delta x'^2 + n'^2 \Delta y'^2)\right] \cdot \text{DFT}\left\{I(m, n) \exp\left[j \frac{k}{2d'} (m^2 \Delta x^2 + n^2 \Delta y^2)\right]\right\} \quad (6)$$

$$\Delta x' = \frac{\lambda d'}{N_x \Delta x}, \quad \Delta y' = \frac{\lambda d'}{N_y \Delta y} \quad (7)$$

3 the main strategy of our method

Let us give a thought that, when we look at the spectrum domain of the hologram, the zero-order diffraction is located in the low frequency region. This is because that, according to eq.3, **the zero-order diffraction is mostly made of the energy of the hologram.** An easiest way to eliminate the zero-order diffraction is to directly remove such frequency parts from the spectrum domain of the hologram. However, doing so will cause the **degradation of contrast** when reconstructing the recorded object. **Meanwhile,** this method is too brutal. In the Fresnel diffraction region, the intensity distribution $|O(x, y)|^2$, the amplitude distribution $|O(x, y)|$ and the phase distribution $\phi(x, y)$ on the infrared focal plane array is slowly varying with (x, y) [10]. Since the first part of eq.3 is contributed by the reference wave on the infrared focal plane array along, it is a constant under ideal situation. The second part is contributed by the object wave on the infrared focal plane array. **In** the neighbourhood of a certain pixel, this part can be recognized as almost static. The third part in the interference intensity distribution of object wave and reference wave on the infrared focal plane array, it will be varied by the phase factor of $k(x \cos \theta_x + y \cos \theta_y)$.

Considering the common spatial filtering method in the spectrum domain [7], researchers **used** a window which **had** a certain size in both dimensions to select the spectrum of the real image or the conjugate image. **The window in the spectrum domain was some kind of like a band-pass filter.** Although it **worked on only a small region of the whole spectrum domain,** it **gave** us an inspiration. We can **create** a new band-elimination filter based on the spectrum distribution of zero-order diffraction which works in either the amplitude or the phase of the hologram. This band-elimination filter contains two parts of filtering: 1. The Gaussian low-pass filtering on the amplitude distribution and 2. The mean filtering on the phase distribution. The Gaussian kernel function is a radial base function, and it is given as:

$$g(x, y) = \exp\left(-\frac{(x - x_c)^2 + (y - y_c)^2}{2\sigma^2}\right) \quad (8)$$

Where σ represents the filtering effect of the kernel, x_c and y_c are the coordinates of a center pixel in the 3×3 Gaussian filtering window. The two dimensional Gaussian function has the advantage of symmetry and low-passing. When we adapt the Gaussian kernel function to the hologram, only low frequency parts will stay, thus we can spot out the region of the zero-order diffraction approximately.

Meanwhile, when we conduct the FFT and FFT-shifting on the hologram, we can see two crossover bars located in the center of the whole spectrum, these bars have to be

eliminate as well. We design a phase averaging filter to do so. According to the analysis above, the phase varying is caused mostly by the phase factor of $k(x \cos \theta_x + y \cos \theta_y)$, ergo, by $\cos[\phi(m,n) - \varphi(m,n)]$, where $\varphi(m,n) = km\Delta x \cos \theta_x + kn\Delta y \cos \theta_y$. We use a 3×3 un-weighted phase averaging filtering to the hologram, and it can be written as:

$$\begin{aligned} & \text{Mean} \left\{ \begin{array}{ccc} \cos[\phi(m-1,n-1) - \varphi(m-1,n-1)], & \cos[\phi(m-1,n) - \varphi(m-1,n)], & \cos[\phi(m-1,n+1) - \varphi(m-1,n+1)] \\ \cos[\phi(m,n-1) - \varphi(m,n-1)], & \cos[\phi(m,n) - \varphi(m,n)], & \cos[\phi(m,n+1) - \varphi(m,n+1)] \\ \cos[\phi(m+1,n-1) - \varphi(m+1,n-1)], & \cos[\phi(m+1,n) - \varphi(m+1,n)], & \cos[\phi(m+1,n+1) - \varphi(m+1,n+1)] \end{array} \right\} \\ &= \frac{1}{9} \sum_{i=-1,0,1} \sum_{j=-1,0,1} \cos[\phi(m,n) - \varphi(m,n) - ik\Delta x \cos \theta_x - jk\Delta y \cos \theta_y] \\ &= C \cos[\phi(m,n) - \varphi(m,n)] \end{aligned} \quad (9)$$

Where $C = \frac{1}{9} \left[\begin{array}{l} 1 + 2\cos(k\Delta x \cos \theta_x) + 2\cos(k\Delta y \cos \theta_y) + \dots \\ 2\cos(k\Delta x \cos \theta_x - k\Delta y \cos \theta_y) + 2\cos(k\Delta x \cos \theta_x + k\Delta y \cos \theta_y) \end{array} \right]$. In

eq.9, the term Mean represents un-weighted average. Since the pixel size, wave number and the angle between the object wave or reference wave and the optical axis are certain, **C is then a constant**. Considering that in off-axis digital holography, θ_x and θ_y cannot be

$\frac{\pi}{2}$ at the same time, thus C cannot be equal to 1.

Here we can perform these two filtering parts on the hologram to eliminate the zero-order diffraction. We use the Gaussian filter to determine the zero-order diffraction and the phase averaging filter to determine the two crossover bars. We have to point out that, since these two bars occupy both low and high frequency regions in the spectrum domain, the Gaussian filter can only spot out the relatively low frequency zero-order diffraction, it cannot spot out these two bars. This is where the phase averaging filter get to work. After the cut out frequency has been set correctly within eq.8 and eq.9, these two filtering parts can fully spot out the interference terms in the spectrum domain. We can then get the non-interference results by means of subtraction of the original reconstruction of the hologram and the filtered results, leave only the clean real image and conjugate image with no degradation of the contrast. The whole process will be shown in the next section by experimental figures.

4 experimental results

In this section, we will give experimental demonstration and discussion about how our new zero-order diffraction elimination method works. We use the Mach-Zender interferometry to capture holograms for the experimental object as follows:

Fig.3 infrared digital hologram with strong zero-order diffraction. (a) the captured original hologram; (b) the process result of the hologram after FFT; (c) the three-dimensional mesh result of (b).

Fig.3 shows the problem caused by the zero-order diffraction and the two crossover bars. Here we have to explain something first, that is, it can be found that, the hologram is captured using a 384×288 microbolometer, the shape of the hologram is rectangle. But as in fig.3(b), the reconstruction of the hologram has the shape of square. This is because that, since the spatial resolution of a microbolometer is naturally low, we have added the zero-padding [11] to the original hologram and make the new resolution of the hologram upgraded to 1024×1024 , just to prevent the overlap in the frequency domain. In fig.3(b) we can see that, the reconstruction of the object has been seriously affected by the zero-order diffraction, with such strong low frequency energy, the whole contrast of the reconstruction of the object is not good enough too. Fig.3(c) is a three-dimensional mesh of fig.3(b), here we use the logarithm to rescale the display energy so that the zero-order diffraction can be illustrated along with the real image and conjugate image. We can see from fig.3(c) that, even though the logarithm has been used, the zero-order diffraction and the two crossover bars are too strong on the spectrum domain, which cause the failure of observing the reconstruction of the object.

In the above section, we have discussed that the whole filtering process of eliminating the zero-order diffraction and the two crossover bars contains two kinds of filter, that is, a Gaussian low-pass filter which works to spot out the zero-order diffraction and a phase averaging filter which works to spot out the two crossover bars. When the cut off frequencies of these two filters have been determined, we can get a pleasing filtering result of eliminating them. Here we have to point out that, since the phase averaging filter is a high-pass filter, the cut off frequency of it is set to a fixed value because if the cut off frequency of the phase averaging filter is too high, it will not work at all. If it is set too low, the over-filtering effect will cause the reconstruction fail to be observed. On the other hand, the cut off frequency of the Gaussian filter has to be chosen carefully. This is because that, the zero-order diffraction appears to be occupying different low frequency region on the spectrum domain, the cut off frequency has to be slightly changed to adapt the zero-order

diffraction. In our experiment, we use the stand deviation σ in eq. 8 to control the cut off frequency which will affect the eliminating effort of the zero-order diffraction. The results are shown below:

(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

Fig.4 the performance of our method. (a)(b)are the original reconstruction of hologram; (c)(d) $\sigma = 2$, the filtering results of the hologram; (e)(f) $\sigma = 1$, the filtering results of the hologram; (g)(h) $\sigma = 0.7$ the filtering results of the hologram.

According to fig.4 we can see that, the elimination of the zero-order diffraction can improve the visual effort of the reconstruction of the hologram. The contrast of the whole reconstruction can be upgraded to a much pleasing level, as well as the image details of the reconstruction. In our experiment, the contrast of fig.4(a) is 3.1472, while in fig.4(c), it increases to 16.5324. As we mentioned above, our method will not cause contrast degradation during the filtering, so in fig.4(e), the contrast is 17.8199, and in fig.4(g), it is 18.2045. Meanwhile, the σ works just as we predicted to control the filtering effect of eliminating the zero-order diffraction. It can be seen from fig.4 that, if σ has been set as 2, the zero-order diffraction and the two crossover bars are suppressed, but not enough. This is because that, according to the discussion in the last section, the determination of σ will affect the cut off frequency of the Gaussian low-pass filter, the bigger σ is, the larger the cut off frequency is. If the cut off frequency of the Gaussian filter has overlapped with the cut off frequency of the phase averaging filter, the situation in fig.4(c) will happen. Although the zero-order diffraction and the two crossover bars will still be suppressed, the result is not satisfying. Then we lower the value of σ and find that, the zero-order diffraction and the two crossover bars start to be fully eliminated. In fig.4(g), they are no longer an thread to the reconstruction of the hologram, which proves that our method is surely performs well in the elimination of the zero-order diffraction.

5 Conclusion

In this paper, we have proposed a new method to eliminate the zero-order diffraction

of the reconstruction of holograms. This method is based on a Gaussian low-pass filter and a high-pass phase averaging filter. The two filters work together can eliminate both the zero-order diffraction and the two crossover bars of the reconstruction. This method will not cause any degradation of the contrast of the reconstruction. Since this method is working under single-shot manner of infrared digital holography, and no specific optical devices or equipment are needed in the process, we believe that this method will give great help in this field of research.

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