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A new method of aperture synthetizing in digital holography*

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This paper proposes a new method of aperture synthetizing in digital holography based on the principle of holography. In the new method aperture synthetizing is achieved by reconstructing each sub-hologram respectively, firstly, moving each reconstructed wave field referred to the benchmark reconstructed wave field according to the relationship between spacial motion and frequency shift, and finally splicing them by using superposition. Two different recording ways, using plane wave to record and using spherical wave to record, are analyzed, and their moving formula is deduced, too. Simulation and experiment are done. The results show that in comparison with the traditional method of aperture synthetizing in digital holography, the new method can decrease calculation and save reconstructed time obviously which has better applicability.

Keywords: holography, digital holography aperture synthetizing resolution calculation time
PACC: 4200, 4240K, 4280Q

1. Introduction

How to improve the resolution of digital holographic system, this is the most important problem in the development of digital holography In recent years, some papers have proposed several methods to solve the problem.[1−3] One of them is to use synthetic aperture technique in digital holography, which can improve the quality of reconstructed image obviously without a lot of equipment and complex management. Since Le Clerc and others published a paper[4] on using the synthetic aperture technique in digital holography in Optics Letters, many papers have had the relevant reports and obtained some results.[5−14] However, in these papers, the realization of synthetic aperture is achieved by synthetizing all the sub-holograms to a large hologram and then reconstructed it by using the FFT algorithm. There is a problem in this situation: when the synthetized hologram is very large, it is very difficult to reconstruct it by using the FFT algorithm directly because the capacity of the computer is finite. Sometimes it cannot be achieved if the hologram is too large. For this reason, a new method of aperture synthetizing in digital holography is proposed, which can decrease the computation and save the calculation time in the numerical reconstruction effectively. The principle of the method is introduced and the formula is induced. The simulation and experiment are done and the results prove the feasibility of the method.

2. Principle

According to holographic theory, for a dispersion hologram any its small parts can be reconstructed to get the reconstructed wave field, whose resolution is lower than the whole one. For this reason, when a large hologram is reconstructed, it can be divided into some small holograms which are reconstructed respectively and then synthetized to get the reconstructed wave field which is almost the same as the one of the large hologram. That is the basic principle of the new method and two situations are analysed according to different reference waves.

2.1. Plane wave as reference wave

The sketch is shown in Fig.1. In the recording plane when the charge coupled device (CCD) is moved

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from CCD1 to CCD2, the wave field of the same object point O is changed, as shown in Fig.1. Under the condition of approximate axis, the change of phase can be regarded to be linear for the change of coordinate in image plane, which can be described as

$$\begin{aligned}&\Delta\phi(d_x, d_y)\\ &= \exp(\mathrm{i}\Delta\varphi)\\ &= \exp(\mathrm{i}k\cdot\Delta r)\\ &= \exp[\mathrm{i}k(d_x\sin\alpha + d_y\sin\beta)]\\ &= \exp\left[\mathrm{i}\frac{2\pi}{\lambda}\left(d_x\sin\frac{d_x}{Z} + d_y\sin\frac{d_y}{Z}\right)\right], \end{aligned} \quad (1)$$

where d_x and d_y are the offset of CCD in the direction of x and y, respectively, λ and Δr represent wave length and optical path difference respectively, α and β represent tilt angle between the object piont O and the centre of CCD in the direction of x and y respectively, while Z is the distance between object and CCD.

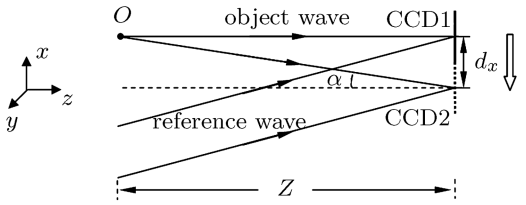


Fig.1. Phase shift of using plane wave to record.

From Eq.(1) we can see that when the reference is plane wave, the numerical reconstruction of the large synthetic hologram can be achieved as follows: firstly, one sub-hologram is chosen as the benchmark one and reconstructed, then the others are multiplied with the phase-shift calculated by Eq.(1) in the spectrum region and reconstructed, finally, all the results are of linear superposition and the reconstructed wave field of the large synthetic hologram is obtained.

In some cases, it is only concerned about the intensity distribution of wave field, especially for the scattered objects whose phase distribution is stochastic and is difficult to calculate. Under the condition the most important factor is to get the relationship between the movement offset of CCD and the shift of the reconstructed wave field in the numerical restruction course. As the movement of CCD can be used to see the motion of object in the opposite direction, considering the relationship between the spatial resolution in holographic plane and the one in image plane, we can describe the moving formulas as:

$$l'_x = \frac{\Delta x^2 M l_x}{\lambda Z}, \quad l'_y = \frac{\Delta y^2 N l_y}{\lambda Z}. \quad (2)$$

Here CCD has $M \times N$ pixels with pixel pitch Δx and Δy in the two orthogonal directions. The l_x and l_y represent respectively the offsets of CCD in the direction of x and y while l'_x and l'_y are the shifts of the reconstructed wave field in the direction of x and y respectively. After the movement, according to Eq.(2), the reconstructed wave field of the large synthetic hologram can be gained by linear superposition of each reconstructed wave field of sub-hologram.

2.2. Spherical wave as reference wave

The sketch is shown in Fig.2. Under the condition of approximate axis, though the angle θ between the object wave and reference wave is almost the same regardless of any position of CCD, it does not affect the spectrum of hologram when the CCD is moving. In this case, the position of the reconstructed wave field of each sub-hologram has not changed, so superposition of the reconstructed wave field of all the sub-holograms is just the result of the large synthetic hologram. At the same time, it can decrease the impact of speckle and noise by superposition because the speckle and noise are generally uncorrelated. For the above considerations, the effect of numerical reconstruction can also be improved.

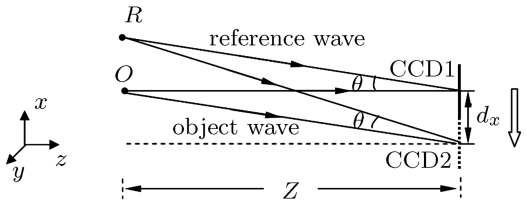


Fig.2. Phase shift of using spherical wave to record.

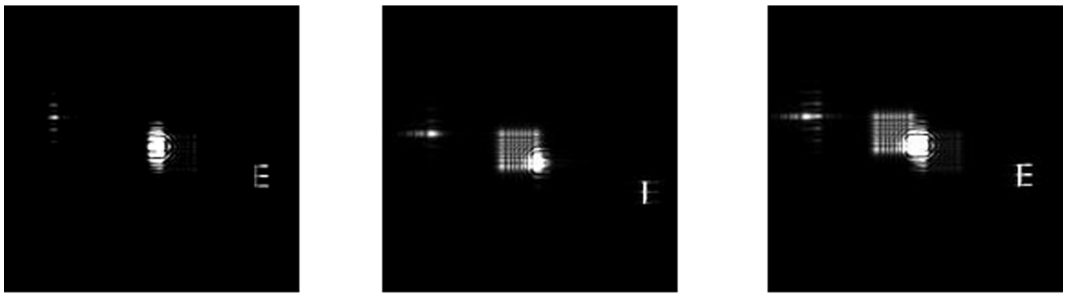
3. Simulation

To prove the veracity of the moving formula, a simulation is done. The simulated object is a black-and-white film written as the letter E, as shown in Fig.3. The simulation parameters are shown as follows: $M = N = 256$, $\Delta x = \Delta y = 10$ μm, $\lambda = 632.8$ nm, $Z = 300$ mm.



Fig.3. Simulated object.

The CCD is moved in two directions to achieve two-dimensional synthetic aperture. Two sub-holograms are selected as an example whose movement offsets are 260 pixel and 120 pixel in the x and y direction respectively. The reference wave is plane wave and from Eq.(2) we can calculate the movement off-set of the reconstructed wave field in the opposite direction, the obtained results are 35 pixel and 16 pixel. The results are shown in Fig.4, where Figs.4(a), 4(b), 4(c) are the reconstructed intensity field of sub-hologram 1, sub-hologram 2 and the synthetic aperture digital hologram respectively. Comparing Figs.4(a), 4(b) and 4(c) with each other, we can draw a conclusion that by using our method, we know that the scene of CCD increases and the resolution is improved, thus proving the validity of our new method.



(a) (b) (c)

Fig.4. Reconstructed intensity field of digital holograms: (a) reconstructed intensity field of sub-hologram 1; (b) reconstructed intensity field of sub-hologram 2; (c) reconstructed intensity field of synthetic aperture digital hologram.

4. Experiment

The setup of our experiment is based on the off-axis digital holography. No phase shifters are required, this results in a less complex setup. Firstly the reference wave is a plane wave with wave length 632.8 nm and the recorded object is a black-and-white film with letters 'PiscGs', whose size is 11 mm × 4 mm. The recording distance is 750 mm. The CCD is fixed on a platform which can move in one dimension. The type of CCD camera is MTV—1802CB with the pixel pitch 0.010 mm × 0.0108 mm. The size of each sub-digital hologram is 512×512 pixels. The main computer parameters in the experiment are as follows: CPU: P4 3.2G, memory: 512M.

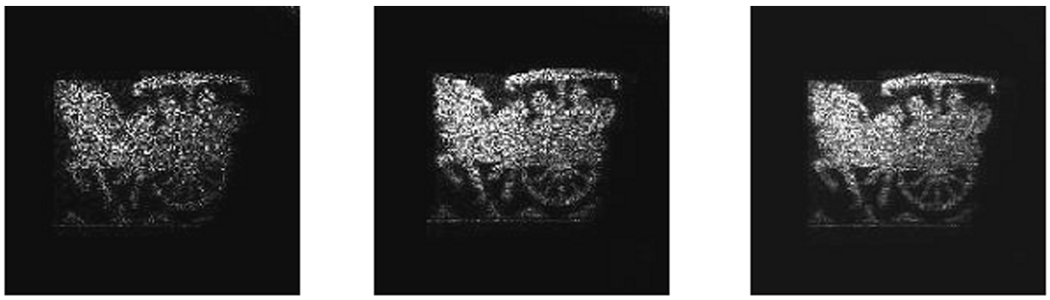
The experimental results are shown in Fig.5. Four sub-holograms are gained with movement offset 280 pixel each other. Figure 5(a) shows the reconstructed intensity field of a sub-hologram. Figure 5(b) shows the reconstructed intensity field of the synthetic hologram with size 1239×512 pixels by using the conventional reconstructed method and the calculation time is 34.875 s while Fig.5(c) shows the reconstructed intensity field of synthetic hologram by using the new method of aperture synthetizing with calculation time 5.094 s. The area of dotted line is the enlarged reconstructed intensity field. Comparing Fig.5(b) with Fig.5(c), we see that the two methods have achieved the synthetic aperture course and improved the resolution, but the calculation time of our method is only 1/6 of the conventional method, which has better applicability.



(a) (b) (c)

Fig.5. Using plane wave to record: (a) reconstructed intensity field of one sub-hologram; (b) reconstructed intensity field of synthetic hologram by using conventional method; (c) reconstructed intensity field of synthetic hologram by using new method.

For the spherical wave as the reference wave, the recording object is a cart with size 20 mm × 14.2 mm and the recording distance is 850 mm. Lensless Fourier transform digital holography is used and a ground glass is put in front of the object to record all the object field. The experimental results are shown in Fig.6, where Fig.6(a) shows the reconstructed intensity field of sub-hologram. Figure 6(b) shows the reconstructed intensity field of synthetic hologram by using conventional method and Fig.6(c) shows the reconstructed intensity field of synthetic hologram by using our method. The results also show the feasibility of the new method.



(a) (b) (c)

Fig.6. Using spherical wave to record: (a) reconstructed intensity field of sub-hologram; (b) reconstructed intensity field of synthesizing hologram by using conventional method; (c) reconstructed intensity field of synthesizing four sub-holograms by using new method.

5. Conclusion

A new method of aperture synthetizing in digital holography is proposed. Compared to the traditional method of aperture synthetizing in digital holography, the new method can decrease calculation and save reconstructed time obviously under the conditions of achieving the synthetic aperture course and improving the resolution. Simulation and experimental results show the applicability of the new method.

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