Automatic Phase Aberration Compensation and Imaging of Digital Holographic Microscopy

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Abstract :The accuracy of numerical reconstruction phase directly affect the result of the digital holographic detection. Because the microscope objective causes additional secondary phase factor, resulting in phase distortion of the reconstructed image. In order to find the phase distortion present in the reconstruction process and take the appropriate way to achieve automatic compensation of phase, digital holographic microscopy in phase compensation issues are studied. Least-squares curve fitting method and choose a background profile data approach is employed to produce the phase mask, and several iterations of correction of mask data by profile data. The theoretical analysis and experimental comparison of this method was validated. The results show that this method can quickly and accurately for better phase distortion correction, while providing new ideas for efficient extraction of real phase.

Keywords: digital holographic microscopy; phase aberration; the phase mask ;unwrapping

OCIS Codes090.1995**;** 090**.**1000

1 Introduction

There are various forms of digital holograms in the process of reconstruction is always primary and secondary phase distortion, or even higher. And these distortions caused by the differences between the numerical simulation of the reference light and reference light in the actual and the optical device of digital holographic recording [1]. To solve this problem, many scholars put forward solutions: Zhao Jianlin [2], who proposed the subtraction of phase program to realize phase distortion compensation. Use the method of subtraction of phase background hologram and the specimen hologram to eliminate distortion. This method requires recording two holograms and requiring high optical stability. Kim [3], who use physical compensation method. The microscope that was identical to the light path was added in the reference optical path, which can eliminate secondary phase distortion. This method requires the placement of a microscope is very precise, while increasing the cost and difficulty of the experiment. T Colomb [4], who proposed the use of digital phase mask (digital phase mask, DPM) to correct the phase distortion, phase distortion compensation expression is made of general application, it can effectively compensate for a secondary or higher order phase distortion.

This article is based on the phase mask on the use of the least square fitting method [5,6] to obtain a digital phase mask .Eventually to compensate for phase distortion and unwrapping. This paper improves the conventional digital phase mask

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method,and unwrapping is added in the calculation of the phase mask. In this paper, a number of iterations to correct the phase mask, using this method greatly reduce the complexity of the real phase extraction and simplifying the calculation process.

2 The principle of compensating phase distortion based on digital phase mask

T Colomb proposed reconstructed wavefront $U(x_{i,}y_i)$ expression contains the digital phase mask [4,7,8,9]

$$\begin{aligned} U(x_i,y_i) &= \Phi(x_i,y_i)\frac{exp(jkd')}{j\lambda d'}exp[\frac{jk}{2d'}(x_i^2+y_i^2)] \\ &\times\iint R'(x,y)H(x,y)exp\left\{\frac{jk}{2d'}\left[(x-x_i)^2+(y-y_i^2)\right]\right\}dxdy \end{aligned} \tag{1}$$

This expression describes the the Fresnel propagation of the reconstructed wavefront over a distance d from the hologram plane (x,y) to the observation plane$(x_{i,}y_i)$. $R'(x,y)$is expressed as a reproduction light, $\Phi(x_i,y_i)$is defined as the phase mask, $H(x,y)$ is defined as hologram.

In the optical path of the pre-amplified off-axis holography, microscope objective was added to amplify light, but the secondary phase distortion was also generated. $\Phi(x_i,y_i)$is used to compensate for the above-mentioned secondary phase distortion, which was expressed as follows:

$$\Phi(x_i,y_i) = exp[-\frac{jk}{\lambda A}(x_i^2+y_i^2)] \tag{2}$$

Where the A is adjusted to compensate distortion parameters and the reproducing light $R'(x,y)$ was expressed as follows:

$$R'(x,y) = exp[jk(k_x x+k_y y)] \tag{3}$$

Where the parameters k_x, k_y define the propagation direction of the reproducing light.Theoretically reproducing light to be consistent with the direction of the reference light. That is, both the k_x and k_y must be the same. But in reconstruction, commonly reproducing light vertical illumination hologram, not in accordance with the angle of the reference light irradiates the hologram, thus creating a phase distortion [10]. In summary, the resulting phase distortion into a second phase distortion and phase distortion, and effect of distortion compensation parameters are four parameters（k_x， k_y， d'， A）, where d' is reconstruction distance can affect the sharpness of the image, k_x and k_y can compensate for the phase distortion, the parameter A can be adjusted the second phase distortion. By the formula (2) shows that the phase mask contains only four parameters, and it can not fully compensate for phase distortion. To make the mask with more ability to compensate, $R'(x,y)$ is placed outside the integral. So the new expression is proposed to take advantage of Fresnel diffraction translation invariance:

$$U(x_i,y_i)=-j\Phi(x_i,y_i)exp[j2\pi\frac{d'}{\lambda}]R'_d(x_i,y_i)\times FFT[H(x,y)](x_i,y_i) \tag{4}$$

Where $R'_d(x_i,y_i)$ was expressed as follows:

$$R'_d(x_i,y_i)=exp\left[j\frac{2\pi}{\lambda}\left(k_x x_i+k_y y_i\right)-j\pi\frac{d'}{\lambda}\left(k_x{}^2+k_y{}^2\right)\right] \tag{5}$$

Binding of formula (2) and the formula (5), the new equation of digital phase mask $\delta(x_i,y_i)$ is obtained:

$$\delta(x_i,y_i)=exp\left\{\frac{2\pi}{\lambda}\left[2\left(k_x x_i+k_y y_i\right)-\frac{x_i{}^2+y_i{}^2}{A}-d'(k_x{}^2+k_y{}^2)\right]\right\} \tag{6}$$

From the above equation, the new digital mask $\delta(x_i,y_i)$can compensate for a secondary phase distortion. The formula simplified mathematical model as follows:

$$\delta\left(x,y\right)=\exp\left[-j\left(a_1x+b_1y+a_2x^2+b_2y^2\right)\right] \tag{7}$$

3 least squares fit of the phase mask

This article by the above formula (7) shows that the mathematical model of the phase mask is a quadratic polynomial function, and sectional data by least squares fitting polynomial coefficients. Finally, the correct phase information is obtained by multiplying the phase mask data. Traditional true phase extraction process including compensation and phase unwrapping and difficult to master. In this paper, the phase unwrapping and phase distortion are fused together and reconstructed wrapped phase map can quickly get the real phase information. The specific process is as follows:

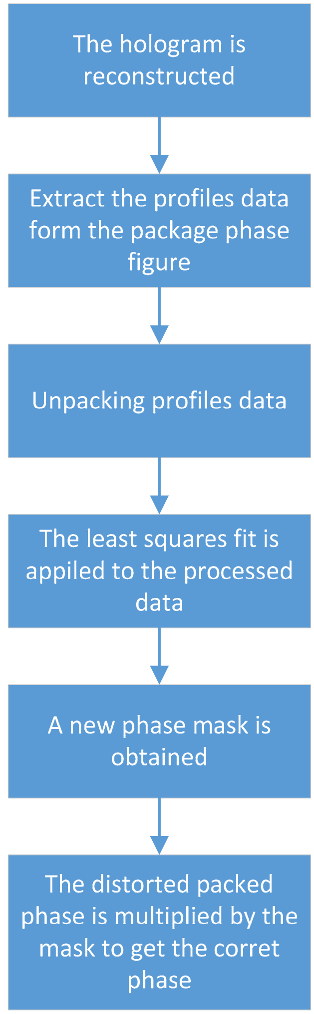


Fig 1 Process on phase distortion of the automatic compensation

Seen from the above flow chart, profiles data are obtained on the amplitude figure after the reconstructed based on the Fresnel diffraction integral. Here the profiles data needs to try to select the no phase transition of the background area. Because the reconstructed phase map is more difficult to distinguish smooth background area. So the profiles data is selected in magnitude figure. The required phase profile data was obtained after the profile data corresponds to the phase figure. Because the phase that obtained from profiles data is wrapped, it is nececssary to be unwrapping. In this paper, a one-dimensional approach was used to unwrap the profiles data instead of the the two-dimensional approach to unwrap the whole image. The method of least squares fitting the above mathematic model coefficients after Data obtained between [-π, π], thereby obtaining a mask to compensate for the distortion.

In the process of making the mask, the one-dimensional unwrapping and least-squares fit polynomial coefficients process multiple cycles. Because the process of unwrapping may exist failure point and fitting mask will fail, so here must be multiple cycles. The whole image is subjected to distortion compensation and unwrapping by using a phase mask and wrapping phase multiplied. Finally get the correct phase.

In this paper, a one-dimensional phase unwrapping method is used for no obvious phase jumps background area unwrapping. This method is primarily targeted at smaller radian phase specimens and you can quickly get the real phase.

4 Experimental System

This paper set up the pre-amplified off-axis digital holography experimental apparatus and optical structure shown in Figure 2. A laser beam emitted by a laser, the beam through mirrors M1, M2 after collimation and expanding and was divided into object light and reference light. The object light through the microscope after irradiate the sample. Then reference beam and object beams formed hologram in the CCD plane.

The object to be tested is the standard resolution test targets and it is on the glass substrate plating chromium layer composed of different frequencies of line width .

Light source used in the experiment is He - Ne laser ($\lambda = 632.8\text{nm}$). The CCD is form Germany PCO company and its pixel size $\Delta_x \times \Delta_y = 7.4\mu\text{m} \times 7.4\mu\text{m}$. The numerical aperture of the microscopic objective NA = 0.55 and the magnification is 50X. In the figure 2, the distance between resolution test targets and microscopic lens is 4.45 mm, the distance between CCD and microscope objectives is 375.05 mm, recording distance is 120 mm.

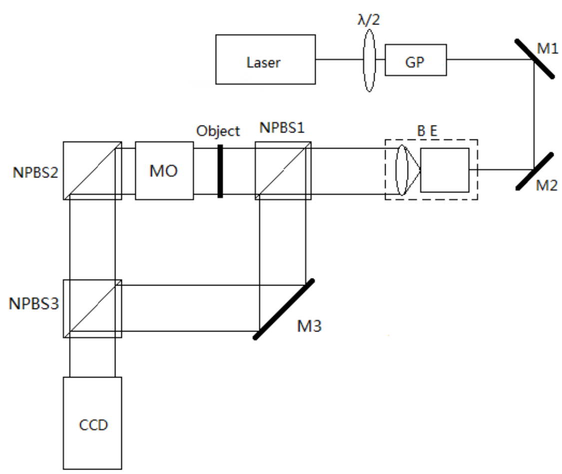
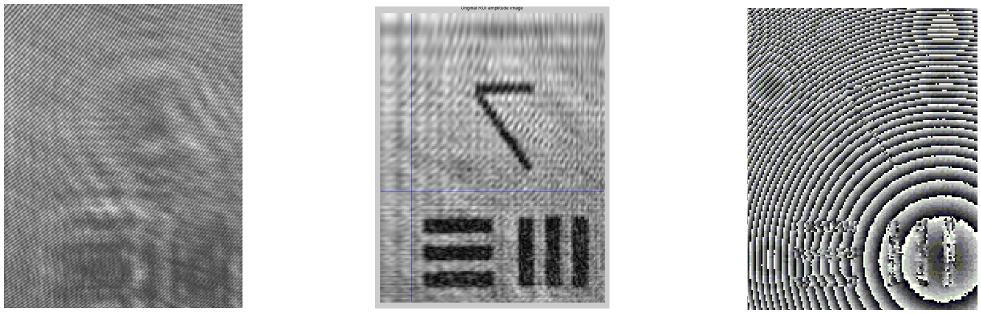


Fig2 Experimental setup for recording pre-magnification off-axis Fresnel digital hologram



（a）　　　　　　　　（b）　　　　　　　　（c）

Fig. 3 The hologram and reconstruction of resolution test targets: (a) hologram;(b) amplitude figure after reconstruction;(c) phase diagram after reconstruction

Figure 3 (a) is hologram of the light path. The figure 3 (b) is the amplitude and figure 3 (c) is package phase. They were obtained after hologram was reconstructed and selected "+ 1" image in the spectrum diagram. Objects real phase was wrapped can be seen from the figure 3 (c) and phase distortion was existed, true phase information can not be extracted directly.

5 analyze and discuss

The resolution test targets of the seventh group for the first unit line is 128 per mm group and computing available lateral resolution is less than $4\mu m$. In order to obtain the correct phase information, the data is subjected to the above-described flowchart of Fig2.

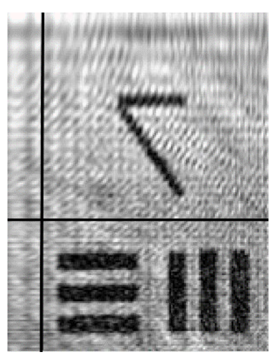


Fig4 extraction sectional data on the magnitude of the target area after reconstruction.

As shown in Fig. 4, it is first necessary to extract the profile data from the amplitude figure. The profile should be selected as much as possible without significant phase jump background area and record the selected coordinate location. The coordinates are mapped into the phase figure, and the profiles data are unpacked and least squares fitted.

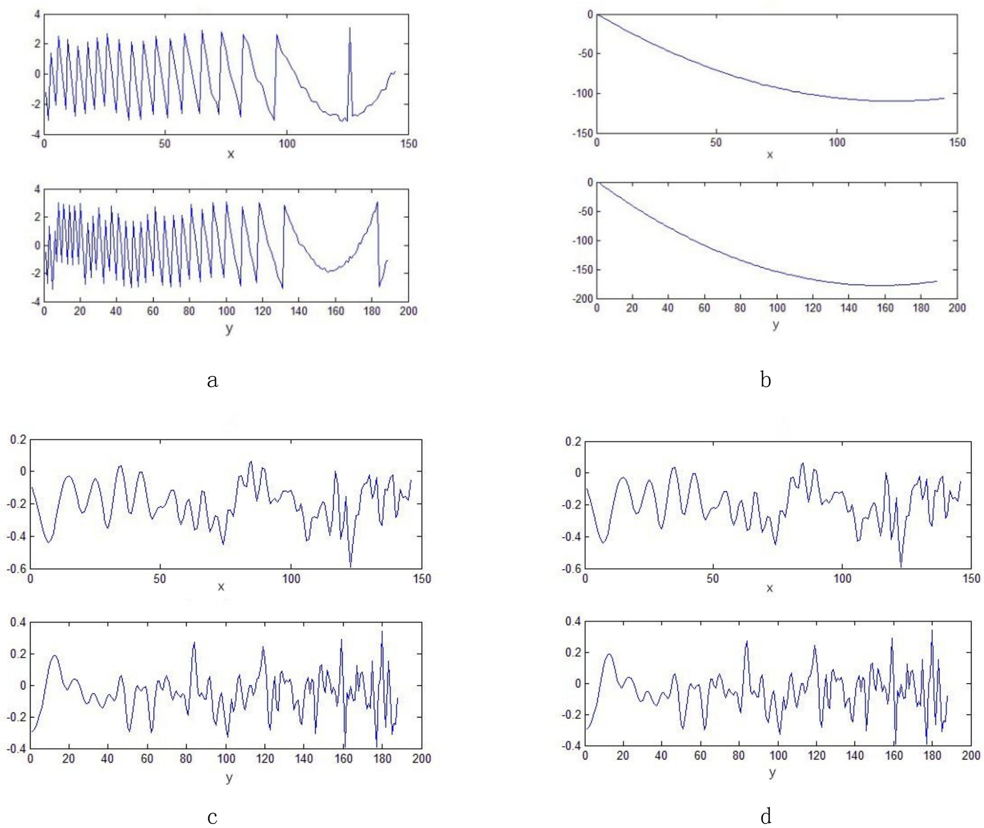


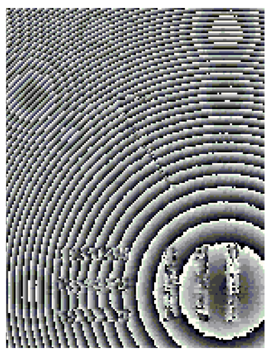
Figure 5 Profiles data:(a) extracting the wrapped phase diagram of profile data;(b) profile data after the first solution package; (c) and (d) is the second and third solution package of profile data

Fig .5 (a) is the data of two profiles (X and Y cross-sections). The abscissa in Fig. 5 is the number of data points of profile and the ordinate is the corresponding phase value. It can be seen from the figure that the data are wrapped between [-π, π]. The data after the first unpacking process is shown in Fig. 5 (b). The unwrapped data is a continuous curve, but most of the data of the profile is a smooth background area without phase jump. There is no continuous rise or fall curve. Therefore, the unwrapping data shown in Fig. 5 (b) is not true. In order to prevent the above-mentioned situation, this article carries on the iterative process. Iteration consists of unpacking and least-squares fitting. First, the profile data is unpacked and the least squares fit of the unpacked data. The coefficients of the polynomial of the phase mask are obtained. Next, the coefficient at this time is stored, and the cycle is repeated again. Unpacking and least-squares fitting are performed again on the basis of the data of the last unpacking. This results in a new set of polynomial coefficient for phase masks. The new coefficients of the polynomial are used to correct the coefficients obtained in the last cycle. As shown in Fig. 5 (c) and (d), the results of the iterative two and three iterations are relatively gentle. There is no significant difference between the second cycle and the third cycle, indicating that the profiles data truly reflect the phase information. In the loop, the newly obtained polynomial coefficients are used to correct the mask polynomial coefficients obtained in the previous step, and the coefficients of the final mask are shown in Table 1.

Table 1 least-square fitting polynomial coefficients

a_1	a_2	b_1	b_2
−1.9505	0.0073	−2.3679	0.0073

From the Table 1 the coefficients can be obtained phase mask. As shown in Figure 6, the mask multiplied by the phase diagram of Figure 3 (c), and the correct phase information is obtained.



a

b

Fig6 Phase diagram of resolution test targets : (a) with phase distortion wrapped phase map;(b) the real phase diagram after DPM;

Figure 6 (a) shows the untreated package distortion phase information. It can be seen from the figure that there is obvious phase distortion, and can not clearly observe the information of the original solution test targets. Figure 6 (b) is the processed real phase information. It can be seen from the figure that the phase map processed by the math phase masks does not have any distortion, and the original information can be clearly seen from the figure, which shows the effectiveness of the method.

6 Conclusion

In the digital micro-holography, the object light through the microscope will lead to secondary phase distortion. In this paper, the problem of phase distortion is solved by analyzing the mathematical model of digital phase mask. When the hologram is reconstructed, the profile data is obtained by selecting the amplitude map for the background without significant phase jumping region. The digital mask is obtained by multiple iterations including unpacking and least squares fitting. The resulting mask can correct the secondary phase distortion caused by the microscope. The experimental results show that the method is effective and effective. This method provides a new method to solve the phase distortion problem in holography reconstruction.

7 References:

[1] Wang Yan, ZhouHao, ZhaoHongbo, etal..Automatic phase aberration compensation of image plane in digital holographic microscopy[J]. OPTICAL TECHNING, 2013, 39(4): 339-342.

[2] Di Jianglei, ZhaoJianlin, FanQi,et al..Phase Correction of Wavefront Reconstruction in Digital Holographic Microscopy[J].ACTA OPTICA SINICA,2008,28(1):56-61.

[3]M K Kim.Applications of Digital Holography in Biomedical Microscopy[J].Opt Soc Korea,2010,14(2):77-89

[4] Tristan Colomb, Etienne Cuche, Florian Charrière,et al.. Automatic procedure for aberration compensation in digital holographic microscopy and applications to specimen shape compensation[J].Applied Optics, 2006, 45(5) : 851-863.

[5] Qian Xiaofan, Zhang Yong′an, Li Xinyu, et al..Phase Unwrapping Algorithm Based on Mask and Least-Squares Iteration[J]. ACTA OPTICA SINICA,2010,30(2):440-444.

[6] Luo Ting, Wang Dayong, Zang Yizhuo,et al..Study on the digital holograpy imaging of the fingerprint acquisition[J].Journal of Optoelectronic·lase, 2012, 23(5):967-971

[7]Frédéric Montfort, Florian Charrière, Tristan Colomb.Purely numerical compensation for microscopeobjective phase curvature in digitalholographic microscopy: influence of digital phasemask position[J]. Opt. Soc. Am. A, 2006,23(10): 2944-2954.

[8]T.Colomb, J. Kühn, F. Charrière,et al.. Total aberrations compensationin digital holographic microscopy with a referenceconjugated hologram[J]. OPTICS EXPRESS,

2006,14(10):4300–4306.

[9] Wang Huaying, Liu Feifei, Liao Wei,et al.. Optimized digital micro-holographic imaging system [J]. Acta Phys. Sin. 2013,62(5): 054208

[10] Wang Tian, Yu Jia, Yang Yu, et al. Correction method of phase distortion in digital holographic microscopy detection[J].Infrared and Laser Engineering, 2014,43(11): 3615-3620