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A New Phase Error Compensation Method in Digital Holographic Microscopy

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Abstract: In this paper we present a new method to compensate for phase aberrations and image distortion with recording single digital hologram in digital holographic microscopy. In our method, tilt is removed from the aberrated phase map first. Then an area of interest (AOI) is generated by flood filled algorithm. By fitting AOI with discrete orthogonal Zernike polynomials, error phase map in the form of a series of Zernike polynomials is obtained. Final result can be calculated by subtracting the error phase map from the aberrated phase map. Through applying our method in microlens testing, phase aberrations and image distortion introduced by microscope objective are well suppressed.

Key words: Digital holography Zernike polynomials Phase error compensation

1. Introduction

Digital Holographic Microscopy (DHM) has become a powerful technique for tomography inspection such as micro electro-mechanical system (MEMS) and micro opto-electro-mechanical systems(MOEMS) since the charge coupled device (CCD) was successfully applied in recording the amplitude image[1]. The reconstruction of the phase map only needs one digital hologram. The reconstructed phase leads to a sub-wavelength axial accuracy. However, the reconstruction needs a well knowledge about physical configuration of objective and reference wavefront. The introduction of a microscope objective (MO) using to improve the lateral resolution also introduces a wavefront curvature in the object wavefront. Furthermore, the misalignment of optical setup will introduces off-center errors unenviably. Numerical compensation methods have been widely studied due to their low cost and easy control features. A phase mask was used for phase aberrations compensation[2-4].A reference hologram was used to compensate the phase aberrations and image distortion[5]. Tilt phase aberration was compensated by spectrum method[6] and interference patterns[7]. Anisoplanatic phase errors was corrected by propagating the aberrated fields from

the hologram plane to the error introduced plane[8]. Lens aberration was modeled and compensated[9]. By decomposing the phase map into a set of values of uncorrelated variables, the extracted aberration terms were compensated[10].

In this paper we present a Zernike polynomials fitting method to compensate for phase aberrations. The method is based on the reconstructed phase map from hologram without any specimen. After calculation of the centroid of the phase image, a discrete Zernike polynomials fitting is implemented on the unified circle which has maximal the radius from the centroid to the vertexes of phase map. Furthermore, the phase errors are expressed in a series of Zernike polynomials with signification of optical aberrations. A result of microlens phase is obtained by removal of the phase errors in the reconstruction.

2. Principle

Here, we introduce W_R and W_o as errors of reference and objective wavefront when there is no specimen. These two terms may be caused by defocus aberration, spherical aberration, astigmatism, coma, and so on. We rewrite reference and objective wavefront when the specimen is present:

$$E_R(x, y) = |E_R(x, y)| \cdot \exp[i(k_x x + k_y y)] \cdot \exp[iW_R(x, y)] \quad (1)$$

$$E_o(x, y) = |E_o(x, y)| \cdot \exp[i\varphi(x, y)] \cdot \exp[iW_o(x, y)] \quad (2)$$

Where k_x , k_y define the propagation direction associated to the angle θ between the object and reference waves. $\varphi(x, y)$ is the object wavefront.

We assume that there are only phase aberrations in the hologram plane.

$$\begin{aligned} I &= R^*(x, y)O(x, y) \\ &= |R(x, y)||O(x, y)| \exp[-i(k_x x + k_y y)] \exp[i(\varphi + W_o(x, y) - W_R(x, y))] \\ &= |R(x, y)||O(x, y)| \exp[-i(k_x x + k_y y)] \exp[i(\varphi + W(x, y))] \end{aligned} \quad (3)$$

Where $W(x, y) = W_o(x, y) - W_R(x, y)$. From above model, we can see that no matter what kind of numerical reconstruction method we use, the aberrations will exist in final phase map. Zernike polynomials fitting program will implement on the final phase map to compensate optical aberrations.

We use Zernike polynomials fitting to exact and represent the optical aberrations in the phase map. Zernike polynomials can be written[71]

$$Z_{even\ j}(\rho, \theta) = \sqrt{2(n+1)}R_n^m(\rho)\cos m\theta, \quad m \neq 0 \quad (4a)$$

$$Z_{odd\ j}(\rho, \theta) = \sqrt{2(n+1)}R_n^m(\rho)\sin m\theta, \quad m \neq 0 \quad (4b)$$

$$Z_j(\rho, \theta) = \sqrt{n+1}R_n^0(\rho), \quad m = 0 \quad (4c)$$

Where index n represents the order of the polynomial, m is called the azimuthal frequency. $R_n^m(\rho)$ is the radial polynomials and

$$R_n^m(\rho) = \sum_{s=0}^{(n-m)/2} \frac{(-1)^s (n-s)!}{s! \left(\frac{n+s}{2}-s\right)! \left(\frac{n-s}{2}-s\right)!} \rho^{n-2s} \quad (5)$$

The index j is a polynomial-ordering number and has relationship with n and m in the form

$$n = [(2j-1)^{0.5} + 0.5]_{int} - 1 \quad (6)$$

$$m = \begin{cases} 2\{[2j+1-n(n+1)]/4\}_{int} & \text{when } n \text{ is even} \\ 2\{[2(j+1)-n(n+1)]/4\}_{int} - 1 & \text{when } n \text{ is odd} \end{cases} \quad (7)$$

The Zernike polynomials and the relationship among j , n , and m are given in table 1. Each polynomial has its meaning in form of optical aberration.

Table 1 Zernike polynomials

j	n	m	Zernike polynomials	Aberration name
1	0	0	1	Piston
2	1	1	$\rho \cos \theta$	x tilt
3	1	1	$\rho \sin \theta$	y tilt
4	2	0	$\sqrt{3}(2\rho^2 - 1)$	Defocus
5	2	2	$\sqrt{6}\rho^2 \sin 2\theta$	Primary astigmatism at 45°
6	2	2	$\sqrt{6}\rho^2 \cos 2\theta$	Primary astigmatism at 0°
7	3	1	$\sqrt{8}(3\rho^3 - 2\rho)\sin \theta$	Primary y coma
8	3	1	$\sqrt{8}(3\rho^3 - 2\rho)\cos \theta$	Primary x coma
9	3	3	$\sqrt{8}\rho^3 \sin 3\theta$	
10	3	3	$\sqrt{8}\rho^3 \cos 3\theta$	
11	4	0	$\sqrt{5}(6\rho^4 - 6\rho^2 + 1)$	Primary spherical
12	4	2	$\sqrt{10}(4\rho^4 - 3\rho^2)\cos 2\theta$	Secondary astigmatism at 0°
13	4	2	$\sqrt{10}(4\rho^4 - 3\rho^2)\sin 2\theta$	Secondary astigmatism at 45°
14	4	4	$\sqrt{10}\rho^4 \cos 4\theta$	
15	4	4	$\sqrt{10}\rho^4 \sin 4\theta$	

Here, we use area of interest (AOI) to represent the whole error phase map. This area contains more accurate optical aberrations information than single profile line. Then iterative least square fitting method is used to exact Zernike coefficients on AOI. After that, the aberrations in wavefront is reconstructed by summing the product of each Zernike polynomial and its coefficient. This method improves the phase mask accuracy with high order optical aberrations. Tilt aberration is removed before generating the AOI.

$$W_r(x, y) = W(x, y) - W_{tilt}(x, y) \quad (8)$$

Then we use flood fill algorithm to generate AOI. This process is manual because program cannot determine which part of area is feature free. We use array $W_{AOI}(x, y)$ to record the data in AOI and a flag array $W_{flag}(x, y)$ to mark the AOI. In detail, If the point (x, y) is in AOI, the $W_{AOI}(x, y)$ value is the same as $W_r(x, y)$ and flag value $W_{flag}(x, y)$ is true; otherwise, the $W_{AOI}(x, y)$ value is 0 and the flag value $W_{flag}(x, y)$ is false. The Coordinate of $W_{AOI}(x, y)$ must convert from Cartesian coordinate into Polar coordinate $W(\rho, \theta)$. It then can be expanded in terms of orthonormal Zernike polynomials $Z_j(\rho, \theta)$ in the form

$$W_r(\rho, \theta) = \sum_j a_j Z_j(\rho, \theta) \quad (9)$$

Where a_j is the Zernike coefficient. To ensure the fitting is implemented on the AOI, the Zernike polynomial $Z_j(\rho, \theta)$ is adjusted by flag array $W_{flag}(x, y)$. If the flag is true, then $Z_j(\rho, \theta)$ is calculated by its definition; otherwise, the $Z_j(\rho, \theta)$ is 0.

Zernike polynomials are orthogonal on continuous unitary circle but not on discrete unitary circle, so Gram-Schmidt orthogonalization is carried out to construct a set of polynomials which are orthogonal on the discrete unitary circle

$$V_j(\rho, \theta) = Z_j(\rho, \theta) + \sum_{s=1}^{j-1} d_{js} V_s(\rho, \theta) \quad (10)$$

Where $j = 1, 2, 3, \dots, L$, and $V_1(\rho, \theta) = Z_1(\rho, \theta)$. The polynomials also can be written in a complete linear compound of Zernike polynomials

$$V_j(\rho, \theta) = Z_j(\rho, \theta) + \sum_{i=1}^{j-1} c_{ji} Z_i(\rho, \theta) \quad (11)$$

Where $c_{ji} = \sum_{s=1}^{j-i} d_{j,j-s} c_{j-s,i}$, with $i = 1, 2, 3, \dots, j-1$ and $c_{jj} = 1$. We can rewrite the equation 9 as

$$W_r(\rho, \theta) = \sum_{j=1}^L b_j V_j(\rho, \theta) \quad (12)$$

On the discrete unitary circle, the polynomials $V_j(\rho, \theta)$ satisfy the following condition

$$\sum_{i=1}^{MN} V_j(\rho_i, \theta_i) V_l(\rho_i, \theta_i) = 0 \quad (13)$$

We define the measured wavefront data as $W_0(\rho_i, \theta_i)$, the deviation of fitting is δ^2 .

The wavefront and orthogonal polynomials were fitted with least square method

$$\begin{aligned} \delta^2 &= \sum_{i=1}^{MN} (W_0(\rho_i, \theta_i) - W(\rho_i, \theta_i))^2 \\ &= \sum_{i=1}^{MN} (W_0(\rho_i, \theta_i) - \sum_{j=1}^L b_j V_j(\rho_i, \theta_i))^2 \end{aligned} \quad (14)$$

In order to make the δ^2 as small as possible, we take differential on the both side of equation 14. Then we solve the equation to get coefficients b_j .

$$b_j = \frac{\sum_{i=1}^{MN} W(\rho_i, \theta_i) V_j(\rho_i, \theta_i)}{\sum_{i=1}^{MN} (V_j(\rho_i, \theta_i))^2} \quad (15)$$

Till now, b_j is derived on the whole wavefront area. When we implement fitting, b_j is calculated on AOI. This needs to determine the flag array value first. If the flag value $W_{flag}(x, y)$ on point (x, y) is true, then this point is taken into account for calculating b_j ; otherwise, the point is ignored.

Since we know the coefficients b_j and c_{ji} , the Zernike coefficients a_j can be got by substituting the equation 11 and 12 into the equation 9.

$$W_r(\rho, \theta) = b_1^{(1)} Z_1(\rho, \theta) + \sum_{j=2}^L b_j^{(1)} (Z_j(\rho, \theta) + \sum_{i=1}^{j-1} c_{ji} Z_i(\rho, \theta)) \quad (16)$$

Comparing with 3.32, we can get the coefficients a_j

$$a_j = b_j^{(1)} + \sum_{i=j+1}^L b_i^{(1)} c_{ij} \quad (17)$$

Where $j = 1, 2, 3, \dots, (L - 1)$ and $a_L = b_L$.

Finally, we get aberration-free phase map $W_f(\rho, \theta)$

$$W_f(\rho, \theta) = W(x, y) - W_{tilt}(x, y) - \sum_j a_j Z_j(\rho, \theta) \quad (18)$$

3. Experiment

To illustrate the procedure for compensation of phase aberrations, an experimental is studied. A hologram of a microlens is recorded with 40X MO. ASM is used for numerical reconstruction. Figure 1(a) shows the wrapped phase reconstruction of this

hologram without aberration compensation. Figure 1(b) shows the unwrapped phase map. Figure 1(c) shows tilt has been removed from the unwrapped phase map. Figure 1(d) shows generated fitting area in black.

Fig.1 (a) The wrapped phase. (b) The unwrapped phase. (c) Tilt removed. (d) Fitting area

Figure 2(a) shows Zernike fitting result. Figure 2(b) shows the reconstructed aberrations phase map. Figure 2(c) shows the wrapped reconstructed aberrations phase map.

Fig. 2 (a) Zernike coefficients. (b) Reconstructed aberrations. (c) Wrapped aberrations.

Figure 3(a) shows the reconstructed phase of a microlens without any aberration compensation. Figure 3(b) shows two plots in 500th row from Figure 1(b) and Figure 3(a). Through comparison of Figure and Figure, we can see that the aberrations are well compensated.

Fig.3 (a) Phase map removal of aberrations. (b) 500th row plots comparison.

4. Conclusion

The proposed method can make use of area without interested object and improve the fitting accuracy compare to single line fitting method. We find out that the method achieves a complete compensation for the phase errors caused by optical aberrations. The method can also be applied in reflection configuration of DHM. The method demonstrates that numerical compensation in the reconstruction procedure allows obtaining high quality phase image.

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