

Calibration Method to Eliminate Zeroth Order Effect in Lateral Shearing Interferometry

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Abstract: In this paper, a calibration method is proposed which eliminates the zeroth order effect in lateral shearing interferometry. An analytical expression of the calibration error function is deduced, and the relationship between the phase-restoration error and calibration error is established. The analytical results show that the phase-restoration error introduced by the calibration error is proportional to the phase shifting error and zeroth order effect. The calibration method is verified using simulations and experiments. The simulation results show that the phase-restoration error is approximately proportional to the phase shift error and zeroth order effect, when the phase shifting error is less than 2° and the zeroth order effect is less than 0.2. The experimental result shows that compared with the conventional method with 9-frame interferograms, the calibration method with 5-frame interferograms achieves nearly the same restoration accuracy.

Keywords: Calibration; phase measurement; phase shifting interferometry

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1. Introduction

The lithography lens is an essential component of the lithography machine. The measurement of system wavefront aberration for the projection lens is one of the core technologies for the development of lithography [1–4]. There are several methods to measure system wavefront aberration, such as grating lateral shearing interferometry [5–8] and point diffraction interferometry [9–12]. Compared with the point diffraction interferometry, it is easy to realize the ultra-high precision measurement of high

numerical aperture (NA) projection lens with grating lateral shearing interferometry. As a result, the grating lateral shearing interferometry is a promising technology for system wavefront aberration measurement [13].

In grating lateral shearing interferometry, the undesired zeroth order diffracted beam will reach the detector, causing the zeroth order effect error. Furthermore, the error is not negligible for wavefront aberration measurement of lithography lens. In 2004, Zhu *et al.* proposed a 9-frame phase shifting algorithm to solve the zeroth order effect

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problem under the condition of small phase shifting error [14]. In 2013, we improved the 11-frame algorithm to solve this problem under the condition of large phase shifting error [15]. The above mentioned solutions are achieved by designing a special phase shifting algorithm to suppress the zero order effect. These solutions increase the complexity of the phase shifting algorithm and require the collection of more frames of interferograms. It takes a longer time to collect more interferograms when more random errors, such as temperature, pressure, and vibration, are introduced. Moreover, it also increases the phase shifting amount, which requires design and fabrication of more complex phase shifter.

In this paper, we propose a calibration method to eliminate the zeroth order effect in lateral interferometry. A procedure of phase shifting calibration is performed before the procedure of phase shifting interferometry. The calibration procedure quantitatively calculates the zeroth order effect to eliminate its influence and thus reduce the complexity of the specially designed phase shifting algorithm. The principle of calibration is analyzed theoretically, and the analytical expression of the calibration error function is deduced. The relationship between the phase-restoration error and the calibration error is established. Finally, the simulations and experiment are described.

2. Principles

A typical grating lateral shearing interferometer is shown in Fig. 1. Grating divides the incident beam into diffracted beams. The ± 1 st order diffracted beam passes through a spatial filter, and the 0th and higher order diffracted beams are eliminated. However, there is still a certain percentage of the 0th order beam reaching the charge-coupled device (CCD) detector that causes the zeroth order effect error.

Therefore, the error of the zeroth order effect must be eliminated before phase shifting

interferometry. The method to eliminate the zeroth order effect is mainly achieved in two procedures. One procedure is the constant calculation during phase shifting calibration, and the other one is the removal of the zeroth order effect during phase shifting interferometry. The calibration constant is calculated once for one tested lens.

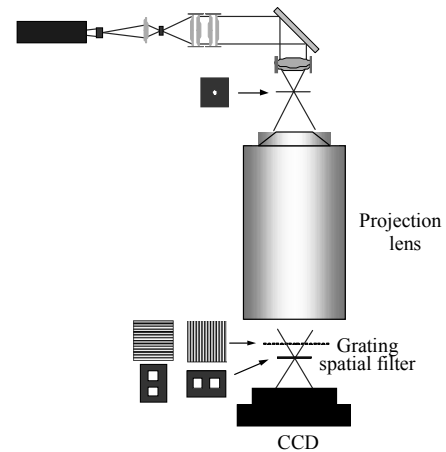


Fig. 1 Block diagrams of grating lateral shearing interferometer.

2.1 Calculation of calibration constant

We propose a 9-step phase shifting calibration method to calculate the calibration constant to quantify the zeroth order effect. The phase shifting amount for each step is $\pi/2$, then the phase shifting amount in the calibration procedure can be expressed as

$$\phi_n = n \frac{\pi}{2} \quad (1)$$

where n ($n = -4, -3, \dots, 0, \dots, 3, 4$) is the number of step.

The 0th and ± 1 st order beams interfere with each other in the calibration procedure. The fringe intensity distribution of I_n for the n -th step is

$$I_n = Q + V_1 \cos(\theta_1 + \phi_n) + V_2 \cos(\theta_2 + \phi_n / 2) + V_3 \cos(\theta_3 + \phi_n / 2) \quad (2)$$

where θ_1 is an unknown phase needing to be restored, θ_2 and θ_3 are undesired phases distorted by the 0th order beam, V_1 is the intensity modulation of the tested interference, and V_2 and V_3 are the intensity

modulations of the undesired interference.

In order to calculate the zeroth order effect, the calibration constants of K_1 and K_2 are defined as follows:

$$\begin{cases} K_1 = V_2 \sin \theta_2 + V_3 \sin \theta_3 \\ K_2 = V_2 \cos \theta_2 + V_3 \cos \theta_3. \end{cases} \quad (3)$$

According to (1) to (3), the calibration constants can be calculated as follows:

$$\begin{cases} K_1 = -\frac{\sqrt{2}}{4}(I_1 - I_{-1}) - \frac{\sqrt{2}}{4}(I_3 - I_{-3}) \\ K_2 = -\frac{1}{4}(I_4 + I_{-4}) - 2I_0. \end{cases} \quad (4)$$

2.2 Removal of the zeroth order effect

In the phase shifting interferometry procedure, the intensity distribution of I_j for the j -th step is

$$I_j = Q + V_1 \cos(\theta_1 + \varphi_j) + V_2 \cos(\theta_2 + \varphi_j / 2) + V_3 \cos(\theta_3 + \varphi_j / 2) \quad (5)$$

where φ_j is phase shifting amount in the interferometry.

The intensity distribution of the zeroth order effect to be calibrated is represented as follows:

$$\begin{aligned} I_{cj} &= V_2 \cos(\theta_2 + \varphi_j / 2) + V_3 \cos(\theta_3 + \varphi_j / 2) \\ &= K_2 \cos(\varphi_j / 2) - K_1 \sin(\varphi_j / 2). \end{aligned} \quad (6)$$

After calibrating K_1 and K_2 , the zeroth order effect with corresponding phase shifting amount can be calculated according to (6). The intensity distribution of each frame after removing the error of the zeroth order effect can be expressed as follows:

$$I_{ij} = I_j - I_{cj} = Q + V_1 \cos(\theta_1 + \varphi_j). \quad (7)$$

From (7), we conclude that the intensity distribution is not affected by the zeroth order effect. The calibration and removal of the zeroth order effect are achieved.

3. Error analyses

3.1 Intensity distribution calibration error

Owing to the manufacturing error and alignment error of micro displacement stage and grating, the

phase shifting error always exists in the phase shifting calibration procedure. The phase shifting amount for n -frame is

$$\phi_n = n \cdot \frac{\pi}{2} + n \cdot \varepsilon \quad (8)$$

where ε is the phase shifting error.

We substitute (8) into (4) and express (4) as two sets of Taylor expansions for the phase shifting error of ε , ignoring the higher order of ε^2 or more. The calibration constants are approximated as follows:

$$\begin{aligned} K'_1 &\approx V_2(1 - \frac{1}{2}\varepsilon) \sin \theta_2 + V_3(1 - \frac{1}{2}\varepsilon) \sin \theta_3 \\ &= (1 - \frac{1}{2}\varepsilon)K_1 \end{aligned} \quad (9)$$

$$K'_2 \approx V_2 \cos \theta_2 + V_3 \cos \theta_3 = K_2. \quad (10)$$

In the phase shifting interferometry, the intensity distribution of the zeroth order effect with phase shifting calibration error can be expressed as follows:

$$\begin{aligned} I'_{cj} &= K'_2 \cos(\varphi_j / 2) - K'_1 \sin(\varphi_j / 2) \\ &= I_{cj} + \frac{\varepsilon}{2} K_1 \sin(\varphi_j / 2). \end{aligned} \quad (11)$$

The intensity distribution calibration error of the zeroth order effect is expressed as follows:

$$\Delta I_{cj} = I'_{cj} - I_{cj} = \frac{\varepsilon}{2} K_1 \sin(\varphi_j / 2). \quad (12)$$

In general, the intensities of the ± 1 order beams are equal, therefore, $V_2 = V_3$. The intensity distribution calibration error is expressed as

$$\Delta I_{cj} = \varepsilon V_2 A \quad (13)$$

where $A = (\sin \theta_2 + \sin \theta_3) \sin(\varphi_j / 2) / 2$ is a constant.

From (13), we conclude that the intensity distribution calibration error of the zeroth order effect is proportional to the phase shifting error and the zeroth order effect. As the phase shifting error increases, the calibration error increases linearly. As the zeroth order effect increases, the calibration error increases linearly.

3.2 Phase-restoration error

The intensity distribution calibration error is

shown as the gray of the interferogram, which is an intermediate quantity in the measurement. The final result of the measurement is phase. Therefore, it is necessary to establish the relationship between the phase-restoration error and the calibration error.

The intensity distribution of I'_{ij} affected by calibration error is denoted as follows:

$$I'_{ij} = I_{ij} - \Delta I_{cj}. \quad (14)$$

Here, the widely used Hariharan algorithm is used to illustrate the method to establish the relationship between the phase-restoration error and calibration error [16]. The phase shifting amount for each step of the Hariharan algorithm is $\pi/2$. The Hariharan algorithm is expressed as

$$\tan \theta = \frac{2(I_1 - I_{-1})}{(I_2 + I_{-2}) - 2I_0} \quad (15)$$

where θ is the phase to be restored.

The phase with the calibration error is expressed as

$$\tan \theta' = \frac{2(I_{1t} - I_{-1t}) - \sqrt{2}\varepsilon K_1}{(I_{2t} + I_{-2t}) - 2I_{0t}} = \tan \theta (1 - 2\varepsilon V_2 B) \quad (16)$$

where

$$B = \frac{\sqrt{2} (\sin \theta_2 + \sin \theta_3)}{2 (I_{12} + I_{1-2}) - 2I_{10}} \quad (17)$$

and B is a constant.

Considering that the phase-restoration error of $\Delta\theta$ is small, the phase-restoration error is as follows:

$$\begin{aligned} \Delta\theta &= \theta - \theta' \approx \tan(\theta - \theta') \\ &= \varepsilon V_2 B \sin 2\theta. \end{aligned} \quad (18)$$

From (18), the phase-restoration error introduced by the calibration error of the zeroth order effect varies as the sine of double phase, and the worst condition is at $\pi/4$. The phase-restoration error is also proportional to the phase shifting error and zeroth order effect. As the phase shifting error increases, the phase-restoration error increases linearly. As the zeroth order effect increases, the phase-restoration error increases linearly.

4. Simulations

In this section, a lateral shearing interferometry affected by the zeroth order effect is simulated to verify the analyses. The wavefront with common aberrations locates in unit circle. The wavefront is sheared in the x direction, the shearing ratio is 0.1, and the zeroth order effect is $V_2 = V_3 = 12.5\%V_1$. The shearing phase is shown in Fig. 2.

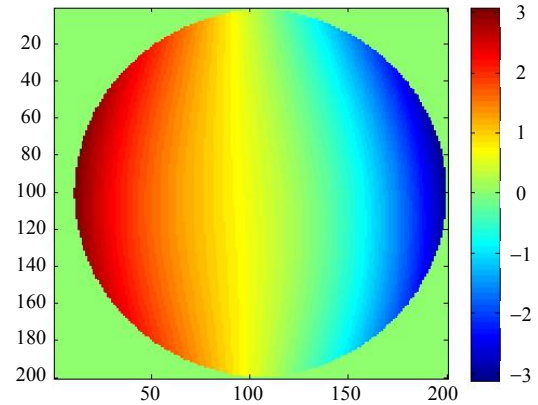


Fig. 2 Shearing phase in the simulation.

According to the calibration method, under the conditions of $\varepsilon = 1^\circ$ and $V_2 = V_3 = 12.5\%V_1$, the phase shifting amount of each step is $\pi/2$, and a sequence of 9-frame interferogram is obtained in the calibration procedure. According to (4), the calibration constants K_1 and K_2 are calculated. When $j = -2$, the calibration result of the zeroth order effect is shown in Fig. 3.

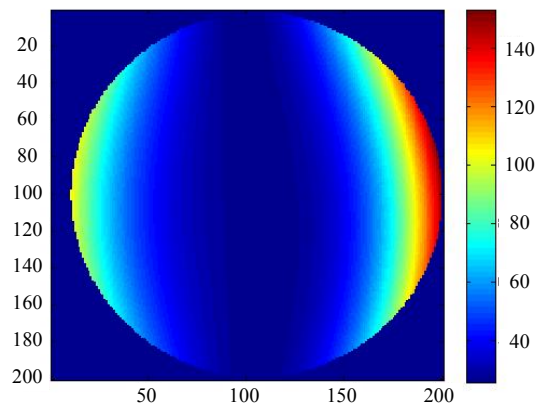


Fig. 3 Calibration results of the zeroth order effect when $j = -2$.

Depending on the calibration constants, the phase is restored using the Hariharan algorithm in

the interferometry procedure. The restoration phase is illustrated in Fig. 4.

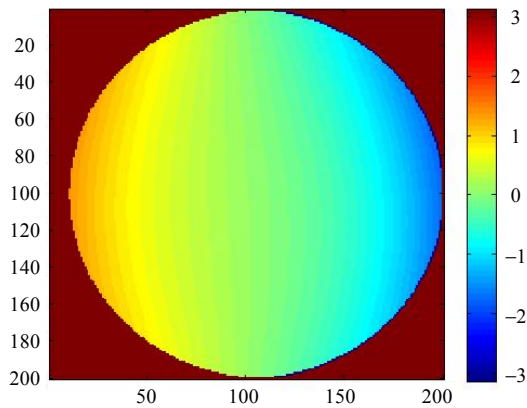


Fig. 4 Restoration phase after removing the zeroth order effect.

By comparing the results of Figs. 2 and 4, the phase-restoration error is obtained, as shown in Fig. 5. The root mean square (RMS) of phase-restoration error is 0.001598 rad. Under the same condition, the RMS of phase-restoration error is 0.001509 rad with the 9-frame phase shifting algorithm proposed by Zhu [14]. Two different methods are used to deal with the interferograms with the zeroth order effect, and the relative error of the phase-restoration error is less than 6%. Therefore, the calibration method is expected to be available.

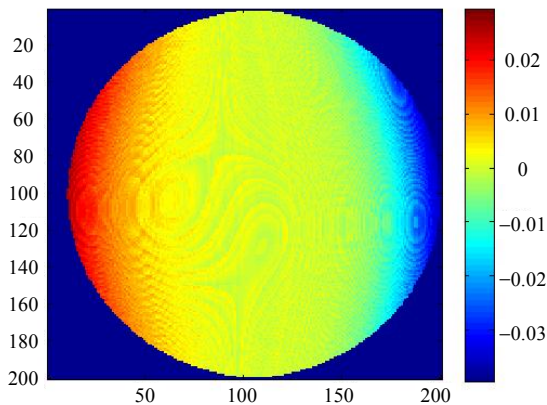


Fig. 5 Phase-restoration error caused by the calibration error of the zeroth order effect.

Under the condition of $V_2 = V_3 = 12.5\%V_1$, simulations with different phase shifting errors are carried out, respectively. We linearly fit the

relationship between the phase-restoration error and the phase shifting error, as shown in Fig. 6. The fit result shows the coefficient of determination is 0.9794, which is closed to 1. Therefore, when the phase shifting error is less than 2° , the phase-restoration error approximately increases with the phase shifting error linearly, that is consistent with the theoretical analysis in Section 3.

Under the condition of $\varepsilon = 1^\circ$, simulations with different zeroth order effects are carried out. We linearly fit the relationship between the phase-restoration error and the zeroth order effect, as shown in Fig. 7. The fit result shows the coefficient of determination is 0.9888, which is close to 1. Therefore, when the zeroth order effect is less than 0.2, the phase-restoration error increases with the zeroth order effect approximately linearly, that is consistent with the theoretical analysis in Section 3.

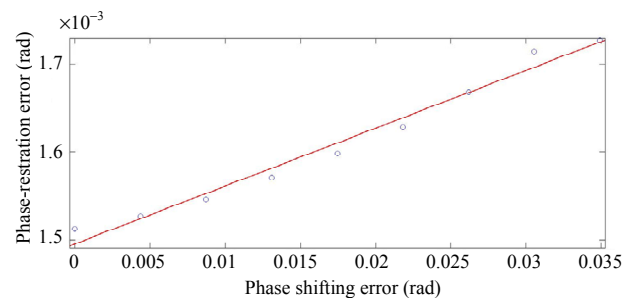


Fig. 6 Relationship between the phase-restoration error and phase shifting error.

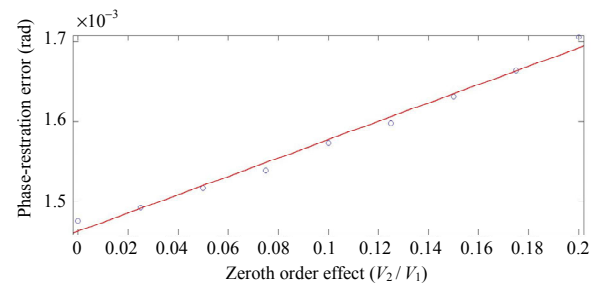


Fig. 7 Relationship between the phase-restoration error and the zeroth order effect.

5. Experiments

The experimental grating lateral shearing interferometer is shown in Fig. 8.



Fig. 8 Experimental lateral shearing interferometer.

With the calibration method described in Section 3, the restoration phase is shown in Fig. 9 by using the experimental interferometer. With the conventional 9-frame phase shifting algorithm, the restoration phase is shown in Fig. 10. The difference between the two restoration phases is shown in Fig. 11.

With the calibration method, the RMS of the phase with the calibration method is 5.5342 rad. With the 9-frame phase shifting algorithm, the RMS of the phase is 5.5346 rad. We compare the results of the two phases point by point, the RMS of the phase difference is 0.1134 rad. Relative error of the RMS is less than 2.5%. We perform 10 experiments under the same experimental conditions. The experimental results are shown in Fig. 12. The average relative error is 2.07%, and the RMS of relative error is 0.01%.

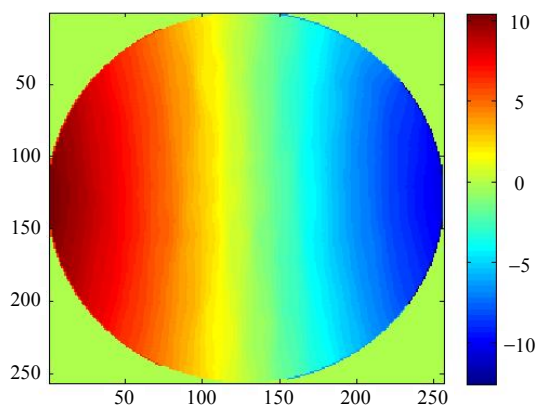


Fig. 10 RMS of the restoration phase with the conventional 9-frame phase shifting algorithm.

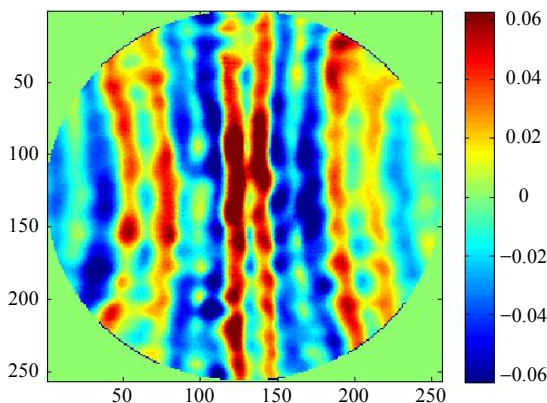


Fig. 11 RMS of the restoration phase difference with two methods.

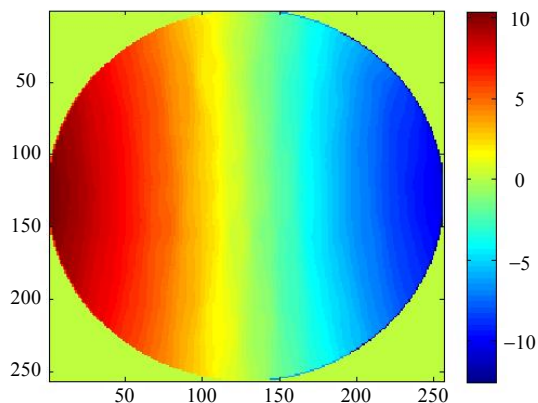


Fig. 9 RMS of the restoration phase with the calibration method.

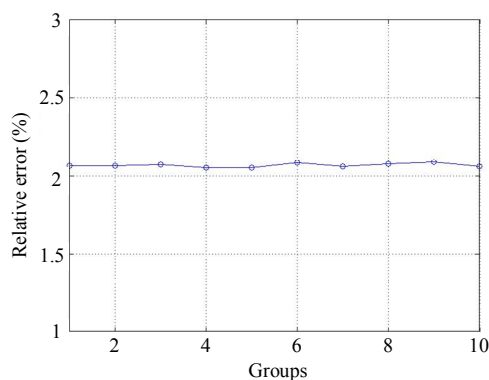


Fig. 12 Relative errors with 10 experiments.

Compared the conventional method with 9-frame interferograms, the calibration method with 5-frame interferograms achieve nearly the same restoration accuracy. Hence, the calibration method is available to eliminate the zeroth

order effect.

6. Conclusions

A calibration method to eliminate the zeroth order effect is proposed in the paper. The principle of calibration is analyzed theoretically, and the analytical expression of the calibration error caused by the phase shifting error is deduced. Using the Hariharan algorithm, the relationship between the phase-restoration error and calibration error is established. The results show that the calibration error of intensity distribution is proportional to the phase shifting error and zeroth order effect. The phase-restoration error introduced by the calibration error of the zeroth order effect is also proportional to the phase shifting error and zeroth order effect. The calibration method is verified by carrying out simulations and experiments. The simulation results show that the phase-restoration error is approximately proportional to the phase shift error and zeroth order effect, when the phase shifting error is less than 2° and the zeroth order effect is less than 0.2. Simulations are consistent with the theoretical analysis. The experimental result shows that compared with the conventional method with 9-frame interferograms, the calibration method with 5-frame interferograms achieves nearly the same restoration accuracy. Therefore, the calibration method is available to eliminate the zeroth order effect.

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