One-shot surface profile measurement using polarized phase-shifting

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Abstract

An instantaneous polarized phase-shifting interferometer (IPSI) with an optical image combiner is designed to form a one-shot surface profile measurement system. The interference images are captured simultaneously by using one CCD camera. Digital image correlation (DIC) method is applied effectively to correct the position mismatch among the images. Test of the measurement system on flat mirror, tilted mirror and wafer are given. An average error between 0.07μm~0.09μm can be achieved, and the maximum error is about 0.2μm.

Keywords: Polarized phase-shifting, digital image correlation, surface profile measurement

1. Introduction

Phase-shifting technique is widely used in lots kind of interferometric surface profilometer to determine the altitude of specimen quickly and accurately from the captured interference patterns with difference phase. Traditionally surface measurement interferometer with phase-shifting technique often needs to use PZT (Piezoelectric Translator) or stepping-motor to move the reference surface of spacemen or use rotational polarizer and other elements to change the phase of the interference pattern to difference phase. These kinds of phase-shifting method would cause time lag problem and the accuracy can be affected by the surrounding environments easily such as air turbulence and vibrations.

In order to reduce the influence of environment and increase the accuracy and stabilization, various instantaneous phase-shifting interferometry (IPSI) technique, such as multi-CCD cameras [1], diffraction grating [2], micro-retarder array [3], phase mask [4] and holographic optical element [5] are introduced. Use of multi-CCD cameras is simpler to record the four phase-shifted images, and the accuracy is also satisfactory. However misalignment of these images might cause larger error in the calculated phase value. Traditional alignment is done by manually tilting the specimen to align the CCD cameras. That is a time consuming process and the alignment may not be reliable. Application of digital image correlation (DIC) method to align the four phase-shifted images automatically and reliably has been reported [6]. Nevertheless, synchronization of the four CCD to obtain four images simultaneously is relatively complicate and inconvenient for practical use. In the present study, one CCD and a self-designed image combiner is developed to form a one-shot measurement system. In the following sections, the principles of IPSI interferometer, DIC method, and experimental system are introduced. Test results are shown and discussed.

2. One-shot IPSI theory

The schematic diagram of a self-designed one-shot instantaneous phase-shifting interferometer is shown in Fig. 1, where QWP45° is 45 degree quarter-wave plate, PBS is polarized beam-splitter, L1, L2 and L3 are convex lens, the image combiner consists of beam-splitters and right-angle prisms; the polarizer set consists of four polarizers with transmission
Fig. 1. Schematic diagram of one-shot instantaneous phase-shift interferometer.

axes of 0°, 45°, -45°, and 90°, respectively. As the light emerges from a linear polarized He-Ne laser and passes through the spatial filter and lens L1, using the Jones vectors [7], the S-wave and P-wave can be represented by $E_s$ and $E_p$, as given in Eq (1).

$$E_s = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad E_p = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

The S-wave and P-wave pass through and reflected by the polarized beam-splitter respectively, can be given in Eq. (2), where PBS(0) is the light pass through the PBS, and PBS(π/2) is the light reflected by PBS.

$$PBS(0) = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \quad PBS(\frac{\pi}{2}) = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$$

The Jones Matrix for a 45 degree quarter-wave plate can be represented as Eq. (3)

$$QWP\left(\frac{\pi}{4}\right) = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & i \\ i & 1 \end{bmatrix}$$

The light wave passes through a quarter-wave plate with its fast axis at an azimuth $\phi=\pi/4$, and then reflected by reference or object surface and pass through the same quarter-wave plate can be represented by $Q$, as shown in Eq. (4) [8]. And the light pass through a polarizer at an azimuth $\theta$, the Jones Matrix of the polarizer is given in Eq. (5)

$$Q = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

$$P(\theta) = \begin{bmatrix} \cos^2(\theta) & \cos(\theta)\sin(\theta) \\ \cos(\theta)\sin(\theta) & \sin^2(\theta) \end{bmatrix}$$

For the light pass through polarizer P45°, the reference wave represented as $E_{RI}$, and the object wave represented as $E_{OI}$, are given in Eqs. (6) and (7).

$$E_{RI} = b \cdot P\left(\frac{\pi}{4}\right) \cdot QWP\left(\frac{\pi}{4}\right) \cdot PBS(0) \cdot Q \cdot PBS\left(\frac{\pi}{2}\right) \cdot E_s$$

$$E_{OI} = a \cdot e^{i\alpha} \cdot P\left(\frac{\pi}{4}\right) \cdot QWP\left(\frac{\pi}{4}\right) \cdot PBS\left(\frac{\pi}{2}\right) \cdot Q \cdot PBS(0) \cdot E_p$$

where $a$ and $b$ are the light intensity reflected by object surface and the reference respectively, $\alpha$ is an unknown phase, which is related to the altitude difference between object and
reference surface. Thus the light intensity captured through the polarizer P45°, denoted as $I_1$, can be given as shown in Eq. (8). Similarly, the intensities of light, $I_2$, $I_3$, and $I_4$, captured through the polarizer P90°, P-45°, and P0°, can be given as shown in Eqs (9)-(11).

$$I_1 = |E_{n1} + E_{o1}|^2 = \frac{1}{2} (a^2 + b^2 + 2ab \cdot \cos[\alpha])$$  \hspace{1cm} (8)

$$I_2 = \frac{1}{2} \left( a^2 + b^2 + 2ab \cdot \cos[\alpha - \frac{\pi}{2}] \right)$$  \hspace{1cm} (9)

$$I_3 = \frac{1}{2} \left( a^2 + b^2 + 2ab \cdot \cos[\alpha - \pi] \right)$$  \hspace{1cm} (10)

$$I_4 = \frac{1}{2} \left( a^2 + b^2 + 2ab \cdot \cos[\alpha - \frac{3\pi}{2}] \right)$$  \hspace{1cm} (11)

The unknown phase $\alpha$ can be determined from Eq. (12). The altitude $h$ of the object surface can be determined from the unwrapped phase by using Eq. (13) with the wavelength of laser light, $\lambda$.

$$\alpha(x, y) = \tan^{-1} \left( \frac{I_2 - I_4}{I_1 - I_3} \right)$$  \hspace{1cm} (12)

$$h(x, y) = \frac{\lambda}{4\pi} \alpha(x, y)$$  \hspace{1cm} (13)

3. **Digital image correlation**

In order to make the interference images well aligned pixel to pixel, the digital image correlation method, based on the following equation, is employed to determine the position mismatch values between two images.

$$\bar{C}(\hat{p}) = \sum_{x,y \in X \cap X', \alpha \in \alpha, \beta \in \beta} \left( G_o(x, y) - G_d(x', y') \right)^2$$

$$= \sum_{x,y \in X \cap X', \alpha \in \alpha, \beta \in \beta} G_o^2(x, y)$$  \hspace{1cm} (14)

where $\bar{C}(\hat{p})$ is the correlation value between the original image and the position mismatch image, $G_o(x,y)$ and $G_d(x',y')$ are the gray level of the original image and the position mismatch image, respectively, and $G_o(x,y)$ is equal to $G_d(x',y')$. Consider the in-plane translation only, the relationship of $x$ and $x'$ is given as:

$$x' = x + u$$

$$y' = y + v$$  \hspace{1cm} (15)

where $u$ and $v$ are the position mismatch values of these two images.

4. **Experimental test and discussion**

According to Fig. 1, an experimental system consisting of the IPSI with a He-Ne laser of wavelength 633 nm, and a PC-based image processing system with a 1600x1200 pixel CCD camera was constructed. The position mismatches of the four images captured by the CCD were calculated by using the DIC method first. Figure 2 shows the four images of a marked flat mirror. The calculated position mismatch values relative to image 1 are listed in Table 1. These values were used later to correct the interference images of object to be measured.

In order to evaluate the accuracy of the one-shot IPSI system, a 9mm 7.5mm rectangle area on a flat mirror was measured by the system, and a vertical line across the measured area is also measured by the ET3000 α-Step profilometer (Kosaka Laboratory Inc. Japan). The four phase-shifted interference images of the flat mirror captured is given in Figs. 3(a)-3(d).
Firstly the interference images were corrected to align pixel to pixel. Then phase values of every pixel of the images were calculated by Eq. (12) as shown in Fig. 3(e). After unwrapped by using Macy's [9] algorithm, the surface profile of flat mirror was calculated and plotted as shown in Fig. 3(f).

To assess the stability of the instantaneous measurement system, the flat mirror was measured ten times. An average mean error of 0.075μm with standard deviation of 0.053μm is obtained for ten measurements. The maximum error is about 0.185μm. The stability of the experiment estimated by the value 3σ is 0.011μm. It shows the stability of IPSI system is satisfactory. Figure 3(g) shows the comparison of one result measured by one-shot IPSI system and the α-Step profilometer.

Similarly, the surface profile of a tilted flat mirror was measured by the system. The interference image, phase map and 3D plot of the tilted mirror are shown in Fig. 4. Comparing to the profile measured by α-step profilometer, an average mean error of 0.089μm with standard deviation 0.048μm is achieved, and the maximum error is 0.166μm and the 3σ is 0.013μm for ten measurements. Application of the system to measure a silicon wafer coated with 1000Å Ti was done. Figure 5 shows the interference image, phase map and 3D plot of the wafer. Again, comparing to the profile measured by α-step profilometer, an average mean error of 0.095μm with standard deviation 0.049μm is achieved, and the maximum error is 0.172μm and the 3σ is 0.013μm for ten measurements.

Table 1. Position mismatch values.

<table>
<thead>
<tr>
<th>Image NO.</th>
<th>x-shift (pixels)</th>
<th>y-shift (pixels)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
<td>-3</td>
<td>-78</td>
</tr>
<tr>
<td>4</td>
<td>51</td>
<td>-92</td>
</tr>
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</table>
5. Conclusion
A one-shot instantaneous phase-shifting interferometer system using polarized light using for surface profile measurement has been developed. With this technique, the interferometric images can be captured at the same time by one CCD camera, and the effect of surrounding environment can be largely reduced. By applying digital image correlation, the interference images captured can be aligned pixel to pixel in a short period of time and more reliable than the manual procedures. Use of the system to measure the surface profile of flat mirror, tilted mirror and silicon wafer reveals that an average error between 0.07μm~0.09μm and the 3σ of 0.013μm for ten measurements can be achieved.

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References