

Sinusoidal phase modulating interferometer for real-time surface profile measurement

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The optical interferometry for the surface profile measurement is high accuracy, non-contact, and has a wide application in industry and scientific research. In this paper, a sinusoidal phase modulating (SPM) interferometer to realize real-time surface profile measurement is proposed, and its measuring principle is analyzed theoretically. In the SPM interferometer, the interference signal is detected by a high speed image sensor based on a low-speed CCD and a signal processing circuit is used to obtain the phase of each point on the surface. Therefore, the surface profile can be measured real time. The experiments measuring the surface profile of a wedge-shaped optical flat show that the measurement time of the SPM interferometer is less than 10 ms, the repetitive measurement accuracy is 5.2 nm. The experimental results confirm the validity of the SPM interferometer, and the merits of the interferometer is simple structure, high measurement accuracy.

Keywords: real-time measurement, surface profile, SPM interferometer.

1. Introduction

Surface profile is one of the most important features of objects, and it is the key factor to guarantee and enhance the properties of mechanical, electronic and optical devices. Recently, the surface profile measurement technique becomes a research spot in the field of measurement [1–6]. There exist two methods in the surface profile measurement. One is contact measurement, and the other is non-contact. There exist some problems in the contact measurement, such as low accuracy and easy damage to the surface, *etc.* The non-contact measurement includes capacitance method, optical interference method, and scanning electronic microscope method, *etc.* [7–10]. In these

methods, the optical interference method is intensively researched for the merits of high accuracy, high sensitivity, and whole field of view [11, 12]. And it has been widely used in industry.

The high accuracy surface profile interferometry measurements include heterodyne interferometric method, phase-shifting interferometric method, and sinusoidally phase modulating (SPM) interferometry. The heterodyne interferometry need to shift the optical frequency accurately, which is very difficult. The phase-shifting interferometry has some faults, such as inaccurate phase-shifting, strong noise, low resistance to environmental disturbance, and complex structure, *etc.* Since among the characteristics of the SPM interferometry are simple phase-shifting, high accuracy, and excellent resistance to disturbance, *etc.*, it becomes an important surface profile measurement technique [16–20]. However, at present in the SPM interferometry also exist some faults, such as bad performance in real-time, complex circuit, *etc.* [21]. In this paper, we propose a new method to realize the real-time surface profile measurement by using the sinusoidal phase modulating interferometer, and analyze the measuring principle theoretically. In this SPM interferometer, a high speed image sensor based on a low speed CCD is used to detect an interference signal, and a designed circuit is used to process the phase-demodulation of the interference signal to get the phase distribution of each point on the surface. According to the phase distribution, the surface profile can be obtained. And we utilize this SPM interferometer to measure the surface profile of a wedge-shaped optical flat. The experimental results confirm the validity of this SPM interferometer.

2. Principle

The setup of a SPM He-Ne laser interferometer for real-time 2-D surface profile measurement is shown in Fig. 1, which consists of the optical and electrical systems. A Twyman–Green interferometer is used as the optical system. After being collimated by the lens and split by the beam splitter BS, a He-Ne laser beam is split into two interference beams. One beam is reflected by a mirror and serves as a reference beam, the other is reflected by an object and serves as an object beam. The two beams interfere to form the interference signal. And this signal is imaged onto a CCD image sensor. The reference beam is phase modulated with the sinusoidally vibrating mirror which is driven by a piezoelectric transducer (PZT) attached to the back of the mirror. The interference signal is detected by a high speed image sensor based on a low speed CCD (including a special drive circuit and noise-removal circuit of CCD). After phase demodulated real-time by a signal processing circuit to the CCD output video signal, the phase distribution of the measured surface can be obtained. Therefore, we can obtain the surface profile.

The processing circuit is shown in Fig. 2, which mainly consists of a real-time phase-demodulation processing circuit, and time sequential circuit. The real-time phase-demodulation processing circuit is made up of a calculator, filter, and amplifier.

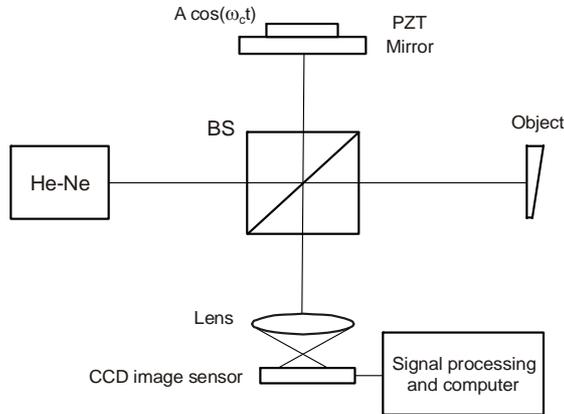


Fig. 1. Experimental setup of a SPM He-Ne laser interferometer for real-time surface profile measurement.

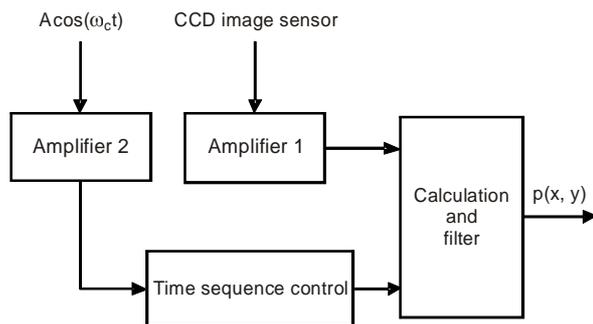


Fig. 2. The signal processing circuit.

Under the control of the time sequential circuit, the video signal is phase demodulated by the real-time phase-demodulation processing circuit, and the phase distribution can be obtained. According to the phase distribution of the surface, we can obtain the surface profile.

The modulated voltage signal $V(t)$ acted on the PZT is given by

$$V(T) = A \cos(\omega_c t) \quad (1)$$

where A is the amplitude, ω_c the angular frequency. The interference signal accepted by CCD can be given by [21]

$$s(x, y, t) = s_1(x, y) + s_0(x, y) \cos \left[z(x, y) \cos(\omega_c t) + \alpha_0 + \alpha_r(x, y) \right] \quad (2)$$

where s_1 is the dc component of the interference signal, s_0 – the amplitude of ac component, $z = 4\pi A/\lambda$, λ – the wavelength of the He-Ne laser, x and y – coordinates

of the measured surface; α_0 is the phase change of the interference signal when the mirror is still and it is determined by the optical path difference between the two interference arms $2D_0$. It can be given by

$$\alpha_0 = \frac{4\pi}{\lambda} D_0 \quad (3)$$

$\alpha_r(x, y)$ is the phase change of the interference signal arising from the measured surface profile, and it can be given by

$$\alpha_r(x, y) = \frac{4\pi}{\lambda_0} r(x, y) \quad (4)$$

where $r(x, y)$ is the surface profile of any point on the measured surface.

Expanding Eq. (2) and neglecting the dc component, we have [22]

$$s(x, y, t) = s_0 \left\{ \cos[\alpha(x, y)] \left[J_0(z) - 2J_2(z) \cos(2\omega_c t) + \dots \right] - \sin[\alpha(x, y)] \left[2J_1(z) \cos(\omega_c t) - 2J_3(z) \cos(\omega_c t) + \dots \right] \right\} \quad (5)$$

where $\alpha(x, y) = \alpha_0 + \alpha_r(x, y)$, and $J_n(z)$ is the n -th order Bessel function. The signal $s(x, y, t)$ and modulation voltage signal $A \cos(\omega_c t)$ are amplified by amplifier 1 and 2, respectively. The two amplified signals are phase demodulated and filtered, and we obtain the signal $p(x, y)$

$$p(x, y) = K_A K_m K_L s_0 A J_1(z) \sin[\alpha(x, y)] \quad (6)$$

where $K_A = K_1 K_2$; K_1 and K_2 are the gains of the amplifier, corresponding to amplifier 1 and 2, respectively; K_m is the coefficient of calculation circuit, and K_L is the gain of the filter. According to the above equation, and near the position $\alpha_r(x, y) = 2n\pi \pm \pi/2$ ($n = 0, 1, 2, \dots$), we can obtain

$$\alpha(x, y) = \alpha_0 + \alpha_r \approx \frac{p(x, y)}{K} \quad (7)$$

where the system conversion coefficient $K = K_A K_m K_L s_0 A J_1(z)$. Neglecting the dc component α_0 , we can obtain

$$r(x, y) = \alpha(x, y) \frac{\lambda_0}{4\pi} \quad (8)$$

Near the position $\alpha(x, y) = \pm\pi/2$, the signal $p(x, y)$ is proportional to the surface profile $r(x, y)$. According to Eq. (6), the span of the phase $\alpha(x, y)$ locates between

$-\pi/2$ and $+\pi/2$, therefore, the measured range of $r(x, y)$ is $\lambda_0/4$. Therefore, if we obtain the signal $p(x, y)$, the surface profile can be obtained.

According to above description, the high speed image sensor based on a low speed CCD can convert the interference signal into the original video signal by the special drive circuit. The noise of the original video signal can be eliminated, and we obtain the video signal. Under the control of the time sequential circuit, the real-time signal processing circuit will amplify, calculate, and filter the video signal. Therefore, we can obtain the signal $p(x, y)$. According to Eq. (8), the surface profile can be obtained real time.

3. Experiments

The home-made high speed image sensor based on a low speed CCD is served as an electro-photonic detector. The resolution is 30×30 , the frame rate 800 frame/second. The experimental setup is shown in Fig. 1. The light source is a He-Ne laser with the wavelength 632.8 nm and output power 8 mW. The measured object is a wedge-shaped optical flat which can cancel the disturbance of the back reflection light. The light path difference $2D_0$ between the two interference arms is 6 cm. The gain K_1 of amplifier 1 is 60.2, the gain K_2 of amplifier is 288.6, the coefficient of a multiplier K_m equals 5×10^{-5} 1/mV. In this experiment, we choose a 4-level low-pass, low-energy filter with the cut-off frequency 100 Hz and the gain $K_L = 100$. The modulated voltage signal frequency acted on PZT is 398 Hz, and the modulation voltage is 500 mV. The sinusoidal phase modulation depth is 2.58. The measured ac component s_0 is 1.452 mW. The system conversion coefficient $K = 2.351 \times 10^3$ mV/rad.

According to the detective signal $p(x, y)$, the displacement curve can be measured real-time. In order to enhance the measurement accuracy, we acquire 8 maps sequentially, and calculate the mean value of each point. The measured surface profile is shown in Figs. 3a and 3b, while the time interval is a few minutes between the two maps. The x and y are the position axis in units of $5 \mu\text{m}$, while z axis means the roughness in the units of nanometer. The repetitive measurement accuracy of

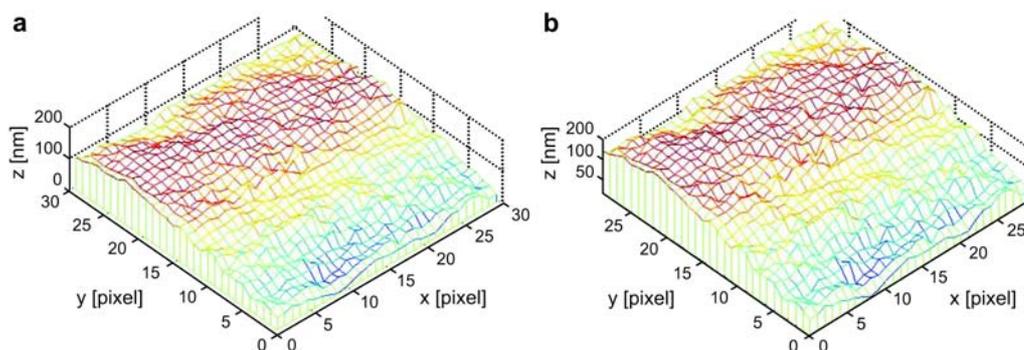


Fig. 3. The measured surface profile of the wedge-shaped (a), the measured surface profile after a time interval of a few minutes with a (b).

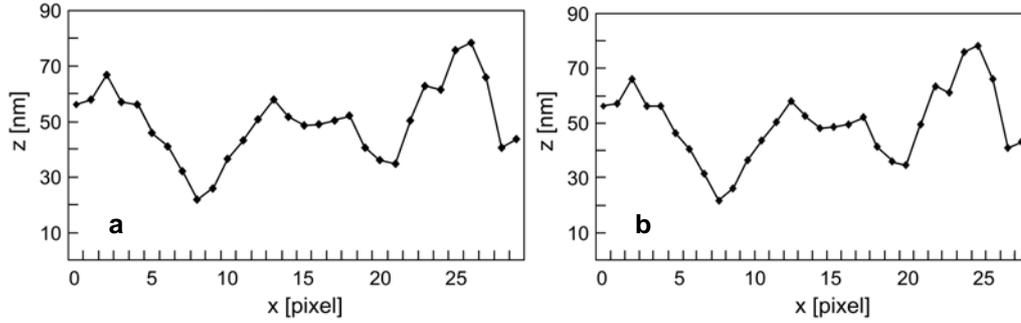


Fig. 4. Surface profile of the wedge-shaped optical flat along the x axis (a), measured result after an interval of a few minutes (b).

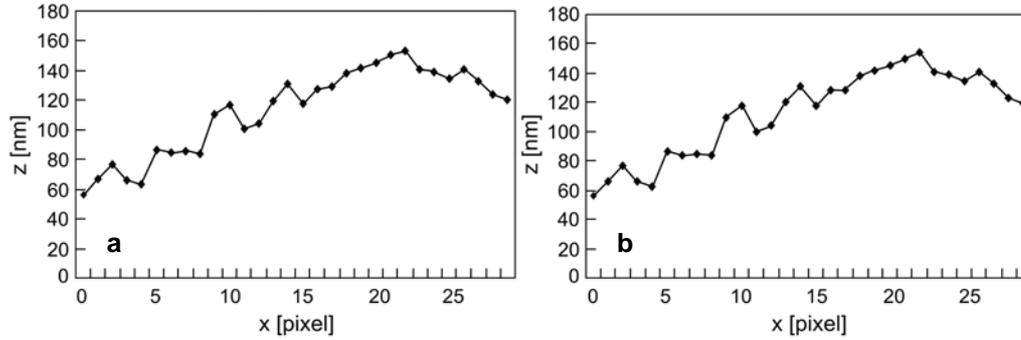


Fig. 5. Surface profile of the wedge-shaped optical flat along the y axis (a), measured result after an interval of a few minutes (b).

Fig. 3a is 5.2 nm. The related coefficient of Figs. 3a and 3b is 0.9826, and the maximum difference value is 3.6 nm. The read-out time of a pixel is 0.125 μs , and the retardation time of the circuits is less than 200 ns. The time for phase-demodulation and calculation is less than 8 ms. Therefore the measurement time is less than 10 ms.

In order to analyze the measurement accuracy clearly, we can select a row or column from Fig. 3a randomly to analyze the accuracy. Figures 4a and 4b show the maps of the first row in the direction of x axis of Figs. 3a and 3b, respectively. The repetitive measurement accuracy of Fig. 4a is 3.681 nm, while that of Fig. 4b is 3.653 nm. In the same way, we select the first column in the direction of y axis of Figs. 3a and 3b, results are shown in Figs. 5a and 5b. The repetitive measurement accuracy of Fig. 5a is 3.852 nm, while that of Fig. 4b is 3.925 nm. The related coefficient of Figs. 4a and 4b is 0.9821, while that of Figs. 5a and 5b is 0.9825.

4. Conclusions

In this paper, a sinusoidal phase modulating (SPM) interferometer to realize real-time surface profile measurement is proposed, and its measurement principle is analyzed

theoretically. In the SPM interferometer, the interference signal is detected by a high speed image sensor based on a low-speed CCD and a signal processing circuit is used to obtain the phase of each point on the surface. Therefore, the surface profile can be measured real time. The experiments measuring the surface profile of a wedge-shaped optical flat show that the measurement time of the SPM interferometer is less than 10 ms, the repetitive measurement accuracy is 5.2 nm. The experimental results confirm the validity of the SPM interferometer, and the merits of the interferometer are simple structure and high measurement accuracy.

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