A New Method for Phase Readout in Phase Modulated Interferometer*

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A simple time-counting phase readout method for a sawtooth phase modulated interferometer is proposed. In this method, the measured phase is estimated from time intervals between zero points of only one modulated interference signal. A compact differential interferometer using a laser diode as the light source is described. The interferometer is calibrated with a capacitance-type displacement sensor by exploiting the advantages of a lever system, and some experimental results are presented.

Key Words: Differential Interferometer, Displacement Measurement, Phase Modulation, Phase Readout, Sensor Calibration, Stability

1. Introduction

Due to high resolution and a wide measurement range, ac interferometers are widely used to measure displacement⁽¹⁾ and surface profiles⁽²⁾. Three methods are commonly used to determine displacement from the interference signals of an ac interferometer. The first is the counting method which requires two interference signals with a definite phase difference⁽³⁾ or a reference signal and an interference signal⁽⁴⁾. The second is the phase-locked method^{(5),(6)} in which one interference signal and a modulation signal are used, and phase difference is determined by harmonic analysis of the interference signal. The third is the Fourier transform method⁽⁷⁾, which is based on the relationship between the spatial frequency and spectrum of the interference signal. Although these methods can achieve a resolution of between 0.1 - 1.0 nm, the

optical and electrical design of the systems required are relatively complicated and expensive.

In this paper, we propose a simple time-counting method in which displacement is estimated from time intervals between zero points of only one modulated interference signal, and describe a compact differential interferometer using a laser diode as the light source. Experiments show that the resolution of the interferometer is approximately 0.662 nm, the repeatability is approximately 5.2 nm, and the stability is better than 5.18 nm over a five-min period.

2. Principle of Operation

2.1 Optical system

The optical system of the apparatus is shown in Fig. 1. A laser beam from a low-noise (<60 dB) laser diode with a wavelength of 785 nm (LT 022 MD, Sharp Co., Ltd.) is linearly polarized and p-polarly oriented. After being collimated to about 1 mm in diameter, the beam is split into two beams with equal intensity by half-mirror HM1. After being reflected by mirror M, one arm of the interferometer passes through a phase modulation unit consisting of a right-angle prism RAP3 attached to a PZT transducer.

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Fig. 1 Optics of interferometer

Fig. 2 Modulation signal (a) and detected interference signal (b)

The PZT is subjected to a sawtooth-modulated voltage in order to introduce phase modulation into the interferometer. The beam then passes through polarizing beam splitter PBSB and a quarter-wave plate before reaching the M-B mirror. Reflected beam B returns to PBSB through the wave plate, where it is changed to an s-polarized beam that is reflected to the detector through another half mirror, HM2. The beam comprising the other arm of the interferometer follows an optical path similar to beam B. A path adjustment unit with a micro-stage is inserted to make the optical paths of the two beams equal. Consequently, an interference signal corresponding to the differential displacement of mirrors M-A and M-B can be detected by the photo diode PD.

2.2 Signal processing

Figure 2 shows one cycle of the modulation signal (a) and the detected interference signal (b). The interference signal can be expressed as:

$$V_0 = A \cos [\varphi_m(t) + \varphi_x(t)], \quad (1)$$

where

$$\varphi_m(t) = \frac{4\pi}{\lambda} \cdot d_m(t) \text{ and } \varphi_x(t) = \frac{4\pi}{\lambda} \cdot x(t).$$

Here, $\varphi_m(t)$ is sawtooth-modulated phase corresponding to the modulation displacement of PZT, expressed as:

$$\varphi_m(t) = \begin{cases} +\alpha \cdot t & (0 \leq t \leq \frac{T}{2}) \\ -\alpha \cdot (t - T) & (\frac{T}{2} \leq t \leq T) \end{cases}, \quad (2)$$

where α is a constant determined by the modulation frequency and T is the cycle of the modulation signal. $\varphi_x(t)$ is the measured phase corresponding to differential displacement x , which is caused by the relative movement of the mirrors. Therefore, displacement x can be considered as a function of time $x(t)$.

In the following discussion, we assume that the i -th cycle of the modulation signal is being considered, and the velocity of the measured target satisfies the following condition:

$$\left| \frac{dx(t)}{dt} \right| < \alpha. \quad (3)$$

In the period of $(0 \leq t \leq \frac{T}{2})$, the modulated phase increases and this period is referred to as the "+" period. Measured parameters of this period are designated by a "+" sign for simplicity. Therefore, we have:

$$\varphi_m(t) + \varphi_x(t) > 0. \quad (4)$$

The phase difference between any two adjoining zero points, such as b and c , of the interference signal is determined as follows:

$$\varphi_{bc}(t) = \varphi_m(t) + \varphi_x(t) = \pi^+. \quad (5)$$

Thus, the measured phase can be determined by:

$$\varphi_x(t) = \pi^+ - \varphi_m(t) = \pi^+ - \alpha \cdot t_{i2}^+. \quad (6)$$

In the period of $(\frac{T}{2} \leq t \leq T)$, the modulated phase decreases and the measured parameters of this period are designated by a "-" sign. Then we have:

$$\varphi_m(t) + \varphi_x(t) < 0. \quad (7)$$

Therefore, the phase difference between any two adjoining zero points, such as g and h , of the interference signal is determined by:

$$\varphi_{gh}(t) = \varphi_m(t) + \varphi_x(t) = -\pi^-. \quad (8)$$

Thus, the measured phase can be obtained by:

$$\varphi_x(t) = -\pi^- - \varphi_m(t) = -\pi^- + \alpha \cdot t_{i2}^-. \quad (9)$$

Near the turning point of the modulation signal, the phase difference between zero points e and g yields:

$$\varphi_{eg}(t) = \varphi_m^+(t) + \varphi_m^-(t) + \varphi_x(t) = 0, \quad (10)$$

and the measured phase can be obtained by :

$$\varphi_x(t) = -[\varphi_m^+(t) + \varphi_m^-(t)] = -\alpha \cdot t_{i5}^+ + \alpha \cdot t_{i1}^-. \quad (11)$$

Therefore, we can calculate the accumulated phase difference between points b and p as follows :

$$\begin{aligned} \varphi_{ix}(t) &= (M_i - 1)\pi^+ - (N_i - 1)\pi^- \\ &\quad - \alpha \left[\sum_{j=2}^{M_i+1} t_{ij}^+ - \sum_{j=1}^{N_i+1} t_{ij}^- + t_{(i+1)1}^+ \right] \\ &= (M_i - 1)\pi^+ - (N_i - 1)\pi^- \\ &\quad - \alpha \left[\sum_{j=1}^{M_i+1} t_{ij}^+ - \sum_{j=1}^{N_i+1} t_{ij}^- - t_{i1}^+ + t_{(i+1)1}^+ \right], \end{aligned} \quad (12)$$

where M_i and N_i are the zero point numbers in the periods of $(0 \leq t \leq \frac{T}{2})$ and $(\frac{T}{2} \leq t \leq T)$ in the i -th cycle, respectively. As an example shown in Fig. 2, we have $M_i = N_i = 4$.

It is noted that in any cycle of the modulation signal we have :

$$\sum_{j=1}^{M_i+1} t_{ij}^+ = \sum_{j=1}^{N_i+1} t_{ij}^- = \frac{T}{2}. \quad (13)$$

Consequently, we can obtain the measured phase in i -th cycle of the modulation signal by :

$$\varphi_{ix}(t) = (M_i - 1)\pi^+ - (N_i - 1)\pi^- - \alpha[t_{(i+1)1}^+ - t_{i1}^+]. \quad (14)$$

Thus, if we can detect the number of zero points in the "+" period and the "-" period of the i -th cycle and the first time interval of the i -th and $(i+1)$ -th cycles, we can determine the measured phase of this cycle. Furthermore, we can calculate the accumulated phase difference over q cycles of the modulation signal according to the following equation :

$$\varphi_x(t) = \sum_{i=1}^q (M_i - 1)\pi^+ - \sum_{i=1}^q (N_i - 1)\pi^- - \alpha(t_{f1}^+ - t_{b1}^+), \quad (15)$$

where t_{b1}^+ and t_{f1}^+ are the first time intervals of the beginning cycle and the final cycle, respectively,

Therefore, the measured displacements over q cycles of the modulation signal can be obtained by :

$$x(t) = \frac{\lambda}{4\pi} \cdot \varphi_x(t). \quad (16)$$

It should be noted that the measured phase is expressed using only the first time interval in the period during which modulation signal increases. Thus, the period during which modulation signal decreases is not used for measurement and accordingly the measurement results are not influenced by the hysteresis of PZT modulation.

In the prototype system, the modulation frequency is set to 30 Hz with a modulation depth of $\pm\lambda$. The counting rate is 625 kHz, so the minimum resolution of the interferometer is 0.074 nm/pulse. According to Eq.(3), the limitation of the displacement speed will be $< 46.8 \mu\text{m/sec}$.

2.3 Measurement system

The measurement system, controlled by a personal computer with several extension boards, is illustrated in Fig. 3.

Fig. 3 Measurement system

trated in Fig. 3. The system clock of the computer is divided by a programmable counter on the counter board, and a square wave of 30 Hz is obtained. This square wave is fed into an integrator and converted into a triangular wave. This triangular wave is amplified by a voltage booster in order to drive the PZT and introduce phase modulation. The measured interference signal is amplified and fed into a comparator that detects the zero points of the signal. The programmable counter on the counter board measures the time interval between zero points, and the measured phase is determined according to the phase detecting principles discussed above. The system clock of the computer is used to synchronize the counter with the modulation signal in order to compensate for the influence of frequency errors in the computer system clock. In order to monitor the stability of the measurement system, a digital multimeter is introduced into the system, and a temperature sensor is used to monitor temperature variation during measurement.

3. Experiment

3.1 SNR and resolution

Resolution of the interferometer is determined by the SNR (signal-to-noise ratio) during measurement. Therefore, we will first consider SNR.

There are mainly three kinds of noise source in this system. The first results from the optical feedback effect^{(8),(9)} of the laser diode. The wavelength of the laser diode depends on the resonant cavity length of the diode if no optical feedback exists. However, in most optical systems, feedback light results from the non-ideal characteristics of anti-reflection coatings, or from inappropriate optical design. This causes the number of resonant cavities in the laser diode to exceed three, and the laser diode output and wavelength show a complicated dependence on the entire optical system rather than on only the resonant cavity

of the laser diode. This effect causes fluctuations in the injection current, temperature of the resonant cavity, output power and wavelength of the laser diode.

Generally, an optical isolator effectively prevents this effect. In the present system, the optical isolator is simply composed of polarizing beam splitters and quarter-wave plates shown in Fig. 1. The isolation effect of this configuration is limited by the quality of the polarizing beam splitter and the accuracy of the wave plate. Figure 4 shows the principle of this isolator.

When p-polarized light passes through the PBS and wave plate, it is changed to a circularly polarized beam. If this beam is reflected and passes through the wave plate again, it is changed into an s-polarized beam that is reflected perpendicular to the incident direction and cannot reach the laser diode. Unfortunately, the reflectivity of the PBS to an s-polarized beam is about 98%, meaning that only about 2% of the beam passes through the PBS back to the diode. On the other hand, if the thickness of the wave plate is not sufficiently accurate in relation to the wavelength of the laser diode, the p-polarized beam will become elliptic as it passes through the wave plate, and will not be a fully s-polarized beam when it is reflected back to the PBS again. This causes a different amount of light to pass through the PBS and reach the laser diode.

The experiment shows that the amplitude of noise caused by optical feedback varies periodically with the differential displacement of a period of half a wavelength. A minimum level of noise occurs at the zero point of the signal. According to the principles of signal processing, the influence of this noise can be reduced to a minimum.

The second noise source that requires consideration is environmental noise caused by vibration of the base of the instrument and by air turbulence. Princi-

Fig. 4 Optical isolator

pally, differential interferometers have the advantage of being insensitive to external disturbance if the path lengths of the two arms are adjusted to be equal. Furthermore, this noise can be effectively reduced by setting the interferometer horizontally on a stable stage and enclosing the system within an air-tight cover.

The third noise source arises from the shot noise of the photodiode and the electrical noise of the circuit within the measurement system. This noise is very faint and can easily be controlled by careful electrical design.

In the system described above, the noise is approximately 1 mV when the amplitude of the signal is approximately 589 mV. Accordingly, the SNR is estimated to be 55.4 dB, resulting in a minimum resolution level of approximately 0.662 nm.

3.2 Calibration

Figure 5 shows the calibration setup of the interferometer. A PZT is used in order to produce the measured displacement, and a capacitance-type displacement sensor is used as the calibration standard. The linearity error of the capacitance displacement sensor is known to be approximately 100 nm⁽¹⁰⁾ which is too large for calibrating the interferometer. In order to achieve higher calibration accuracy, we exploit the advantages of a lever system with different arm lengths shown in Fig. 5. The lever is a thin glass plate coated with Au with a ratio of reflectivity of approximately 80%. A movable mirror (M) is used to select the calibration range. The beams of the interferometer are directed to the surface of the lever and the mirror, and are then reflected back to the detector. When the mirror is placed at position B, the interferometer detects displacement of position A which is the same as that of the PZT. The displacement at position C is 5 times that at A. If the mirror is placed at A, the interferometer detects the displacement of B, which is two times that of the PZT, and the displacement at C is 2.5 times that of B.

Figure 6 is a calibration result of the displacement at A, where the repeatability error is about 50 pulses (3.7 nm), corresponding to a measurement

Fig. 5 Calibration system

Fig. 6 Calibration result (3.566 μm range) Fig. 7 Calibration result (6.786 μm range)

Fig. 8 Linearity error of interferometer

range of 3.566 μm . Figure 7 is a calibration result of the displacement at B where the repeatability error is about 70 pulses (5.2 nm), corresponding to a measurement range of 6.786 μm .

Figure 8 shows the linearity error of the interferometer when it was calibrated using the capacitance displacement sensor. These results clearly contain both low- and high-frequency components that can be considered as linearity errors of the reference displacement sensor⁽⁹⁾ and the interferometer, respectively. By separating the low- and high-frequency components shown in Fig. 8, the maximum linearity error of the interferometer was estimated to be approximately 135 pulses (10 nm), and it was periodic with a period of

Fig. 9 Drift of interference signal

Fig. 10 Drift of system

approximately $\lambda/2$. Obviously, the nonlinearity of the modulation PZT 1 can be considered as the main reason for this periodic linearity error.

It must be pointed out that the measurement range of the interferometer is greater than 20 mm, as determined by the coherent length of the laser diode. In the present experiment, almost no change in the amplitude of the interference signal can be observed over a displacement of 20 mm. The interference signal is periodic, thus it is not necessary to calibrate the interferometer throughout the entire measurement range.

3.3 Stability

The following two aspects of measurement system stability were investigated.

The first is the stability of the interference signal when phase modulation is not carried out. Figure 9 illustrates the detected signal measured by a digital multimeter DVM. The drift is approximately 3 mV (2 nm) over 10 minutes. The main cause of this drift is thought to be temperature fluctuations that cause drift of the laser diode wavelength, and variations in the optical paths within the structure.

The second is the stability of the measurement system as a whole when phase modulation is introduced. Figure 10 shows stability when the drift is about 70 pulses (5.18 nm) over 5 minutes which is

larger than the drift of the interference signal shown in Fig. 9. This is caused by instability of the relationship between the displacement and the applied voltage of the PZT when it is alternatively modulated.

4. Summary

A simple method for interferometer phase readout is discussed and a differential interferometer is described. The results may be summarized as follows.

1) In a sawtooth phase modulated interferometer, the measured phase can be obtained by detecting the zero point and measuring the time interval between two adjoining zero points of the interference signal.

2) A simple time interval counting method for interferometer signal processing is proposed, and a compact differential interferometer is described according to this principle.

3) The experimental result shows that the resolution of the interferometer is about 0.662 nm over a measurement range of approximately 7 μm , and that stability is better than 5.18 nm over a 5-min period.

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