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High Precision Displacement-Measuring Interferometer Based on Phase Modulation Technique and Modulation Index Instability Elimination

***Nguyen Vu Hai Linh, Vu Thanh Tung**[*]*

Hanoi University of Science and Technology - No. 1, Dai Co Viet Str., Hai Ba Trung, Ha Noi, Viet Nam

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Abstract

A high precision displacement-measuring interferometer based on a phase modulation technique was developed. A PZT actuator was utilized to drive a mirror of a Michelson interferometer by applying a sinusoidal voltage to the PZT controller. The path difference between two arms of the interferometer was modulated leading to modulation in the phase of the interference signal with a frequency of 3 kHz. The first and second harmonics of the interference signal were detected at the modulation index of 2.63 rad, a special value when the values of the first and second orders of Bessel function are equal. The displacement was determined by the ratio of the second and third harmonic in which the effects of modulation index instability and intensity fluctuation were neglected. Moreover, the direction of the displacement that was ambiguous of the traditional interferometers was clarified in a real time. A measurement precision of 60 nm was obtained using the phase modulation interferometer.

Keywords: Phase modulation, Bessel function, Modulation index, PZT actuator, Michelson interferometer.

1. Introduction

Laser interferometers are widely utilized for displacement measurements with nanometer-order uncertainty because of their inherent accuracy and their traceability to the metric standard through the frequency of the laser source. Various signal processing techniques have been developed for displacement-measuring interferometers such as homodyne [1, 2], heterodyne [3, 4] and phase or frequency modulation techniques [5, 6].

The homodyne interferometer technique is widely utilized in small-displacement measurements with very high measurement resolution. In particular, a measurement accuracy of 10 pm [7] and a resolution of sub-picometer [8] order have been reported. The interference signal of a homodyne interferometer is time independent, and therefore it enables an ultrafast response because interference converts instantaneously phase variations into intensity variations. The upper bandwidth limit is determined by the response time of the photodetector and the bandwidth of the signal-processing electronics. Therefore, homodyne interferometers have the potential to be used for high-speed applications. However, homodyne interferometers require highly stable laser intensity during each measurement. This means that the misalignment of the optics, disturbance of the environment or shifting of a measured point will strongly affect the measurement uncertainty [9].

A heterodyne interferometer is less sensitive to temperature and pressure variations [10] but it is slower because of the delay introduced by electronic signal processing for phase acquisition. The maximum measurable speed of a heterodyne interferometer is limited by the heterodyne frequency [4]. A high cost and complicated system are also disadvantages of heterodyne interferometers.

Among these techniques, the sinusoidal phase modulated (SPM) and sinusoidal frequency modulated (SFM) techniques have many advantages. The signal of SPM or SFM interference, which is a continuous function of time, is a series of harmonics of the modulation frequency. The phase shift, which is induced by the displacement of the target mirror in the interferometer, can be accurately extracted from the interference signal using an lock-in amplifier (LIA) [5, 6]. Moreover, the measurement speed of an SPM or SFM interferometer is only limited by the modulation frequency, for which a very high frequency can be obtained by using an electro-optic modulator (EOM) or by modulating the injection of laser diodes. However, the disadvantaged feature of the SFM technique is the modulation index change when the unbalanced between two arms of the interferometer changes. Contrarily, the modulation index of the SPM

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[*] Corresponding author: Tel.: (+84) 0976.516.396
Email: tung.vuthanh@hust.edu.vn

interferometer is unchanged and the modulation index measurement is unnecessary during the operating time.

In this paper, a high precision displacement measuring interferometer was proposed. The effect of the Bessel function values was neglected by using a suitable modulation index. Consequently, compared with other techniques, SPM is the most competitive for achieving fast measurement and high precision as well as a much wider measurement range.

2. Measurement principle

Fig. 1 illustrates a sinusoidal phase modulation (SPM) Michelson interferometer. A laser beam goes through an isolator which protects the source from the reflection light. On beam splitter, the beam is divided into two paths, one goes to the reference mirror which is attached to a piezoelectric transducer (PZT). The movement of the reference mirror is modulated by sinusoidally modulating the applied voltage of PZT. Consequently, the phase of the interference signal is modulated. Another beam comes to the measurement mirror and returns the beam splitter. Two beams recombine and interfere on the beam splitter. The interference signal is detected using a photodetector.

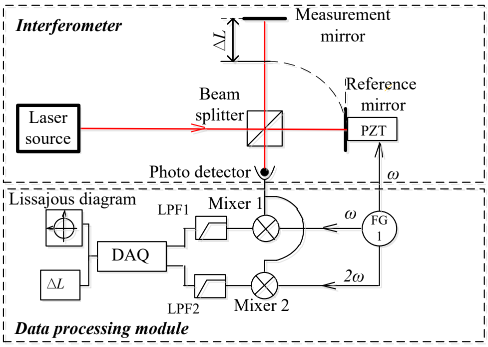


Fig. 1. Phase modulation interferometer. FG: function generation; LPF: low-pass filter; DAQ: data acquisition.

The electric field in the reference arm is modulated sinusoidally and it can be expressed as:

$$E_r(r,t) = E_{0r} \times e^{i(\omega_0 t + m \sin \omega_m t)}, \tag{1}$$

where E_0 and ω_0 represent electric amplitude and carrier frequency of the laser source, ω_m and m are modulation angular frequency and a modulation index, respectively. The beam returning from the measurement mirror is represented by:

$$E_m(r,t) = E_{0m} \times e^{i\left(\omega_0 t + \frac{4\pi n}{\lambda_0}\Delta L\right)}, \tag{2}$$

where ΔL is measured displacement and λ_0 is the wavelength of the light source.

Since I ∝ E^2, the interfering signal of two beams detected by the photodetector is written as [11]

$$\begin{aligned} I &= \langle |E_r(r,t) + E_m(r,t)| \rangle^2 \\ &= \langle E_r(r,t) + E_m(r,t) \rangle \times \langle E_r{}^*(r,t) + E_m{}^*(r,t) \rangle \\ &= I_0 \left[1 + \cos\left(\frac{4\pi n}{\lambda_0} \Delta L + m \sin \omega_m t \right) \right], \end{aligned} \tag{3}$$

where $I_0 = 2|E_{0r}|^2 = 2|E_{0m}|^2$ when the beam splitter divides the beam from the laser source into two beams propagating in the interferometer with the same intensity. From Eq. (3) m is constant and n can be determined then ΔL, the displacement of the measurement object, can be determined. However, to increase the measurement accuracy and determine the moving direction of the object, Lissajous diagram method is applied to this system. Using the Bessel function to expand Eq. (3) and it is given

$$I = I_0 \Big\{ 1 + \Big\{ \cos\left(\frac{4\pi n}{\lambda}\Delta L\right) \times [J_0(m) + 2\sum_{k=1}^{\infty} J_{2k}(m) \times \cos(2k\omega_m t)] - \sin\left(\frac{4\pi n}{\lambda}\Delta L\right) \times 2\sum_{k=1}^{\infty} J_{2k-1}(m) \times \sin[(2k-1) \times \omega_m t] \Big\} \Big\}. \tag{5}$$

LIAs are used to obtain 1st and 2nd harmonic terms from Eq.(5)

$$I_1 = -I_0 J_1(m) \sin\left(\frac{4\pi n}{\lambda}\Delta L\right), \tag{6}$$

$$I_2 = I_0 J_2(m) \cos\left(\frac{4\pi n}{\lambda}\Delta L\right). \tag{7}$$

Equation (6) and (7) show that the 1st and 2nd harmonics of the interference signal are two quadrature phase signals. A Lissajous diagram obtained from the two signal can be used to clarify the direction of movement and to measure the phase shifting caused by displacement concurrently. The displacement ΔL is given by

$$\Delta L = \frac{\lambda}{4\pi n} \times \tan^{-1} \frac{I_1 \times J_2(m)}{I_2 \times J_1(m)}. \tag{8}$$

In Eq. (8), ΔL depends on the intensity of 1st and 2nd harmonics, and Bessel functions $J_1(m)$ and $J_2(m)$. Normally, the intensity fluctuation of laser source limits the measurement accuracy of homodyne interferometer. Using the ratio of 1st and 2nd harmonics (I_1/I_2) the effect of intensity fluctuation is neglected.

However, the Bessel functions, $J_1(m)$ and $J_2(m)$, which depend on the value of m can reduce the signal to noise ratio of the 1st and 2nd harmonics. In this research, a method to neglect the effect of the modulation index is proposed.

Fig. 2 shows the Bessel functions $J_1(m), J_2(m), J_3(m)$, and $J_4(m)$. There are some critical points where two consecutive Bessel functions are equal. $J_1(m) = J_2(m)$ when m=2,62 rad and $J_2(m) = J_3(m)$ when m=3,77 rad. In this research, the modulation index m=2,67 rad is used and Eq. (8) becomes

$$\Delta L = \frac{\lambda}{4\pi n} \times \tan^{-1}\left(\frac{I_1}{I_2}\right). \qquad (9)$$

Equation (9) shows that the displacement ΔL is independent on the modulation index m. The Lissajous diagram is a circular and the normalized method for a nonstandard Lissajous diagram is unnecessary [5]. Therefore, the measurement uncertainties of modulation index measurement and approximation Bessel function value are removed from uncertainty sources of the proposed interferometer.

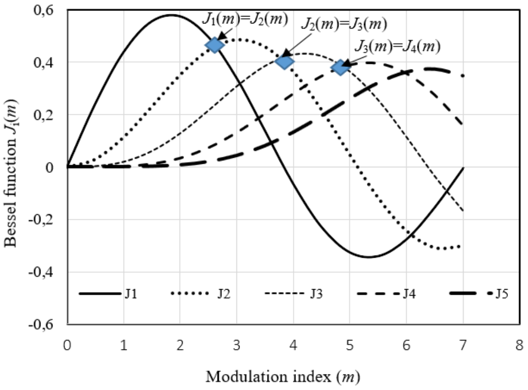


Fig. 2. Bessel function

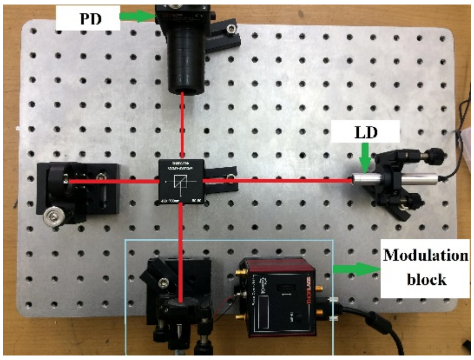
3. Experiment and discussion

The experimental system and the data processing module are shown in Fig. 3. A collimated laser diode (CPS532-C2, Thorlabs Inc.) was used as a light source for the interferometer. The movement of the reference mirror was sinusoidally modulated by a PZT actuator (PA4FKW, Thorlabs Inc.). The PZT actuator was driven by a voltage controller (PK4DMP1, Thorlabs Inc.) with the smallest increment of nanometer order. The interference signal was detected using a photodetector (PDA36A-EC, Thorlabs Inc.), Fig. 3a. A signal processing module was built by combining analog lock-in amplifiers and high-resolution data acquisition (ADS127L01EVM, Texas Inst.), Fig. 3b. The experimental condition is shown in Table 1.

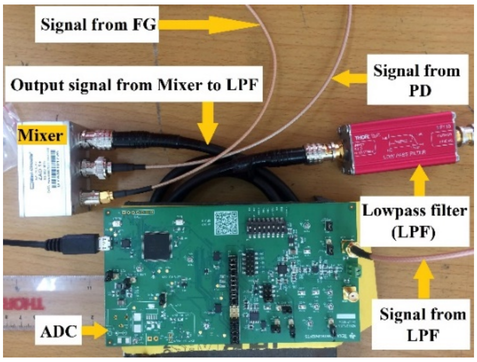
Table 1. Experimental condition

Wavelength of laser source	532 nm
Maximum power	1 mW
Modulation frequency of PZT	500 Hz
Frequency excursion of PZT	1,31 kHz
Modulation index	2,62 rad
Resonant frequency of PZT	270 kHz
Spectral response range of detector	350-1000 nm
Frequency bandwidth of detector	DC-10 Mhz
Resolution of ADC	24 Bit
Sample rates of ADC	512 kSPS

The proposed interferometer was used to measure a displacement which was generated by another PZT stage. The measuring result was compared with the reference displacement of the PZT supplied from the manufacturer (PK4DMP1, Thorlabs Inc.). The reference displacement can be determined from the applied voltage of PZT. The triangular voltage with an amplitude of 8 V and frequency of 1 Hz was applied to PZT and hence a displacement of 0,9 μm with the same frequency was induced. The interference signal and 1st and 2nd harmonics were shown in Fig. 4. The Lissajous diagram of 1st and 2nd harmonic was used to track the movement direction and to calculate the phase change due to the displacement of the object, Fig. 4c. The measured displacement obtained by the interferometer and reference displacement were depicted in Fig. 5.



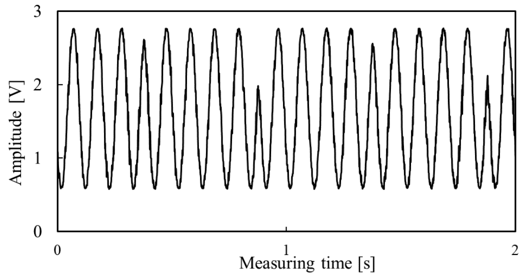
a. Experimental system



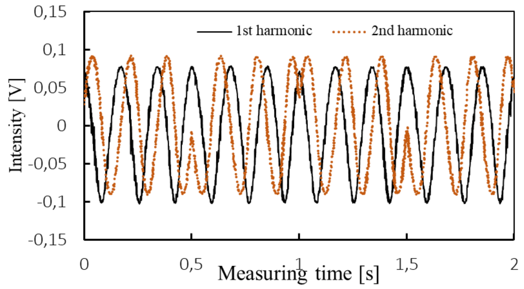
b. Signal processing module

Fig. 3. Phase modulation interferometer system

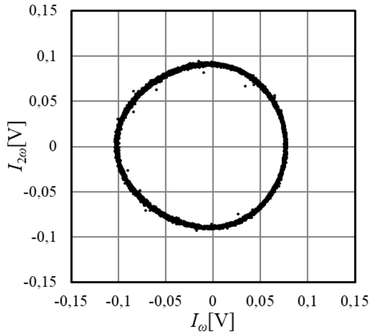
The experimental system was performed in an open space and without an anti-vibration table. However, 1st and 2nd harmonics were detected purely and then the displacement can be determined. It means that the phase modulation interferometer can work well even if there was the existence of the environment effect. In order to clarify the measurement accuracy, the difference of the displacement measurement results using the interferometer and the reference is shown in Fig. 6. The difference was about 60 nm. There were some uncertainty sources can be listed such as the refractive index fluctuation, vibration, and imperfectly optical polarization.



a. Interference signal



b. 1st and 2nd harmonics



c. Lissajous diagram

Fig. 4. Demodulated signals of the phase modulation interferometer

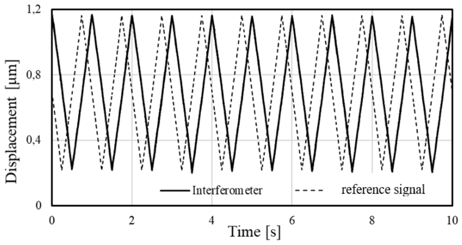


Fig. 5. Displacement measurement results

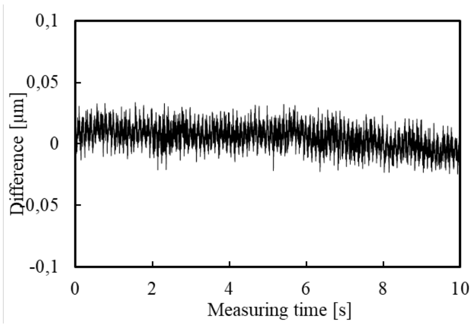


Fig. 6. The difference between the measuring result using the interferometer and the reference

4. Conclusion

A phase modulation displacement measuring interferometer was successfully developed. The measuring system is compact, low-cost, and stable. The measurement accuracy was less than 100 nm. It can be used for industrial applications. For future work, the proposed interferometer should be compared with heterodyne interferometer to clarify clearly the measurement accuracy and measurement resolution.

Acknowledgments

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