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Real-time micro-vibration measurement in sinusoidal phase-modulating interferometry

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Abstract

As there exist some problems with the previous laser diode (LD) real-time microvibration measurement interferometers, such as low accuracy, correction before every use, etc., in this paper, we propose a new technique to realize the real-time microvibration measurement by using the LD sinusoidal phase-modulating interferometer, analyze the measurement theory and error, and simulate the measurement accuracy. This interferometer utilizes a circuit to process the interference signal in order to obtain the vibration frequency and amplitude of the detective signal, and a computer is not necessary in it. The influence of the varying light intensity and light path difference on the measurement result can be eliminated. This technique is real-time, convenient, fast, and can enhance the measurement accuracy too. Experiments show that the repeatable measurement accuracy is less than 3.37 nm, and this interferometer can be applied to real-time microvibration measurement of the MEMS.

Keywords: Real-time measurement; Optic testing; Interferometer; Laser diode; Vibration

1. Introduction

Recently, with the rapid progress in micromechanics, it has become very important to measure accurately the microvibration and microdisplacement of the MEMS. Optic interferometry has been widely used because of its properties of non-contact, high accuracy, good stability, simple structure, etc. [1–3]. A few interferometers adopt a laser diode (LD) because the LD high has many strong points: small size, lightweight, and high efficiency [4,5]. Moreover, the wavelength of the LD can be controlled by its injection current. Using this property, it is possible to constitute a heterodyne interferometer with mechanical elements such as a piezoelectric transducer (PZT). In a sinusoidal phase-modulating (SPM) interferometer [6], the interference signal can be modulated sinusoidally by a modulated injection current of LD. Compared with the traditional heterodyne interferometer, the LD SPM interferometer has many strong points: compact structure, small size, simply phase modulation, and high accuracy. Therefore, this interferometer has progressed greatly [7–10].

Previously, we had proposed a LD interferometer for the real-time vibration measurement [11]. The interferometer directly imposed ac current signal on LD to realize the sinusoidal phase modulation to an interference signal. Its accuracy has relations with the light path

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difference, the magnification times, the modulation depth, and Bessel function. It also needs correction before each use. Therefore, there exist some faults in this interferometer, such as low accuracy, inconvenience, and difficult calibration, and the varying light intensity also decreased the accuracy. In order to overcome these faults, in this paper, we propose a new technique to realize the real-time microvibration measurement based on a LD SPM interferometer. After the interference signal processed by a circuit, the detective signal well reflected the microvibration of the object. The frequency and amplitude of the vibration can be obtained by the observed detective signal shown on the oscilloscope, and the measurement accuracy has been simulated. The theoretical and experimental errors have been analyzed too.

2. Principle

The setup of a SPM LD interferometer for real-time vibration measurement is shown in Fig. 1. A Twyman–-Green interferometer is used as the optical system. After collimation by lens L1 and splitting by beam splitter BS, a LD laser is split into two beams, which serves as the object and reference beams. The two beams are reflected by the object mirror (Mirror) and reference mirror (M), respectively, and interfered to form the interference signal $S(t)$, which is detected by a photo-detector (PD). The interference signal $S(t)$ can be converted into detective signal $P(t)$ by a signal-processing circuit. The optical path difference between the two arms of the interferometer is $2D_0$.

The injection current of a LD consists of DC bias current I_0, and modulation current $I_m(t)$. The central wavelength of the LD is λ_0, which is determined by the DC bias current I_0. The modulation voltage V_m and current I_m are given by

$$V_m = A\cos(\omega_0 t + \theta), \tag{1}$$

$$I_m = a\cos(\omega_0 t + \theta), \tag{2}$$

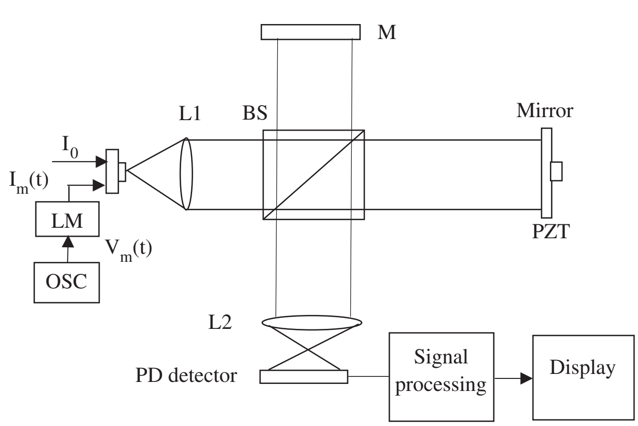

Fig. 1. Experimental setup of a SPM laser diode (LD) interferometer for real-time vibration measurement.

where $a = K_{LM}A$, K_{LM} is the switching coefficient of the LD modulator, and A the amplitude of the modulation voltage. The wavelength changes with the control of the modulation current $I_m(t)$ according to the relationship $\beta I_m(t)$, where β is the modulation efficiency of the LD. When neglecting the noise, the interference signal $S(t)$ can be given by [12]

$$S(t) = S_1 + S_0\cos[z\cos\omega_0 t + \alpha_0 + \alpha_r(t)], \tag{3}$$

where S_1 is the dc component of the interference signal, S_0 the amplitude of ac component, $z = 4\pi a\beta D_0/\lambda_0^2$, and

$$\alpha_r(t) = (4\pi/\lambda_0)r(t). \tag{4}$$

In this interferometer, the displacement $r(t)$ of the measured vibrating object can be measured by determining the phase change α_r at a desired phase α_0. α_0 is given by

$$\alpha_0 = \frac{4\pi}{\lambda_0}D_0. \tag{5}$$

In this paper, the phase α_r can be obtained by signal processing, and the circuit is shown in Fig. 2. The gain of the amplifier is K_1 and K_2, corresponding to amplifier 1 and 2, respectively. The coefficient of the calculation circuit is K_c. The gain and cut-off frequency of the low-pass filter are K_L and $\omega_0/10$, respectively. This circuit has the function of phase demodulation, and can select the phase of the interference signal from the output detective signal $P(x, y, t)$ by the calculation circuit and low-pass filter.

Expanding Eq. (2) and neglecting the dc component, we have [11]

$$\begin{aligned} S(t) = S_0\{&\cos\alpha(x,y,t)[J_0(z) - 2J_2(z)\cos 2\omega_0 t + \cdots] \\ &- \sin\alpha(x,y,t)[2J_1(z)\cos\omega_0 t - 2J_3(z)\cos\omega_0 t + \cdots]\}, \end{aligned} \tag{6}$$

where $\alpha(t) = \alpha_0 + \alpha_r(t)$, $J_n(z)$ is the nth order Bessel function. After amplification, calculation, and low-pass filteration, the interference signal $S(t)$ can be converted into the vibration signal, and the vibration signal can be given by

$$p(t) = k_s \sin\alpha(t), \tag{7}$$

where $k_s = K_1K_2K_cK_LS_0AJ_1(z)$. After normalization, Eq. (7) can be expressed as

$$p(t) = \sin\alpha(t). \tag{8}$$

When near the position $\alpha(t) = 2n\pi$ ($n = 0,1,2,\ldots$), we can obtain

$$p(t) \approx \alpha(t) = \alpha_0 + \alpha_r(t). \tag{9}$$

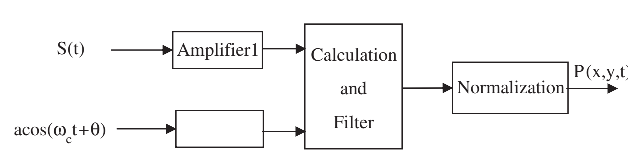

Fig. 2. Circuit of signal processing.