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A surface profile reconstruction system using sinusoidal phase-modulating interferometry and fiber-optic fringe projection

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ABSTRACT

A fiber-optic sinusoidal phase modulating (SPM) interferometer for surface profile reconstruction is presented. Sinusoidal phase modulation is created by modulating the drive voltage of the piezoelectric transducer. The surface profile is constructed basing on fringe projection. Fringe patterns are vulnerable to external disturbances such as temperature fluctuation and mechanical vibration, which cause phase drift and decrease measuring accuracy. We build a closed-loop feedback phase compensation system, the bias value of external disturbances superimposed on fringe patterns can be reduced to about 50 mrad, and the phase stability for interference fringes is less than 5.76 mrad. By measuring the surface profile of a paper plate for two times, the repeatability is estimated to be about 11 nm, and is equivalent to be about $\lambda/69$. For a plane with 100×100 points, a single measurement takes less than 140 ms, and the feasibility for real-time profile measurement with high accuracy has been verified.

1. Introduction

With the excellence in high speed and high accuracy, phase profilometry has been exhaustively studied and widely applied for 3-D sensing, machine vision, robot simulation, industrial monitoring, dressmaking, biomedicine, and other fields [1]. A number of phase techniques have been presented and in-depth studied, such as moiré technique (MT) [2,3], Fourier transformation profilometry (FTP) [4,5], phase measuring profilometry (PMP) [6,7], modulation measurement profilometry (MMP) [8]. Among the phase techniques, SPM interferometry has advantages of a simple configuration, high precision, strong anti-jamming ability. There are two typical modulations: PZT modulation [9,10], and current modulation [11,12]. In SPM laser diode (LD) interferometers, the wavelength of LD is sinusoidally modulated by varying the injection current (IC). However, the light intensity of LD is also modulated by the variation of IC, which results in measurement errors and decreases the signal-to-noise ratio of the interference signal.

In this paper, we describe a novel all-fiber SPM interferometer, which is insensitive to external disturbances. This method takes advantage of Mach–Zehnder interferometer structure and Young's double pinhole principle to achieve interference fringe projection [13]. Instead of varying IC, the SPM is created by driving PZT with a sinusoidal wave. Then the measuring accuracy is not affected by an intensity modulation that usually appears in current modulation. In Section 2, the system configuration and geometry model are presented. In Section 3, the sinusoidal phase integrating-bucket method [10] has been applied to extract phase, and phase compensation method has been described in detail. In Section 4, experimental results for the phase stabilization of interference fringe pattern are shown. Besides, we achieve the reconstruction of the surface profile of a paper plate with 100×100 pixels, and figure out the root mean square error (RMSE).

2. Measuring principle

2.1. System configuration

The system configuration for surface profile measurement is shown in Fig. 1. A laser diode with a wavelength of 760 nm is chosen to be the light source. The light emitted from the laser is collimated by a lens and is projected into a 2×2 optical coupler, and then split into a reference beam and a object beam. The optical fiber arms are lightly twined on the cylinder-shaped PZT to realize SPM, and its fiber exit faces are clamped together with a core distance l. Satisfying far-field and paraxial condition, we can achieve a high-density interference fringe projection of cosine distribution on the object. The optical fiber exposed in the air is sensitive to external disturbances such as temperature fluctuation, mechanical vibration. Then the amplitude and phase of interference fringes will drift with a low frequency. The Fresnel reflections

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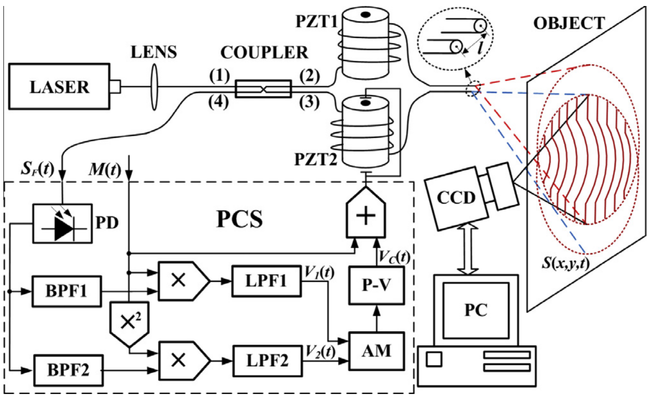

Fig. 1. SPM interferometer and PCS.

on the two fibers' exit faces generate the Michelson interference signal $S_F(t)$, which is detected by the photo detector (PD). The phase compensation system (PCS) described in detail in Section 3.2 aims to generate a compensation voltage $V_C(t)$, which changes the length of optical fiber twined on PZT2. Then external disturbances can be eliminated and the phase of interference fringes will be stabilized at a certain value. The CCD captures the deformed fringe pattern modulated by the object, and surface profile will be reconstructed using integrating-bucket method.

2.2. Geometry model

The geometry model is depicted in Fig. 2. Geometry model's origin is located at the optical center of the camera's lens, and y-axis is along camera's optical axis. x-axis and z-axis are paralleled to camera's horizontal and vertical direction, respectively. The fiber projector is located at $O'(L, 0, 0)$, away from the origin O with a distance L. The projected fringes on object plane are paralleled to z-axis. Assuming $S(x, y, z)$ is one point on the object plane with the projected angle β, and $S_i(m, n)$ is the mapped point on the camera's image plane, where m is the horizontal coordinate and n is the vertical coordinate. Define d as the distance between lens center and image plane. In the triangle $\Delta O'AS'$, the tangent value of β can be calculated. Considering the mapping relation between S and S_i, we obtain

$$\begin{cases} x\sin\beta + y\cos\beta = L\sin\beta \\ \frac{x}{-m} = \frac{y}{d} = \frac{z}{-n} \end{cases} \tag{1}$$

Solving Eq. (1) for coordinate (x, y, z), we obtain

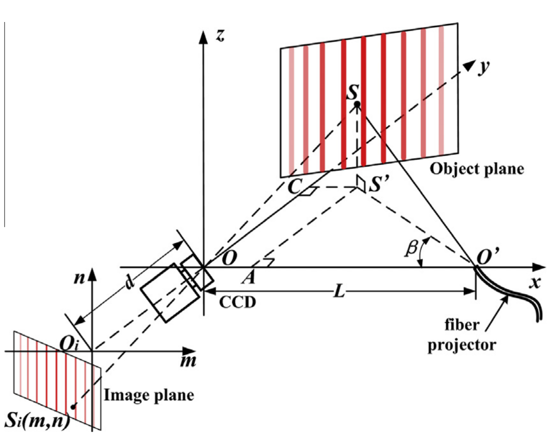

Fig. 2. Geometry model.

$$\begin{cases} x = \frac{mL}{m-d\cot\beta} \\ y = \frac{nL}{m-d\cot\beta} \\ z = -\frac{dL}{m-d\cot\beta} \end{cases} \tag{2}$$

The projected angle and the phase of interference fringes are denoted by β and $\alpha(x, y)$, respectively. They are combined by the following equation.

$$\alpha(x,y) = \frac{2\pi}{\lambda} l\tan(\beta - \beta_0) + \alpha_0 \tag{3}$$

where λ is the wavelength of laser light, β_0 is the projected angle between zero-th order fringe and x-axis, α_0 is the initial phase. Satisfying the far-field and paraxial conditions, the projected fringes are paralleled to z-axis, and $\tan(\beta - \beta_0)$ is equivalent to $\beta - \beta_0$.

Then β can be obtained and simplified as

$$\beta = \frac{\lambda}{2\pi l}[\alpha(x,y) - \alpha_0] + \beta_0 \tag{4}$$

When we get the phase $\alpha(x, y)$, β can be solved from Eq. (4). Taking it into Eq. (2), surface profile information (x, y, z) can be achieved. In the next Section 3, the methods to extract $\alpha(x, y)$ and eliminate α_0 are described.

3. Phase compensation system

3.1. Sinusoidal phase integrating-bucket modulation

In Fig. 1, the SPM has been achieved by driving PZT2, and the modulated signal is presented by

$$M(t) = a\cos(\omega t + \theta) \tag{5}$$

where a is the amplitude of modulated signal and ω is the modulation frequency, θ is the initial phase of modulated signal. The wavelength of laser changes by $\Delta\lambda_T$ with temperature fluctuation, and the optical path difference changes by Δl_V with mechanical vibration. These $\Delta\lambda_T$ and Δl_V cause phase shift in $s(x, y, t)$. The phase shift will be compensated by driving PZT2 to generate Δl_C. Considering all the three components $\Delta\lambda_T$, Δl_V and Δl_C, the time-varying signal is given by

$$s(x,y,t) = A + B\cos[z\cos(\omega t + \theta) + \alpha(x,y) + \delta(t)] \tag{6}$$

where A is the background intensity and B is the contrast between light and dark fringes. z is the phase modulation depth. The additional phase$\delta(t)$ is reduced to zero in Section 3.2, and given by

$$\delta(t) = \frac{2\pi}{\lambda}\left(\Delta l_V + \Delta l_C - \frac{l}{\lambda}\Delta\lambda_T\right) \tag{7}$$

$s(x, y, t)$ is integrated with a CCD image sensor in parallel over the four quarters of the modulation period $T(= 2\pi/\omega)$. These four separate images are given by

$$E_p = \frac{4}{T}\int_{\frac{(p-1)T}{4}}^{\frac{pT}{4}} s(x,y,t)\,dt \quad (p = 1-4) \tag{8}$$

The phase $\alpha(x, y)$ is obtained with the simplified formula under the optimum SPM condition [10] that $z = 2.45$ and $\theta = 0.98$ rad.

$$\alpha(x,y) = \arctan\left(\frac{E_1 - E_2 - E_3 + E_4}{E_1 - E_2 + E_3 - E_4}\right) \tag{9}$$

3.2. Phase compensation method

The Michelson interference signal detected by PD is given by

$$S_F(t) = C + D\cos[z\cos(\omega t + \theta) + 2\alpha_0 + \varepsilon(t)] \tag{10}$$