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A disturbance-free surface profile measuring system with sinusoidal phase integrating-bucket modulation

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ABSTRACT

A surface profile measuring system based on fringe projection and sinusoidal phase integrating-bucket modulation has been thoroughly studied and described in detail. Fringe projection can be achieved using Mach–Zehnder interferometer structure and Young's double pinhole principle. Sinusoidal phase modulation can be achieved by driving the piezoelectric transducer with a cosine voltage signal. To achieve a good insensitivity to disturbances, we build up a feedback subsystem for phase compensation, and a disturbance-free performance can be achieved with a phase stability of 5.25 mrad for fringes, which is conducive to the high-resolution surface profile measurement. By measuring the surface profile of an aluminum plate for twice over an interval of 10 min, the repeatability is about 13 nm. Experiment results confirm that the proposed profile measuring system is applicable for practical application with high accuracy.

1. Introduction

Optical non-contact three-dimensional (3-D) surface profile measurement technique is concerned with extracting the geometry information from the phase distribution of fringe patterns projected on the object surface [1]. With the excellence in non-contact and high precision, phase profilometry with fringe projection has been exhaustively studied for applications in 3-D sensing, machine vision, industrial inspection, quality control, biomedicine, and other fields [2]. Several phase profilometries based on fringe projection has been in-depth studied, including modulation measurement profilometry (MMP) [3], Fourier transformation profilometry (FTP) [4,5], moiré technique (MT) [6], phase measuring profilometry (PMP) [7]. Among phase measuring techniques, sinusoidal phase modulation (SPM) [8,9] is the most appropriate, because it has unique features such as time-continuous operation, simple configuration, high accuracy, and anti-jamming ability. Unlike modulating the wavelength of laser diode (LD) by varying the injection current (IC), which also results in light intensity modulation and decreases measuring accuracy [10], SPM can be achieved by driving the PZT with a sinusoidal voltage signal.

In order to measure the surface profile, a novel all-fiber SPM interferometer insensitive to external disturbances has been described in this paper. Fringe projection can be achieved by combining Mach–Zehnder interferometer structure and Young's double pinhole principle [11]. In Section 2, the system configuration and fringe projection model are presented, and we obtain the relationship between surface profile and fringe phase distribution. In Section 3, the sinusoidal phase integrating-bucket method [8] has been simply presented for completeness. Besides, we build up a feedback subsystem to eliminate external disturbances in fringes. Unlike the method described in [10], in which the phase generated carrier (PGC) [12] method is applied to extract the phase and calculated by arctangent calculation using coordinated rotation digital

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computer (CORDIC) [14], we extract the phase using peak detection method and count it out by arcsine calculation. In Section 5, we check the performance of the eliminating external disturbances in fringes, and confirm the applicability of the proposed method by measuring the surface profile of an aluminum plate with a size of 100 × 100 pixels.

2. System configuration and fringe projection model

2.1. System configuration

The system configuration for surface profile measurement is depicted in Fig. 1. The light source is a DFB laser diode (DFB-LD) with a central wavelength of 760 nm. The output beam of DFB-LD is collimated by a lens, and projected onto the entrance face of fiber arm (a). The beam is split into arm (b) and (c) with equal intensity in a 2 × 2 optical coupler (OC). Arm (b) and (c) are lightly twined on the cylinder-shaped PZT, which is drove by a sinusoidal voltage to realize SPM. A high-density interference fringe projection of cosine distribution can be achieved on the object surface. The CMOS camera captures the deformed fringe pattern modulated by object surface, and we can reconstruct the surface profile using integrating-bucket method [8]. However, its a natural property that fiber arms exposed in the air are vulnerable to external disturbances such as temperature fluctuation, mechanical vibration and air current, which could cause low-frequency phase shift and deteriorate measuring accuracy. So a closed-loop phase compensation system (PCS) described in detail in Section 3 is necessary. Two Fresnel reflections on the exit faces of arm (b) and (c) travel back through optical coupler, and interfere in arm (d). The Michelson interference signal $S(t)$ transmitted out of arm (d) is projected onto a photo detector (PD), and finally fed into PCS to generate a compensation voltage signal, which changes the length of optical fiber twined on PZT2 and eliminates the phase shift in deformed fringes.

2.2. Fringe projection model

The fringe projection model is shown in Fig. 2. The object plane locates on the plane xOz, and the model's

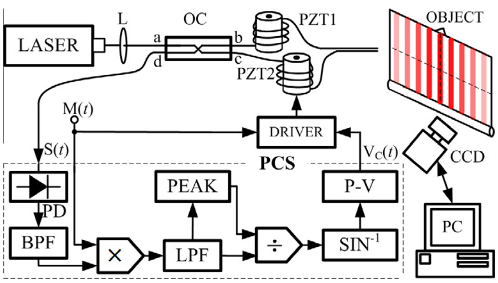

Fig. 1. Configuration of surface profile measuring system. L, coupled lens; OC, optical coupler; PZT, piezoelectric transducer; PD, photo detector; BPF, band-pass filter; LPF, low-pass filter; PEAK, peak detection circuit, P–V, phase to voltage module; SIN-1, arcsine calculation; PCS, phase compensation system; DRIVER, piezoelectric transducer driver.

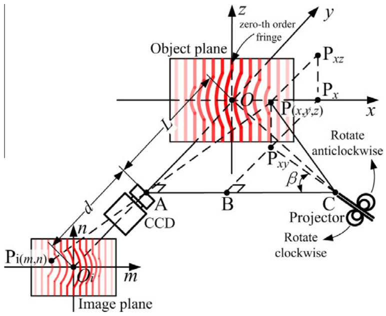

Fig. 2. Fringe projection model.

origin O locates at the center of object plane. The optical center of CMOS camera's lens locates at point A, away from the origin O with a distance L, and CMOS camera's optical axis shoots along y-axis. x-axis and z-axis are paralleled to CMOS camera's horizontal and vertical direction, respectively. The fiber projector located at point C, is fixed on a precision rotary stage with a radius R, which makes sure that $\overline{AC}$ is paralleled to x-axis. Assuming $P(x, y, z)$ locates at the object plane with a projection angle β, and $P_i(m, n)$ is the mapped point located at the image plane. Define d as the distance between lens center and image plane. In the triangle $\Delta P_{xy}BC$, the tangent value of β can be calculated and denoted by

$$\tan\beta = \frac{\overline{P_{xy}B}}{\overline{BC}} = \frac{L+z}{\sqrt{R^2-L^2}-x} \tag{1}$$

Considering the mapping relation between P and P_i, we obtain

$$\frac{x}{-m} = \frac{y}{-n} = \frac{L+z}{d} \tag{2}$$

Solving Eqs. (1) and (2) for the coordinate (x, y, z), which represents profile information, we obtain

$$\begin{cases} x = -\frac{m\sqrt{R^2-L^2}}{d\ \cot\ \beta - m} \\ y = -\frac{n\sqrt{R^2-L^2}}{d\ \cot\ \beta - n} \\ z = -\frac{d\sqrt{R^2-L^2}}{d\ \cot\ \beta - m} - L \end{cases} \tag{3}$$

Besides, the fringe phase distribution of projection fringes denoted by $\alpha(x, y)$ is given by

$$\alpha(x,y) = \frac{2\pi}{\lambda} l_0\ \tan(\beta - \beta_0) + \alpha_0 \tag{4}$$

where λ is the wavelength of DFB-LD, α_0 is the initial phase. β_0 is the projection angle of zero-th order fringe, and denoted by $\beta_0 = \arcsin(L/R)$ when the zero-th order fringe shoots along z-axis. The fiber projector's ends are clamped together with a minus distance l_0, which satisfies the far-field and paraxial condition. So $\tan(\beta - \beta_0)$ is equivalent to $\beta - \beta_0$. The projection angle β can be solved with a simplified formula.

$$\beta = \frac{\lambda}{2\pi l_0}[\alpha(x,y) - \alpha_0] + \beta_0 \tag{5}$$