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Phase stepping methods based on PTDC for Fiber-Optic Projected-Fringe Digital Interferometry

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ABSTRACT

Active homodyne control can be used to stabilize; $\pi/2$-rad phase steps in a Fiber-Optic Projected-Fringe Digital Interferometry. Two beams emitted from a fiber-optic coupler are combined to form an interference fringe pattern on a diffusely reflecting object. Fresnel reflections from the distal fiber ends undergo a double pass in the fibers and interference at the fourth port of the coupler which formed a Michelson interferometer. We suggested a method of PTDC (DC phase tracking) to maintain the interference intensity at quadrature by feedback control. Stepping between quadrature positions force a $\pi/2$-rad phase step. A method based on the ratio of harmonic of the interference signal is proposed to estimate phase step accuracy .A root-mean-square phase stability of 2 mrad and phase step accuracy of 13.8 mrad were measured with PTDC for the Fiber-Optic Projected-Fringe Digital Interferometry. It worked well in 2 h without resetting the integrator.

1. Introduction

Phase-shifting interferometry (PSI) is an important technique in the field of interferometry, providing a tool to measure the optical phase to unprecedented accuracy full-field. Phase-shifting methods may be broadly grouped as temporal and spatial techniques. For temporal algorithms, a discrete or continuous phase shift is introduced. In the phase-stepping technique, the phase is stepped between each intensity measurement, whereas in the continuous phase modulating technique the phase is usually shifted linearly in a saw-tooth like manner or a sinusoidal like manner. Fiber-Optic Projected-Fringe Digital Interferometry has many advantages such as its small size, remote location of the laser source and strong anti-interference ability to electromagnetic radiation and has been used in many areas [1–4]. Automated analysis of interferograms from a Fiber-Optic Projected-Fringe Digital Interferometer by means of phase stepping need the relative phase of the interfering beams to be shifted between the acquisitions of at least three interferograms. In practice the most important type of reasons that may affect the accuracy of the phase measurement technique are errors due to incorrect phase steps between interferograms. Although many algorithms were developed for dealing with arbitrary phase steps [5–7], they need a lot of time and require the interferograms stable. There are algorithms that need the phase steps to be equal regardless of their correct values; it was proposed by Srinivasan years ago [8]. Most of the algorithms need a precise value of the phase step and consequently the phase modulator must be carefully calibrated to minimize systematic errors. The random phase errors are particularly large in fiber interference systems due to temperature (approximately 106(rad/K)/m). Many stabilized phase-stepping approaches have been developed for this Fiber-Optic Projected-Fringe Digital Interferometry.

Quadrant silicon photodiode was used to detect fringe's phase and tuned the laser wavelength to lock phase by Kudryashov and Seliverstov [9], it reached 0.005 λ in rms and 0.0015 λ in p–v of reconstruction error. A phase step by sawtooth-current modulation of a laser diode was locked to a phase difference preset by polarization optics through an electrical feedback system; the optical path difference can be precisely measured [10]. Mercer achieved a root-mean-square phase stability of 7.3 mrad in a 40-Hz band-width in a fiber-optic Michelson interferometer by means of PTAC and the phase carrier applied (0.21-rad amplitude) degraded the fringe visibility by approximately 1% [11]. However, phase-stepping error was not measured. Corke and Josten used a feedback system with a piezo regulator which was used for compensation of the phase fluctuations through PTDC [12,13] and kept a given value of the relative phase stable to within 70 mrad [13]. A root-mean-square phase stability of 0.61 mrad in a 50-Hz band-width and phase step accuracy of 1.17 mrad were measured and suggested a mean to estimate phase-stepping error by Moore using PTDC [14] while the system was complicated.

In this paper, we used PTDC (DC phase tracking) to compensate the phase fluctuations and made some improvements for

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electrical feedback system. A method based on the ratio of harmonic of the interference signal was proposed to real-time estimate phase step error.

2. Active homodyne phase stabilization with PTDC

As Fig. 1 shows, light from a He–Ne laser was coupled into one end of the fiber-optic coupler, polished the output fibers and makes the path difference between the two arms as short as possible. The reflection from the fiber ends constituted a Michelson interferometer. PD detected the interference signal and then interference signal was transmitted to the servo control system.

As shown in Fig. 2, servo control system was constructed by pre-chopper-stabilized preamplifier, a low-pass filter with a bandwidth of 500 Hz, comparator (the voltage U_0 is described followed), high-pass filter and proportional–integral–derivative (PID) controller. The PID controller's signal was exported into the high-voltage Piezoelectric Transducer (PZT) driver.

As shown in Fig. 3, Photodiode (PD) received signal induced by temperature change is almost 0.1 Hz/K. The cutoff frequency of high-pass filter is 0.01 Hz. The high-pass filter introduced here have three advantages: to eliminate the phase fluctuation caused by temperature change, to compensate the change of the DC operating point U_0, to overcome the low frequency electronic noise.

PD received signal is

$$I=k_D[I_0+V\cos(2(\phi_o-\phi_r+s(t))+\phi_e)] \tag{1}$$

I_0 is the light intensity of background. $\phi_o-\phi_r$ is the output fiber phase difference, $s(t)$ is the phase induced by PZT modulated, V ($V\approx1$) is the fringe contrast, phase fluctuation for the phase error is ϕ_e, the phase-voltage coefficient for PD is k_D When the interference intensity is controlled at quadrate

$$2(\phi_d+s(t))=\frac{\pi}{2}+k\pi(k=0,\ \pm1,\ \pm2\ldots) \tag{2}$$

$$I=k_D\left(I_0+\cos\left(\frac{\pi}{2}+k\pi+\phi_e\right)\right)=k_D(I_0\pm\sin\phi_e)\approx k_DI_0 \pm k_D\phi_e(k=0,\ \pm1,\ \pm2\ldots) \tag{3}$$

While $\phi_o-\phi_r=\phi_d$, $U_0=k_DI_0$, the DC operating point is U_0.

Fig. 4 represents the phase feedback control system model. Φ_i is the target phase between two output arms, the actual optical

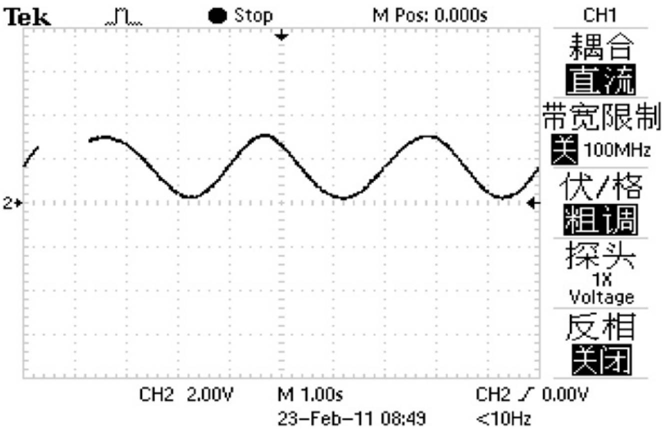

Fig. 3. PD (Photodiode) received signal induced by temperature change.

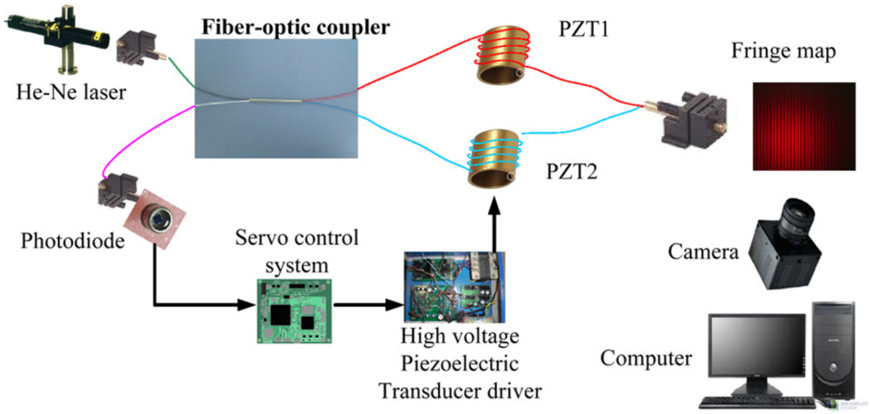

Fig. 1. Fiber-Optic Projected-Fringe Digital Interferometry with PTDC.

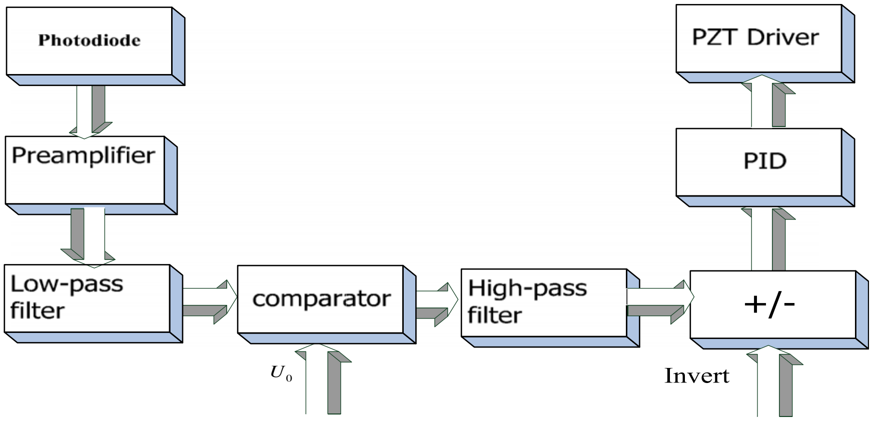

Fig. 2. Servo control system diagram.