Optics and Lasers in Engineering 57 (2014) 93–100

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

Signal processing method of phase correction for laser heterodyne interferometry

Tao Yang, Liping Yan, Benyong Chen*, Yanna Liu, Qiuhong Tian

Nanometer Measurement Laboratory, Zhejiang Sci-Tech University, Hangzhou 310018, China

ARTICLE INFO

Article history:
Received 20 November 2013
Received in revised form
16 January 2014
Accepted 18 January 2014
Available online 7 February 2014

Keywords:
Heterodyne interferometry
Phase measurement
Movement direction identification
Phase correction
Displacement measurement

ABSTRACT

A novel signal processing method of movement direction identification and phase correction is presented for laser heterodyne interferometry. Based on the reference signal, four intervals with phase difference of 90° each other are set up. The real-time movement direction identification and the integer fringe counting are realized by detecting the times that the rising-edge of the measurement signal crosses the intervals. The phase correction approach is proposed in detail to solve the fraction phase compensation when the initial phase difference is not equal to the zero phase difference. Three experiments of the stability test, the nanometer and micrometer displacement tests on bi-directional movement were performed to demonstrate the usefulness and feasibility of the presented signal processing method.

1. Introduction

With the rapid development of precision machining and microelectronics technology, urgent requirements are put forward on nanometer displacement measurement [1–6]. Laser heterodyne interferometer with high precision, high speed and long distance has been widely used in displacement, straightness and micro-angle measurements [7–11]. Signal processing for laser heterodyne interferometer is a key technique to realize nanometer measurement accuracy. In the past few decades, many researchers have focused on this study [12–15]. For example, Demarest developed the heterodyne interferometer electronics to provide a position resolution of 0.31 nm at velocities up to 2.1 m s^{-1} with the designed phase meter consisting of a phase locked loop, a delay line interpolator and a delay-locked loop [8]. Eom et al. described a phase-encoding electronics including the phase demodulating electronics and the nonlinearity compensating electronics [12]. Yim et al. proposed a dual mode phase measurement for heterodyne interferometry whose main idea is combining the high bandwidth frequency counter and the high resolution phase meter with mutually complementary characteristics, and provided a relevant phase correction method of high bandwidth phase counter [14]. Kim et al. presented a phase measurement method that achieves a resolution of 0.15 nm using simple electronics for a target speed of 2.4 m s^{-1} which adopts a frequency-conversion technique to lower the original beat frequency to 100 kHz by mixing it with a stable reference signal generated from a phase-locked loop [15]. These works have been done to mainly improve phase-measuring electronics to obtain higher resolution or speed. In this paper, a novel movement direction identification and fraction fringe phase correction method is proposed for laser heterodyne interferometry. And its feasibility will be verified by experiments.

2. Phase measurement problem

As it is well known, a laser heterodyne interferometer [14,16] is shown in Fig. 1. An orthogonally linearly polarized beam with different frequencies of f_1 and f_2, emitted from a stabilized two-frequency He–Ne laser, is divided into two parts by a beam-splitter (BS). The reflected one passes through a polarizer and projects onto the first detector to generate the reference signal. The transmitted one projects onto a polarizing beam-splitter (PBS) and is split into two beams, i.e. the f_1 an f_2 beams. These two beams separately project onto the reference mirror and the moving mirror and return to PBS where they are recombined into one beam, which is reflected by a reflector and passes through another polarizer and projects onto another detector to generate the measurement signal. When the moving mirror is moved by a measured object, the phase meter is used to detect and accumulate the phase difference ($\Delta\phi$) between the reference signal and the measurement signal. The measured displacement (ΔL) can be

* Corresponding author. Tel.: +86 571 868 43988; fax: +86 571 868 43525.
E-mail address: chenby@zstu.edu.cn (B. Chen).

0143-8166/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.optlaseng.2014.01.016

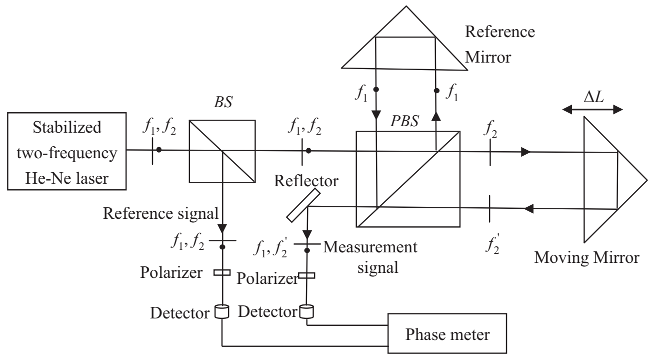

Fig. 1. A block diagram of laser heterodyne interferometer.

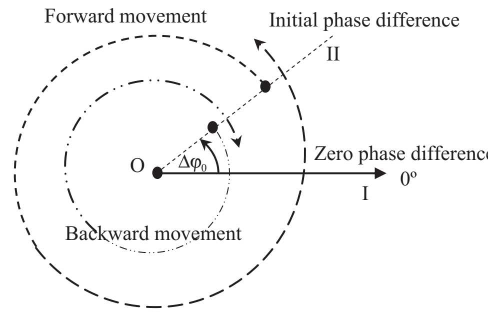

Fig. 2. Schematic of the phase difference change.

expressed as $\Delta L = \Delta\phi\lambda/4\pi$, where λ is the wavelength of light source.

To realize displacement measurement with nanometer resolution, the following phase measurement problem should be addressed:

The zero phase difference means that the phase difference between the reference and measurement signals is 0° (position I in Fig. 2). The initial phase difference is the phase difference between the reference and measurement signals at the beginning of measurement ($\Delta\varphi_0$, position II in Fig. 2). Generally, $\Delta\varphi_0$ is not equal to 0° at the beginning of measurement, and the phase difference will induce a 360° abrupt transition at the zero phase difference during the measurement process. So the measurement error probably occurs if the integer fringe counting adds or subtracts 1 according to crossing the zero phase difference. In fact, the integer fringe counting should be ± 1 only when forward or backward change of the measurement signal makes the phase difference exceed the initial phase difference again (position II in Fig. 2). Therefore, when the initial phase difference is not 0°, it is essential to correct the phase difference in order to achieve right measurement result. In addition, the movement direction of the measured object must be also judged in real time.

3. Signal processing method

In order to solve the above mentioned problem, we propose a signal processing method for laser heterodyne interferometry, including the four intervals movement direction judgment approach and the fraction phase correction approach.

3.1. The basic idea of movement direction identification

Four intervals within one period of the reference signal is set up, the rising-edge of the measurement signal is detected in real time. A fringe counter will count once whenever the rising-edge of the measurement signal crosses one interval. While the measurement signal crosses the interval forward, the counter adds 1. Conversely, the counter subtracts 1. When the accumulated number of the counter is greater than 4 or less than -4, that is, when current phase difference exceeds the initial phase difference forward or backward, an integer fringe counting is completed. The movement direction of the measured object can be judged according to the polarity of the integer fringe counting number.

3.1.1. The establishment of the intervals

As shown in Fig. 3, based on the reference signal ref_1, three signals ref_2, ref_3 and ref_4 are produced by shifting phase of the reference signal with 90°, 180° and 270°, respectively. Then, one period of the reference signal is divided into four intervals (S_A, S_B,

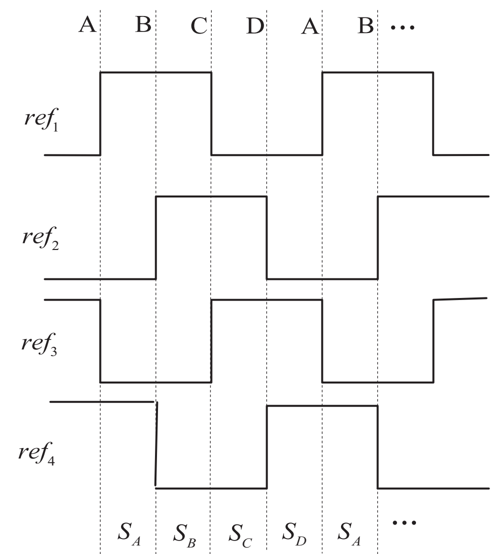

Fig. 3. Establishment of four intervals based on the reference signal.

S_C and S_D) by the four rising-edges (A, B, C and D) of the four signals (ref_1, ref_2, ref_3 and ref_4). Apart from this, if the duty cycle of 50% is guaranteed, the falling-edges of ref_1 and ref_2, together with their rising-edges, can be used to form the four intervals. When the rising-edge of the measurement signal arrives, if the levels of the four signals ref_1, ref_2, ref_3 and ref_4 are "1001", this means that the rising-edge of the measurement signal is in the interval S_A, we define that the measurement signal state is "00". Similarly, the levels "1100", "0110" and "0011" of the four signals correspond that the rising-edge of the measurement signal is in the intervals S_B, S_C and S_D, respectively, and the measurement signal state is "01", "10" and "11", respectively. When the measured object moves forward, that is, the phase difference between the reference and measurement signals increases gradually, the measurement signal state will change with the order "00"→"01"→"10"→"11"→"00"→……. And when the measured object moves backward, that is, the phase difference decreases gradually, the measurement signal state will change with the order "00"→"11"→"10"→"01"→"00"→……. We then define a 24-bit binary variable *num* that represents the change times of the measurement signal state. When the measurement signal state changes once forward, the variable *num* adds 1, that is, $num = num + 1$. On the contrary, $num = num - 1$. The change sequence of the measurement signal state is shown in Fig. 4. Therefore, during the measurement process, as long as the measurement signal state is detected in real time, the movement direction of the measured object can be judged.