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Verification of the positioning accuracy of industrial coordinate measuring machine using optical-comb pulsed interferometer with a rough metal ball target

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ABSTRACT

An optical-comb pulsed interferometer was developed for the positioning measurements of the industrial coordinate measuring machine (CMM); a rough metal ball was used as the target of the single-mode optical fiber interferometer. The measurement system is connected through a single-mode fiber more than 100 m long. It is used to connect a laser source from the 10th floor of a building to the proposed measuring system inside a CMM room in the basement of the building. The repetition frequency of a general optical comb is transferred to 1 GHz by an optical fiber-type Fabry–Pérot etalon. Then, a compact absolute position-measuring system is realized for practical non-contact use with a high accuracy of measurement. The measurement uncertainty is approximately 0.6 μm with a confidence level of 95%.

1. Introduction

A coordinate measuring machine (CMM) is defined by ISO 10360-1 as a measuring system with the means to move a probing system and the capability of determining spatial coordinates on a workpiece surface [1]. CMMs are widely used to measure the three-dimensional sizes, forms, and positions of manufactured parts. However, CMM measurement inaccuracy occurs when there is an error in the relative position between the measured points and the probing points. The errors affecting a CMM have a systematic and a random component. They also directly influence the quality of production inspection [2]. Therefore, CMMs must be calibrated on installation and verified periodically during their operation. The standards and guidelines for CMM verification are based on sampling the length-measurement capability of a CMM to decide whether its performance conforms to the specification [3,4]. Many methods and artifacts are developed to verify CMMs [2–10]. Most standards prefer to use end standards such as a series of gauge blocks, a step gauge, and a ball plate or laser interferometer. However, there is no one perfect method for CMMs, mainly because of the complicated constructions and the three-dimensional positions of many measured points that are necessary in coordinate metrology. In addition, the range of positioning verification is limited by the length of end standards [11,12]. Although a continuous-wave (cw) laser interferometer can measure for the long length, the measuring path cannot be interrupted during the measurement period because it is operated by a cw laser and interference fringe counting method.

Recently, an optical frequency comb has been considered as a useful tool for dimensional metrology, because of their high frequency-stability and direct traceability to SI unit [13]. Several methods for length measurement with an optical frequency comb have been proposed [14–17]. This paper proposes a new technique for the verification of the positioning accuracy of CMMs using an optical-comb pulsed interferometer. A rough metal ball is used as the target of a single-mode fiber interferometer. Because the sphere ball provides 3D targets, the measuring system can be constructed at any location on the surface of a CMM. In addition, the proposed measuring system can be installed on more than one system to measure many positions at the same time with a target as shown in Fig. 1.

A single-mode optical fiber more than 100 m long is used to connect a laser source from a 10th floor of a building to the proposed measuring system inside a CMM room in the basement of the building. The repetition frequency of a general optical comb is transferred to 1 GHz by an optical fiber-type Fabry–Pérot etalon.

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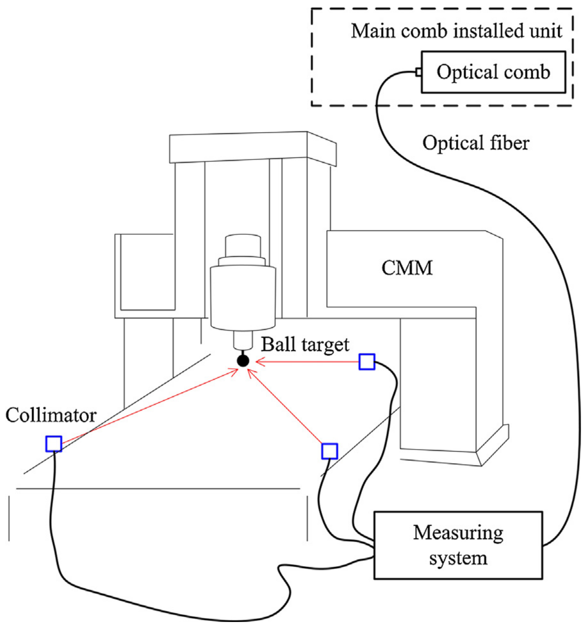

Fig. 1. The concept idea of CMM verification using an optical-comb pulsed interferometer with a rough metal ball target.

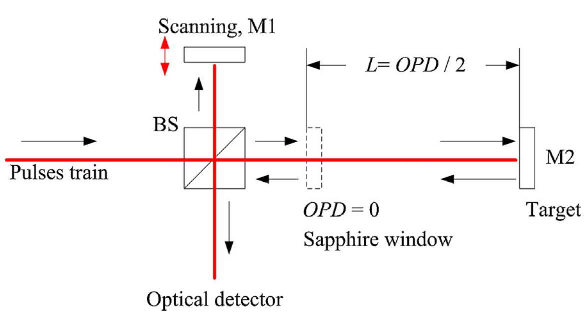

Fig. 2. Principle of an optical-comb pulsed interferometer.

Then, a compact absolute position-measuring system is established based on a single-mode fiber interferometer; a rough metal ball is used as the target because the alignment of the laser beam is easy. The conversion of the time scale, which is presented by envelope interference fringes, to the length scale is measured. The effect of the surface roughness of the target is also examined. The position errors of a moving bridge-type CMM were measured by the proposed measuring system paired with a commercial cw laser interferometer. Finally, the measurement uncertainty is also evaluated. The uncertainty of the measurement is approximately 0.6 μm with a confidence level of 95%. This technique provides enough accuracy for industrial CMMs.

2. Optical-comb pulsed interferometer

Mode-locked lasers generate ultrashort optical pulses by establishing a fixed-phase relationship across broad spectrum of frequencies. The spectrum of each pulse train is separated by the repetition rate of an optical comb, and the series of spectrum lines is called an optical frequency comb. In the time domain, the pulse train is emitted at the same time by a mode-locked laser [13]. The pulsed interferometer remains the principle of an unbalanced-arm Michelson interferometer where an optical comb is a laser source. As shown in Fig. 2, an optical comb generates a pulse train. Laser pulses are divided into two beams by an optical beam splitter (BS). One beam is reflected on a scanning mirror (M1), while the other

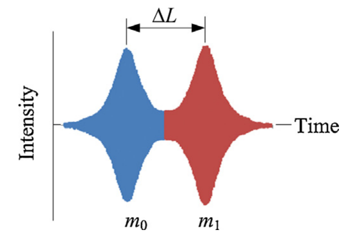

Fig. 3. Two interference fringes of an optical-comb pulsed interferometer; m_0 and m_1 are the fringe order at the reference position and the target position, respectively.

is transmitted through a sapphire window (reference position) to the target mirror (M2).

Subsequently, the reflected light pulses from a scanning mirror (M1) are recombined with the returned light pulses from a sapphire window and a target mirror (M2) to produce interference fringes when the optical path difference (*OPD*) between two arms follows Eq. (1) [14].

$$OPD = \frac{mc}{nf_{rep}} \quad (1)$$

where m is an integer, c is the speed of light in the vacuum, n is the refractive index of air, and f_{rep} is the repetition frequency.

Normally, two interference fringes will overlap when an optical-comb pulsed interferometer exactly satisfies the condition of Eq. (1). In practical use, the envelope peak of the interference fringes will be separated if displacement is provided (ΔL). The result is illustrated in Fig. 3.

Therefore, the position/length under measurement is determined by Eq. (2).

$$L = \frac{OPD}{2} + \Delta L \quad (2)$$

In application, two envelope interference fringes in Fig. 3 are presented in the time domain. The first fringe comes from the reference position when the *OPD* is zero ($m_0 = 0$), and the second fringe comes from the target when the *OPD* is around 300 mm ($m_1 = 1$). Therefore, the conversion of the time scale to the length scale of the peak-to-peak measurement of the envelope interference fringes must be measured because it relates to the speed of the scanning-fringe device. Moreover, the position/length under measurement must be corrected for the group refractive index of air due to changes in environmental conditions [18].

3. Experiments and results

3.1. Time scale and length scale measurement

The relationship between the time scale and the length scale measurement is required because the peak-to-peak of the envelope interference fringes shown in Fig. 3 is presented in the time domain. The measurement setup diagram to determine this relation is shown in Fig. 4.

A laser source (an optical comb C-Fiber Femtosecond Laser, Menlo Systems) generates a short pulse train with a repetition frequency of 100 MHz and a central wavelength of 1560 nm. The repetition rate was modified by a Fabry–Pérot fiber etalon. An optical fiber-type etalon was prepared from a special-cut length of a single-mode optical fiber (SMF-28). Both ends of the fiber are FC connectors (fiber-optic connector) whose surfaces are coated with 93% reflectivity to generate a 1-GHz FSR (free spectral range). The stability of repetition frequency after passing through a Fabry–Pérot fiber etalon was observed by a universal counter (SC-7206, Iwatsu). It was performed at an order of 10^{-9} over 2 h [16]. Subsequently, the laser beam was amplified by an optical amplifier.