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Calibration of linear encoders with sub-nanometer uncertainty using an optical-zooming laser interferometer

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ABSTRACT

The nonlinear errors of high-precision linear encoders were calibrated by using a nanometer-length calibrator that was based on the optical-zooming laser interferometer with an optical frequency comb. A transmission-type linear encoder and a reflection-type linear encoder were calibrated, and the cyclic nonlinear errors were evident. The magnitudes of the observed cyclic errors were 0.1 nm and 0.2 nm, respectively, and the best calibration uncertainties were 0.55 nm ($k = 2$). A traceable calibration service for linear encoders with the best calibration uncertainty in the sub-nanometer range has started based on this work.

1. Introduction

High-precision displacement measurement is an important technology in high-technology manufacturing, such as semiconductor-mask exposure, liquid-crystal manufacturing, and nano-scale processing. Linear encoders are widely used for precise measurement of the displacement of movable stages in these industries. The resolutions of linear encoders increased, and the highest resolution achieved is several tens of picometers. As the resolution increases, evaluating the accuracy of the linear encoders becomes important.

The measurement error of a linear encoder can be separated into linear error and nonlinear error. Linear error is the measurement error that is proportional to the measurement length. Linear errors are evaluated to determine the basic performance of the linear encoder. For the evaluation of linear errors, conventional heterodyne or homodyne laser interferometers are widely used. Vacuum laser interferometers offer an outstanding technique for high-accuracy calibrations of linear encoders [1–3]. Nonlinear error is the nonlinear residual of the linear error. The magnitude of the nonlinear errors of recent high-resolution linear encoders is typically in the nanometer to sub-nanometer range. Since the magnitude of the nonlinear error determines the quality of the linear encoder on the nanometer scale, the evaluation of the nonlinear error is important. Especially, since the cyclic error, which is a component of the nonlinear error showing cyclic behavior, depends on the fundamental design of the linear encoder, such as an optical system or a digital data-processing system, evaluation of the cyclic error of the linear encoder is interesting.

However, the nonlinear errors of high-resolution linear encoders have not been evaluated accurately. The reason is that the cyclic errors of high-resolution linear encoders are too small to measure by using conventional laser interferometers. The resolution of the best commercial laser interferometer is 1 nm, and typical commercial laser interferometers have nonlinear errors of a magnitude of several nanometers [4,5]. Various methods which reduce the nonlinear errors of the general laser interferometers have been proposed [6–8].

The optical-zooming laser interferometer, which uses a two-wavelength interferometric technique based on refractive-index dispersion, was proposed as one of the devices that could, in principle, completely remove the cyclic error and also improve the displacement resolution [9]. Subsequently, an optical-zooming interferometer based on the wavelength-Vernier interferometer was proposed [10]. The use of said interferometer helped to achieve the advantages of reducing the cyclic error and direct traceability to the meter. We developed a precision positioning stage, which was based on the wavelength-Vernier type optical zooming interferometer. Two wavelength-tunable lasers, which were stabilized by using a femtosecond optical comb (fs-comb), were used for the

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purpose of improving the positioning accuracy [11]. The cyclic error of a commercial laser interferometer was observed by using that positioning stage, and the magnitude of said error was 5 nm [12]. The measurement resolution of the magnitude of the cyclic error was 0.1 nm and the measurement uncertainty was 0.6 nm. The measurement uncertainty and the resolution were sufficient for the measurement of the nonlinear errors of high-precision linear encoders.

In this paper, the length calibrator described in Ref. [12] was improved upon and applied to the calibrations of high-resolution linear encoders. The nonlinear errors of two types of linear encoder, the transmission type and the reflection type, were evaluated. In Section 2, a description of the calibrator is given. The measurement procedure and the results are presented in Section 3, and the calibration uncertainties are estimated in Section 4.

2. Calibration system

The length calibration system was constructed by combining the optical-zooming positioning stage and a reference laser interferometer. The details of the system for the optical-zooming positioning stage have been reported in Ref. [12].

A schematic of the calibration system is shown in Fig. 1. The optical-zooming positioning stage is controlled by using two laser interferometers with slightly different operating wavelengths. The first laser interferometer, with operating wavelength λ_1, measures the phase shift caused by the displacement difference between two movable stages: stage1 and stage2. The second laser interferometer, with operating wavelength λ_2, measures the phase shift caused by the displacement of a movable stage, stage1. Since the wavelengths of the two laser interferometers are slightly different, the phase shifts, which are caused by the displacement of stage1, are slightly different in the two laser interferometers. When stage1 moves, the displacement of stage2 is controlled, thus the phase shifts of the two interferometers are the same. As a result, the displacement of stage2 is proportional to that of stage1. The ratio of the displacements of the two movable stages is called the zooming ratio. The zooming ratio is determined as:

$$\rho = \frac{\lambda_2 - \lambda_1}{\lambda_2} \quad (1)$$

where ρ is the zooming ratio. Since the difference between the two operating wavelengths is small, the zooming ratio is also small, and a movable stage with precise displacement can be produced.

The precision linear encoder that was calibrated in this study was mounted on stage2. The glass scale of the linear encoder was glued onto the setting jig, which was made of invar. The setting jig was screwed onto the piezoelectric actuator stage (PZT stage) of stage2. The reading head of the linear encoder was screwed onto the base plate of the calibrator.

The reading of the linear encoder and the displacement of stage2 were compared, and the deviation was stated as the calibrated value. The displacement of stage2 was determined as the product of the displacement of stage1 and the zooming ratio. The displacement of stage1 was measured by a traceable laser interferometer with a wavelength-stabilized He–Ne laser at 633 nm as light source. This light source was calibrated with an iodine-stabilized He–Ne laser, which was calibrated based on the national standard of Japan in AIST. The displacement of stage2 was traceable to meter and determined accurately by multiplying the displacement of stage1 by the zooming ratio.

Since the zooming ratio is only determined by the optical wavelengths, λ_1 and λ_2, it could be determined accurately. We used two external-cavity tunable diode lasers (ECLDs) with center wavelengths of approximately 779.5 nm (λ_1) and 780.0 nm (λ_2). The zooming ratio was approximately $\rho = 0.0006$. The optical frequencies of these two diode lasers were stabilized using a fs-comb. The beat frequency between each diode laser and one of the modes in the fs-comb was stabilized to a reference frequency, which was generated by a quartz crystal oscillator. The stability of the center frequency of each diode laser was 4×10^{-8}, which was equivalent to 15 MHz compared to the center frequency of 380 THz, and the stability of the frequency difference of the diode lasers, which is equivalent to the stability of wavelength difference $\lambda_1 - \lambda_2$, was 1.4×10^{-8}, which was equivalent to 7.3 kHz at an optical frequency difference of 0.5 THz. The wavelengths were measured by the wavemeter, which was calibrated using a stabilized He–Ne laser, at each displacement measurement. The zooming ratio could be determined accurately and was traceable by using the calibrated wavelengths.

We used a stepping motor stage with a control resolution of 1 nm (Sigma Tech Co. Ltd.) for stage1, and a PZT stage driven by the

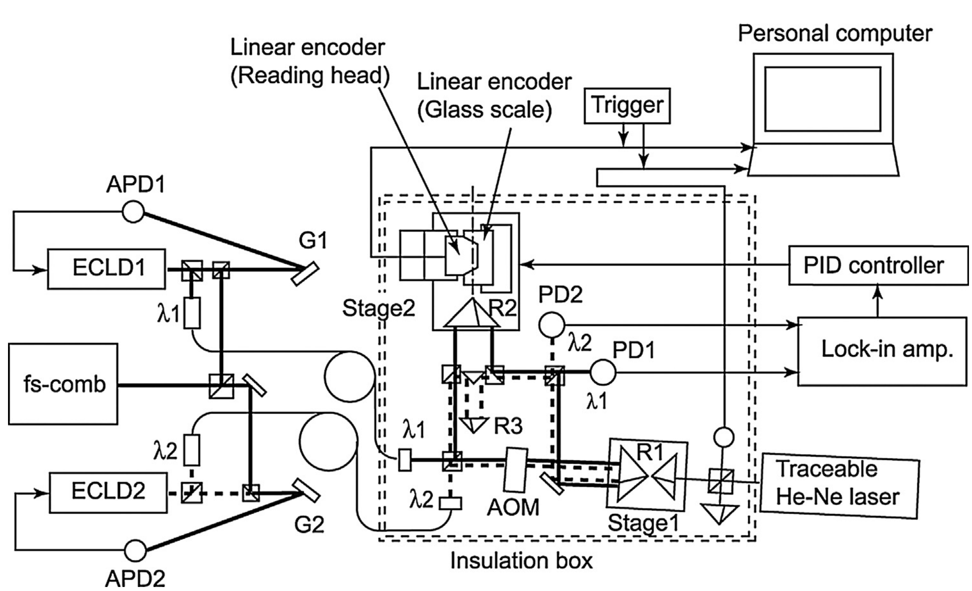

Fig. 1. Schematic of the calibration system. R: reflector, PD: photodetector, AOM: acousto-optical modulator, ECLD: external-cavity tunable diode laser, fs-comb: femtosecond optical comb, G: grating, APD: Avalanche photo diode.