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Periodic error evaluation system for linear encoders using a homodyne laser interferometer with 10 picometer uncertainty

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ABSTRACT

An ultraprecision system to evaluate the *periodic error of linear encoders* (PEL) has been developed. Our system is based on a homodyne laser interferometer as a reference scale. Conventional studies which used an interferometer with unknown periodic error resulted in insufficient reliability because the *periodic error of an interferometer* (PEI) directly overlaps on the evaluated PEL. In this study, we explicitly reveal the homodyne interferometer in the proposed system has a sufficiently small PEI of less than 10 pm. This PEI is determined by analyzing the amplitude variation of interference signals, which we refer to as "self-evaluation method." We have demonstrated the applicability of the proposed system through an actual evaluation of one of the most precise linear encoders with a PEL of sub-nanometer order.

1. Introduction

Linear encoders, as displacement sensors, are widely used in various types of processing or measurement machines for the purpose of precise positioning control of milling heads or sensor probes. Since positioning control and the resultant precision of such machines directly depends on the performance of linear encoders, evaluation and reduction of error factors associated with linear encoders is of fundamental importance for improving processing and measurement precision, which must be of nanometer order or lower.

The error factors of a linear encoder can be categorized into several types: setting error, scale error, and *periodic error*. Among those, the setting and scale errors are controllable in many cases. However, the periodic error is difficult to eliminate and sometimes is a critical problem for linear encoders that prevents them from achieving nanometer accuracy. To determine the periodic error of a linear encoder (PEL), several methods such as using a tuning fork [1] or a laser interferometer [2] have been studied. The method using a tuning fork [1], in which the PEL is clearly separated from the synchronous vibration of the tuning fork in the frequency domain, has a low cost and is easy to use in practice, whereas implementing a metrological reference such as laser interferometer can increase the reliability of the result. When using laser interferometers, it is necessary to manage the periodic error of an interferometer (PEI) and implement specific interferometers having advantages in this regard, such as optical-zooming laser interferometers free from PEI in principle [2], heterodyne interferometers with spatially separated beams avoiding frequency mixing [3,4], and homodyne interferometers with Lissajous signal compensation by elliptical fitting [5,6]. The issue remaining in these studies is to determine the residual PEI. For example, the signal compensation method in [5,6] cannot realize a perfect elimination of the PEI due to the noise in signals [7]. To address this issue, it has been necessary to prepare a more accurate metrological standard such as X-ray interferometry [8]. However, this method complicates the equipment and it is desirable to develop simpler methods that are widely applicable to industry.

In this study, we present a system to evaluate the PEL that is based on a homodyne interferometer with a minimized PEI. In order to determine the residual of the PEI, we established and applied a method to analyze the amplitude variation of the Lissajous signal from the homodyne interferometer itself, which we refer to as "self-evaluation method." Moreover, we demonstrate an evaluation of a linear encoder which has PEL of sub-nanometer order.

In Section 2, we describe the system configuration, the principles of self-evaluation method for PEI, the principles of evaluation for PEL, and these procedures. We show the results of our evaluations and uncertainty estimations in Section 3, and present a discussion and the conclusions in Sections 4 and 5, respectively.

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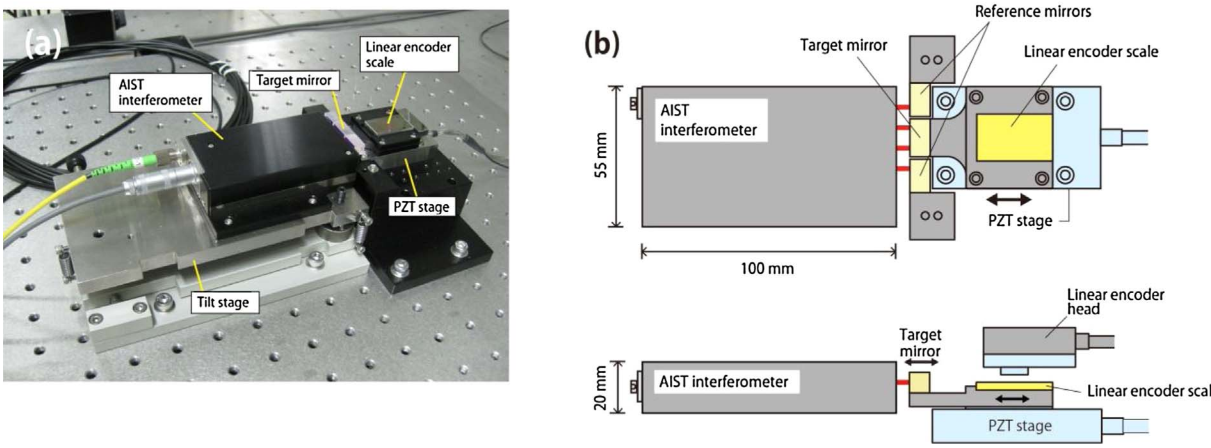

Fig. 1. Evaluation system: (a) photograph, (b) schematic drawing.

2. Evaluation system for periodic error of linear encoders

2.1. Apparatus of the evaluation system

Fig. 1 shows the evaluation system, which consists of a laser homodyne interferometer (AIST interferometer), a piezoelectric transducer (PZT) stage (PI, P-752.1CD), and a linear encoder to be evaluated. Laser beams from the AIST interferometer are reflected by three mirrors. A target mirror located between two reference mirrors is mounted on a moving part of the PZT stage. The two reference mirrors are fixed on the base. The surfaces of three mirrors are arranged in a plane and are parallel to each other within 1″. The optical axis of the AIST interferometer is adjusted so as to be perpendicular to the mirrors. Details of the AIST interferometer are explained in Section 2.2.

In order to demonstrate an actual evaluation procedure, we employed a highly precise linear encoder developed by Nikon Corporation [1] (Fig. 2). This linear encoder applies the so-called scanning probe position encoder (SPPE) principle for the purpose of suppressing its PEL. A piece of the scale of the linear encoder was fixed on a moving part of the PZT stage. This scale has a periodic structure with a 4 µm pitch and a displacement of 2 µm generates one cycle of the signal as output of the linear encoder. In this paper, we refer to a pitch of 2 µm as "optical pitch." The orientation of this scale was adjusted to be parallel to the optical axis of the laser beam from the AIST interferometer. A reading head of the linear encoder was attached on the fixed part with the adequate gap with the scale.

2.2. Optical system of the AIST interferometer

Fig. 3 shows the optical layout of the laser interferometer (AIST interferometer) used as a reference scale for the measurement of the PEL. The principle of the interferometer is homodyne detection with a Michelson-type, double-pass and differential configuration. This optical system is included in a compact package with a size of 100 mm × 55 mm × 20 mm. The light source is a frequency-stabilized He-Ne laser with a wavelength of 633 nm (Spectra Physics 117A) and is introduced to the interferometer through a polarization-maintaining single-mode fiber. The linearly polarized beam after the PBS1 is split into two beams for the target and the reference by the BS, and reflected at both mirrors twice. After these reflections and propagations through the PBS2, the target light and the reference light are overlapped at the PBS3. The interference signal is divided into four signals, referred to as "quadrature signals," whose phase differences are set to 90° from each other by the polarizing optics arranged after the PBS3 (HWP2, NPBS, QWP2, and PBS4 and 5) and detected by PD1, PD2, PD3, and PD4.

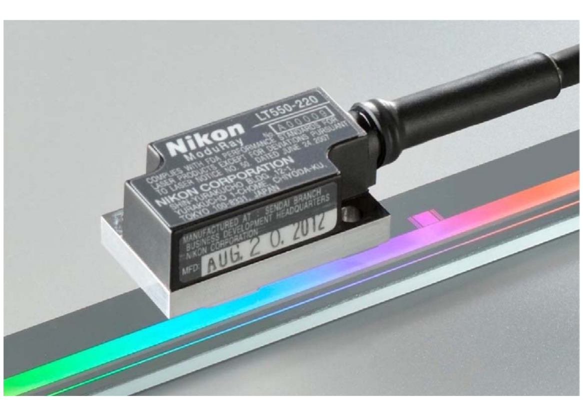

Fig. 2. Nikon linear encoder evaluated in this work.

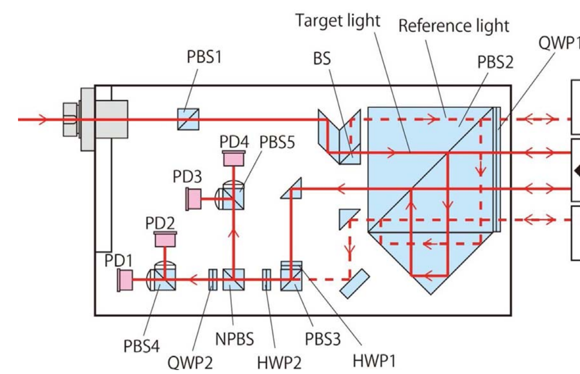

Fig. 3. Optical layout of the AIST interferometer. BS, beam splitter; PBS, polarizing beam splitter; NPBS, non-polarizing beam splitter; HWP, half-wave plate; QWP, quarter-wave plate; PD, photodetector.

Two sets from four interference signals with a phase difference of 180° from each other are subtracted in order to cancel the offset of the signals. Since two signals with a phase difference of 90° are obtained, they form a Lissajous waveform on an oscilloscope that shows a circular shape whose center is located at the origin. Using λ to denote the wavelength of the light source, the displacement is obtained by multiplying $\lambda/4$ by the sum of the number of cycles and a fractional component (phase/2π) of the Lissajous signal; one cycle of the Lissajous signal corresponds to the displacement of $\lambda/4$ because of the double-pass configuration. In general, the center of Lissajous signal is deviated from the origin and the shape is distorted to an ellipse because of imperfections of the optics and/or detectors. As a result, a PEI occurs in the AIST interferometer and, to minimize it, we apply the compensation method for the Lissajous signal by elliptical fitting [5].

Because of quasi-common path configurations and nearly the same