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Measurement of multi-degree-of-freedom error motions of a precision linear air-bearing stage

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Abstract

This paper describes the measurement of straightness error motions (vertical straightness and horizontal straightness) and rotational error motions (pitch, yaw and roll) of a commercial precision linear air-bearing stage actuated by a linear motor. Each of the error motions was measured by two different methods for assurance of reliability. The stage was placed in the *XY*-plane and moved along the *X*-direction. The pitch error and yaw error, which were measured by an autocollimator and the angle measurement kit of a laser interferometer, were about 8.7 and 1.6 arc-s, respectively, over a travel of 150 mm with a moving speed of 10 mm/s. The roll error was measured by the autocollimator through scanning a flat mirror along the *X*-direction. The second method for roll error measurement was to scan two capacitance-type displacement probes along the flat surface placed in the *XZ*-plane. The two probes with their sensing axes in the *Y*-direction were aligned with a certain spacing along the *Z*-axis. The roll error can be obtained by dividing the difference of the outputs of the two probes by the spacing between the two probes. The roll error was measured to be approximately 11.8 arc-s over the 150 mm travel. The horizontal straightness error and the vertical straightness error (*Y*- and *Z*-straightness errors) were measured by using the straightness measurement kit of the laser interferometer. The second method for straightness measurement was to scan the flat surface with a capacitance-type displacement probe. The horizontal and vertical straightness errors of the stage over the 150 mm travel were measured to be approximately 207 and 660 nm, respectively.

Keywords: Measurement; Error motion; Linear stage; Air-bearing; Linear motor; Straightness; Pitch; Yaw; Roll

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1. Introduction

Aerostatic bearings (air-bearings) are widely used in precision linear stages. The averaging effect of the air film on local surface errors allows the air-bearing to have higher precision and better repeatability of motion compared to slide bearings or roller bearings with mechanical contact between elements [1]. Air-bearings are especially suited for high-speed use because of their non-contact characteristics. The low viscosity of air also enables air-bearings to outperform hydrostatic bearings in terms of thermal performance. Thus, linear air-bearing stages have become the best choice for most high-accuracy, high-speed positioning applications in semiconductor manufacturing equipment, ultra-precision machine tools and scanning-type measuring instruments [2–8].

On the other hand, since error motions of a linear air-bearing stage directly influence the performance of the precision positioning system in which the stage is used, measurement of the error motions is important for performance evaluation and/or error compensation of the positioning system. As can be seen in Fig. 1, there are six error motions for a linear stage, three translational errors (the positioning error, horizontal straightness error and vertical straightness error) and three rotational errors (the pitch error, roll error and yaw error) [9]. Among the six error motions, the positioning error, which is the difference between the command position and the actual position along the direction of motion, is the best measured and compensated error

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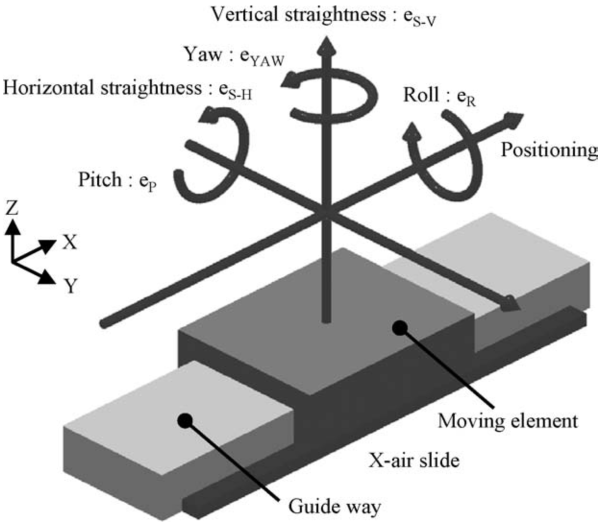

Fig. 1. Multi-degree-of-freedom error motions of a linear stage.

motion for most precision air-bearing stages through closed-loop servo-control based on the position measured by a laser interferometer or a linear encoder [10–14]. The others are not well measured and compensated error motions, however, they are also important factors in precision positioning systems [15–23]. The only data that can be obtained from manufacturers of linear air-bearing stages are simple out-of-straightness values (typically on the order of 100 nm over a 100 mm travel) or brief straightness error curves, which are not detailed enough for error-compensation purposes. Very little data is available on rotational error motions, which may dominate the error motion behavior of a precision linear air-bearing stage at the nanometer scale.

This paper provides measurements of multi-degree-of-freedom (MDOF) error motions (except the well-reported positioning error) of a commercial linear air-bearing stage actuated by a linear motor. For assurance of reliability of the measurement data, each error motion was measured by two different kinds of instruments.

2. Measurement of rotational error motions

Fig. 2 shows experimental setups for the pitch and yaw error measurements. An autocollimator [24] and a laser interferometer with an angle measurement kit [25] were used. The angular reflector of the interferometer and the target mirror of the autocollimator were mounted on the moving element of the linear stage so that the pitch and yaw errors of the stage could be measured by both the interferometer and the autocollimator. The autocollimator had a measurement range of ±600 arc-s, a resolution of 0.01 arc-s and an accuracy of 0.5 arc-s. The measurement range, resolution and accuracy of the laser interferometer were ±10°, 0.05 arc-s and ±0.2% of the measured value, respectively. Because both the interferometer and the autocollimator are capable of two-axis measurement, the pitch and yaw errors were measured simultaneously.

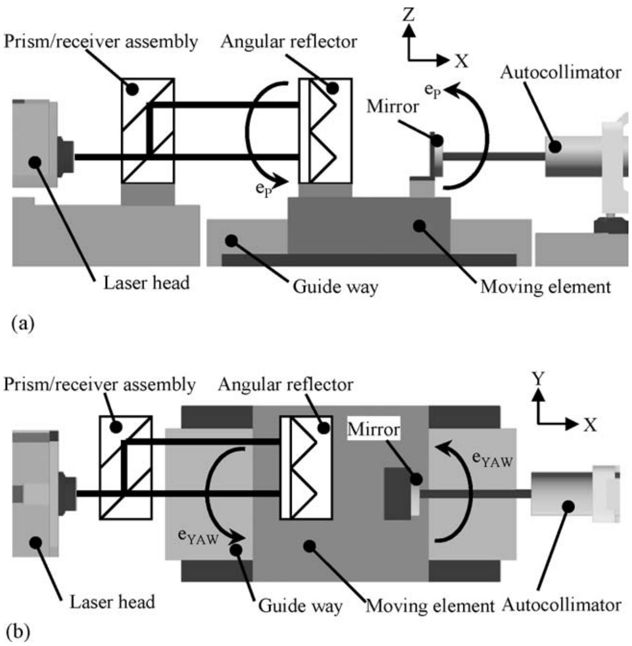

Fig. 2. Experimental setups for pitch and yaw error measurement: (a) pitch and (b) yaw error measurement.

Fig. 3 shows results of the stability test, in which the stage was kept stationary. The test duration was 10 min, and the sampling interval was 0.1 s. As can be seen in Fig. 3(a), the output of the autocollimator varied within a range of approximately 0.5 arc-s in both the pitch and yaw measurements. Fig. 3(b) shows that stabilities of the interferometer output in the pitch and yaw error measurements were 0.4 and 0.6 arc-s, respectively. Fig. 4 shows measurement results of pitch and yaw errors over a stage travel of 150 mm. The moving speed of the stage was 10 mm/s. The movement of the stage was servo-controlled by a PID controller based on the measurement result of a linear encoder. The stage travel range and moving speed were set to be the same for all experiments. The data of 10 repeated travels are shown in the figures. As can be seen in Fig. 4(a), the maximum pitch error of the stage over the 150 mm travel was measured to be 8.59 arc-s with a standard deviation of 0.15 and 8.77 arc-s with a standard deviation of 0.05 arc-s by the autocollimator and the laser interferometer, respectively. The maximum yaw error of the stage (Fig. 4(b)) was measured to be 1.72 arc-s with a standard deviation of 0.20 and 1.45 arc-s with a standard deviation of 0.07 arc-s by the autocollimator and the laser interferometer, respectively. Both the pitch error and yaw error varied linearly with the movement position. The pitch error was approximately five times larger than the yaw error. Considering the stability and accuracy levels of the two instruments, measurements by the autocollimator and laser interferometer showed good agreement.

Fig. 5 shows the experimental setup for roll error measurement. The roll error was measured with the autocollimator