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ULTRA-PRECISION LINEAR MOTION METROLOGY OF A COMMERCIALLY AVAILABLE LINEAR TRANSLATION STAGE

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INTRODUCTION

Many new compact ultra-precision linear translation stages with exceptionally long ranges of motion on the order of tens of millimeters and positioning resolutions on the order of a nanometer are finding their way into emerging nanotechnologies. This class of positioning systems typically has specified linear error motions on the order of a few hundred nanometers or less and angular error motions on the order of 10 " or less. However, measuring and certifying the positioning performance of these new stages with off-the-self instrumentation suggested by existing standards [1-3] can be very challenging if the test uncertainty ratio (TUR) is to be greater or equal to 4:1 as indicated in Ref. [4]. This is because sources of measurement uncertainty that were previously considered insignificant when measuring in the micrometer regime are very significant when measuring in the nanometer regime. In fact, this level of measurement is approaching the limitation of 5 parts in 10^8 for most off-the-shelf laser systems.

To address the challenges in characterizing this class of linear positioning system with appropriate TURs, we began an effort to extend our measurement capabilities for this operational regime and to measure the performance of a commercially available nanopositioner. This paper gives an overview of this effort. Descriptions of the measurement setups used to determine the six error motions of the stage are provided and each are followed by a list of the significant contributors to the combined measurement uncertainty of each positioning error measurement. The resulting measured positioning errors are then stated along with their associated TURs. Finally, the limitations in

our measurement capabilities are identified and a list of suggestions for enhancing the TURs for specified positioning parameters are provided.

NANOPOSITIONER

The system under evaluation is a single axis linear nanopositioner, Aerotech Inc. ANT130 Series [5]. The system is manufactured from Invar and has a travel range of 110 mm (± 55 mm) with a specified positioning resolution of 1 nm. The stage is driven by a linear motor and its position is determined by a linear encoder with a Zerodur scale. With the carriage at the home position (center), the stage has a length of 230 mm, a width of 130 mm, and a height of 45 mm.

LINEAR POSITIONING SET-UP

Linear positioning error [3], *EXX*, was measured using a commercially available single-pass displacement measuring interferometer. The heterodyne system, seen in Fig. 1, consists primarily of a beam splitter, two retroreflectors, and a Helium-Neon laser source with a vacuum wavelength accuracy of ± 0.1 µm/m. Interferometer reference and measurement signals are captured by fiber optic couplings and transmitted via fiber optic cables to a measurement board where displacement is determined with a resolution of 0.62 nm. Each linear positioning (LP) measurement is corrected for changes in laser wavelength due to changes in refractive index of air and for stage encoder growth. When the measurement process is initiated, the refractive index is determined using a form of Edlen's equation [6,7] and by measuring temperature, barometric pressure, and relative humidity with a thermistor, pressure transducer, and humidity sensor with standard uncertainties of ± 0.002 °C, ± 9 Pa, and ± 0.6 %,

respectively. Changes in refractive index are then tracked using a commercially available wavelength tracker that can detect a change in refractive index of 1.1×10^{-9}. An Invar fixture, designed to have the shortest possible thermal loop, supports and positions the interferometer optics with a dead path of approximately 1.6 mm. Alignment of the laser with the axis of travel is achieved using a combination of a laser position sensing detector (PSD) and a precision laser alignment fixture and is estimated to be within 100 ".

The measurement setup resides on top of a passive vibration isolation table located in a environmentally controlled laboratory where the temperature is controlled to 20.6 °C ± 0.3 °C. An enclosure encompassing the measurement setup is used to help minimize the effects of thermal fluctuations created by the laboratory ventilation system. Stage temperature is monitored with platinum resistance thermistors positioned on and around the nanopositioner. All measurements are controlled and monitored remotely from a location outside of the laboratory to further minimize disturbances to the environment.
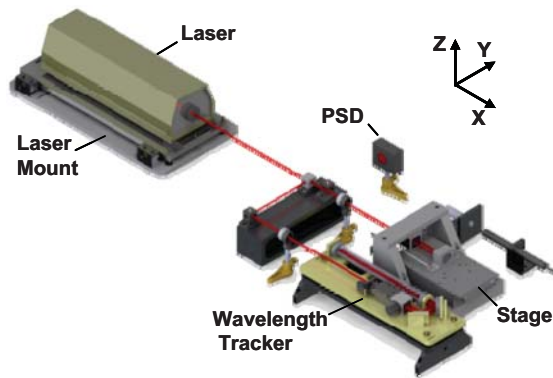

FIGURE 1. EXX measurement setup

LINEAR POSITIONING UNCERTAINTY
A Type B uncertainty analysis [8] based on the methods outlined in [9, 10] revealed that the combined standard uncertainty in measuring a point located at maximum stage travel (110 mm) is approximately 12 nm. The analysis also revealed that the combined standard uncertainties in bidirectional repeatability (R) and accuracy (A) for five bidirectional LP measurement runs are 16 nm and 19 nm, respectively. Assuming a coverage factor of k = 2, R and A can be determined with

expanded uncertainties of approximately 32 nm and 38 nm, respectively. Many sources of measurement error contribute to the combined measurement uncertainties. The most significant contributors are listed in Table 1.

TABLE 1. LP uncertainty contributor estimates

environmental variation	u_{EVE}:	8.0	nm
misalignment	u_{MA}:	7.4	nm
wavelength accuracy	$u_{\lambda A}$:	6.4	nm
refractive index of air	$u_{M,n}$:	3.7	nm
optics nonlinearity	u_{NL}:	2.9	nm

LP MEASUREMENT AND RESULTS
Many linear positioning tests, consisting of five 110 mm bidirectional runs of 23 random target positions within ± 30 % of a nominal 5 mm positioning interval, were performed to evaluate the linear positioning error, EXX. The measured data from the test having the lowest R value is provided in Fig. 2. The A and R values resulting from this test are 115 nm ± 38 nm (k=2) and 47 nm ± 32 nm (k=2), respectively.

STRAIGHTNESS & ANGULAR SETUP
The two straightness errors, EYX and EZX, and the three angular errors, EAX, EBX, and ECX were determined by measuring the lateral deviations of a moving straightness reference with linear displacement sensors [2], as seen in Fig. 3. A 203 mm x 26 mm x 26 mm mirror (straightness reference) with a flatness of 20 nm is mounted to the nanopositioner carriage via a kinematic coupling, which is used to accurately locate the straightness reference with respect to the stage encoder and displacement sensors. Three sets of three balls, which make up half the coupling, are adhered to the three nonmetallic sides of the straightness reference at its Airy points to minimize deflections. Employing three sets of balls provides the ability to accurately rotate and locate the reference between measurements which, in turn, helps to minimize the uncertainty in mapping the straightness errors of the reference, e.g., straightedge reversal and white light interferometry. The other half of the kinematic coupling is adhered to an aluminum plate bolted to the nanopositioner carriage. The nanopositioner is bolted to an aluminum fixture with interchangeable bridges used for holding and locating the displacement sensors in the various measurement locations around the straightness reference. Two capacitance sensors, separated by 50.8 mm during EYX, EZX, EBX, and ECX measurements and 19.05 mm during EAX measurements, are
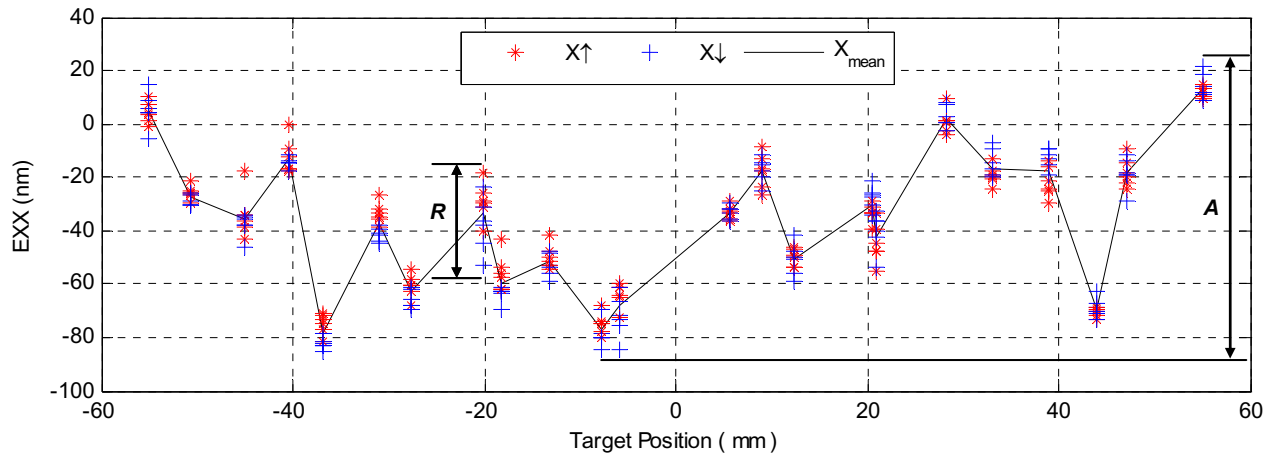
FIGURE 2. EXX data with the best bidirectional repeatability

used for measuring reference displacements. Each sensor has a 250 μm measurement range and a calibration uncertainty, u_{CAL}, of 12.9 nm. Displacement data is captured using commercially available data acquisition hardware and software. Data from the S_1 sensor is used for determining straightness and the difference of S_1 and S_2 sensor outputs is used for determining angular deviation [2].
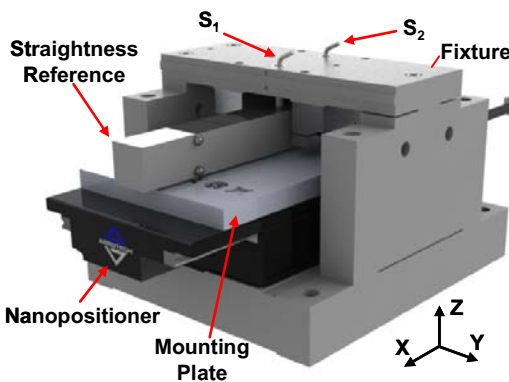

FIGURE 3. EZX and EBX measurement setup

STRAIGHTNESS & ANGULAR UNCERTAINTY
A Type B uncertainty analysis revealed several contributors to the uncertainty in measuring the linear displacement of a moving straightness reference with capacitance sensors. The contributors, listed in Table 2, result in a combined standard uncertainty in measuring straightness of approximately 27.3 nm (i.e., u_{EYX} = u_{EZX} = 27.3 nm). The standard uncertainties in measuring the angular deviations, u_{EAX}, u_{EBX}, and u_{ECX}, are influenced by the uncertainty due to the displacement measurements, the separation tolerance of the sensors (0.130 mm),

and the magnitude of the measured associated angular error. u_{EAX}, u_{EBX}, and u_{ECX} are estimated to be approximately 0.59 ", 0.34 ", and 0.24 ", respectively. Assuming a coverage factor of k = 2, the resulting expanded uncertainties in straightness and angular deviation are U_{EYX} = U_{EZX} = 54.6 nm, U_{EAX} = 1.18 ", U_{EBX} = 0.68 ", and U_{ECX} = 0.48 ".

Table 2. Displacement measurement uncertainty contributor estimates

sensor resolution	u_{SR}:	15.3	nm
misalignment	u_{MA}:	14.1	nm
sensor calibration	u_{CAL}:	12.9	nm
sensor correction	u_{SC}:	8.9	nm
straightness reference	u_{REF}:	5.8	nm
data acquisition noise	u_{DAQ}:	5.1	nm
thermal drift	u_{TD}:	2.6	nm

STRAIGHTNESS & ANGULAR MEASUREMENTS AND RESULTS
Straightness and angular deviation were determined by performing multiple unidirectional runs at 1 mm intervals along the entire 110 mm travel. From these measurements, it was determined that the nanopositioner straightness values, *EYX* and *EZX*, are -470 nm ± 55 nm (k=2) and 385 nm ± 55 nm, respectively. In addition, it was also determined that the nanopositioner's angular errors, *EAX*, *EBX*, and *ECX*, are 2.9 " ± 1.18 ", 7.5 " ± 0.68 " and 7.3 " ± 0.48 ", respectively. Figures 4 and 5 show the typical results from measuring straightness and angular deviation.

DISCUSSION

EYX and *EZX* were measured with TURs of 7:1 and 8:1, respectively and *EBX* and *ECX* with TURs of 11:1 and 15:1, respectively. However, the measurement setup was limited to measuring *EAX* with a TUR of 2.5:1. This was significantly influenced by the spacing of the displacement sensors when compared to the TURs for *EBX* and *ECX*. Employing a wider straightness reference and increasing the distance between the sensors will greatly increase the TUR.
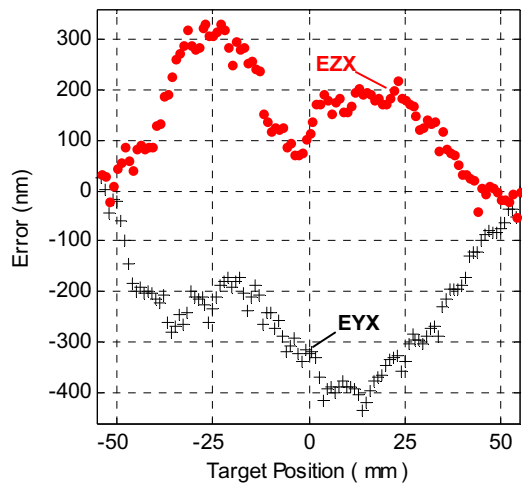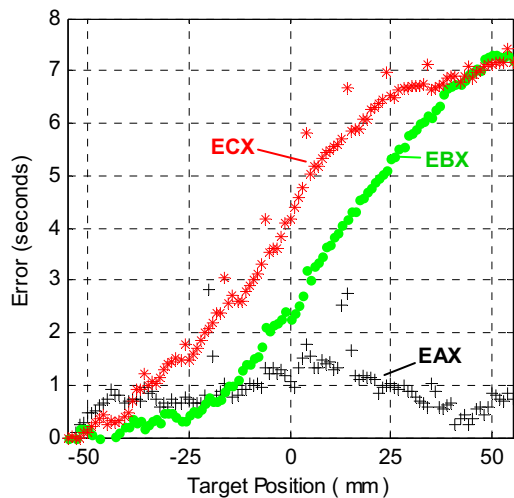

FIGURE 4. Typical EYX and EZX data

FIGURE 5. Typical EAX, EBX, and ECX data

The results from the linear positioning tests indicate that the positioning capability of this linear positioning system has reached the measurement capability of our current LP measurement system. This is highlighted by the

fact that the TUR for *R* was 1.5:1. Achieving a TUR of 4:1 may require the implementation of other technologies and techniques. This may include the integration of an Iodine stabilized laser source that has a wavelength accuracy better than 0.1 nm/m and an absolute refractometer where the refractive index of air can be determined with an uncertainty of 2×10^{-8} [11]. Errors due to the nonlinearity of optics may be eliminated by spatially separating the measurement beams and *EVE* may be minimized with a smaller secondary environmental system. With these implementations, we expect to achieve an expanded uncertainty (k=2) in repeatability of 12 nm (TUR 3.9:1) for five 110 mm bidirectional runs.

CLOSING REMARKS

Measurements were performed to characterize the positioning performance of a commercial ultra-precision linear positioning system. The associated measurement uncertainties have been calculated and suggestions for enhancing the TURs were provided. Future work will involve advancing our measurement capabilities to better measure all sources of error and to further reduce the individual contributions to the combined measurement uncertainties.

REFERENCES

[1] ASME B5.54, 2005, Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers

[2] ISO 230-1:2010, Test code for machine tools – Part 1: Geometric accuracy of machines operating under no-load or quasi-static conditions

[3] ISO 230-2:2006(E), Test code for machine tools – Part 2: Determination of accuracy and repeatability of positioning numerically controlled axes

[4] ANSI Z540.3, 2006, Requirements for the calibration of measuring and test equipment

[5] Aerotech Inc., 101 Zeta Drive, Pittsburgh, PA, www.aerotech.com

[6] Mielke et al., Displacement Measuring Interferometry, Tutorial, ASPE Annual meeting, October 2004

[7] Edlen B., The Refractive Index of Air, Metrologia, 1966; 2: 71-80

[8] Fesperman R.R., Donmez M.A., Moylan S.P., Ultra-precision Linear Motion Metrology, Proceedings of the ASPE Summer Topical Meeting, 2010; 49: 103-108

[9] ISO/TR 230-9:2005, Test code for machine tools – Part 9: Estimation of measurement uncertainty for machine tool tests according to series ISO 230, basic equations

[10] JCGM 100:2008, Evaluation of measurement data – Guide to the expression of uncertainty in measurement, 2008

[11] Egan P., Stone J.A., Absolute refractometry of dry gas to ± 3 parts in 10^9, Applied Optics, V50, N19, pp 3076-3086