# Design and construction of six-degree-of-freedom motion error measurement system in a linear stage using angle sensor-combined grating interferometry

ChaBum Lee[1], Gyu Ha Kim[1], Dong-Jin Lee[1], Sun-Kyu Lee[1,2,]*
[1]*School of mechatronics, Gwangju Institute of Sci. & Tech., Korea*
[2]*RISE, Gwangju Institute of Sci. & Tech., Korea*

*skyee@gist.ac.kr*

**Abstract**

The measurement method of a six-DOF motion error in an ultraprecision linear stage based on grating interferometry is presented. It consists of a diffractive optical element as a grating scale, a corner cube, four separate two-dimensional position sensitive detectors, four photodiodes and auxiliary optics components. With a single traversal of the stage along X direction, the optical sensor measured the motion in high resolution along each axis: less than 0.03 arcsec, 20 nm, and 0.4 nm for the rotational, Y and Z directions, and X direction, respectively. A laser interferometer and autocollimator were used for comparison. As a result, the motion errors were successfully measured and the frequency response of those signals was analysed through a fast Fourier transform.

## 1 Introduction

A high precision multi-degree-of-freedom (DOF) motion measurement technology is important for industrial activities such as manufacturing and inspection because those physical quantities such as the linear and angular displacement are key parameters for keeping and improving quality control of products [1-3]. The laser interferometer calibration system is the most famous instrument for the measurement of displacement. Also, the laser autocollimator can measure the pitch and yaw error, but cannot detect the roll error, which is defined as the angular displacement about the normal axis of the target. Also, those are high-end compared with that of an optical encoder. Many works have been done to measure motion errors [3]. Many studies have been mainly focused on measurement of only motion errors of the stage, but they were restricted to measure not only motion errors but also displacement with a single unit of an optical sensor, simultaneously. Also, the relation between motion errors and dynamic characteristics such as frequency response and driving mechanism of the stage was not investigated. In this paper, the measurement method for six-DOF motion error of the stage was presented, and its optical sensor was constructed and its performance was evaluated.

## 2 Design of measurement system

A simple measurement method was proposed, which is able to measure five motion errors along the driving axis in real time. The overall configuration of the optical sensor is shown in Fig. 1. The linear scale is mounted onto the moving stage and the stage travels along the X direction.

The optical sensor consists of three loops. In Loop I, Y axis displacement error can be measured and in Loop II four-DOF motion error measurement is performed. A stabilized He-Ne laser ($\lambda$= 632.8 nm) is used as an optical source with controlled intensity and frequency, and a polarizer is placed after the laser for linear polarization (45°). Through the beam splitter (BS0), the laser beam is reflected and it is projected onto the linear grating diffracted into each order ($+1^{st}$, $0^{th}$, $-1^{st}$), respectively. The $0^{th}$ diffracted beam incidents back to BS1 and on PSD0 and the $\pm 1^{st}$ diffracted beams are divided into two beams by BS2 and BS3 and projected onto PSD+1 and PSD-1, respectively, as shown in Fig. 2, where, *u*, *v* and *w* are the deviated displacement from the origin of PSD and the subscripts indicate the diffraction order from the grating. *L* is the distance from the beam spot position of the grating to the center of PSD, and $\theta$ is the diffraction angle.

In Loop III, the moving displacement along the X direction is measured by using the circular polarization interferometer [1, 4]. Two sinusoidal signals with 90˚ phase difference were measured and a perfect Lissajous figure was made with a resolution of 0.3nm noise level. Through the calibration process, the resolution was 0.03 arcsec for an angular direction and 20nm for linear direction, respectively. The performance of the optical system was tested and compared with those of a laser interferometer.

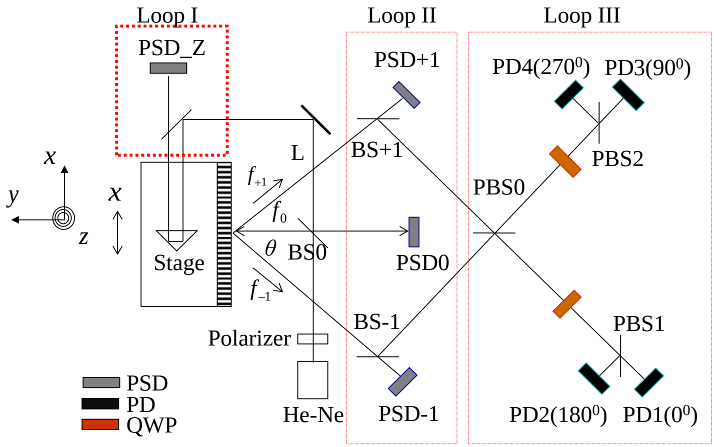


Fig. 1 Configuration of measurement system.

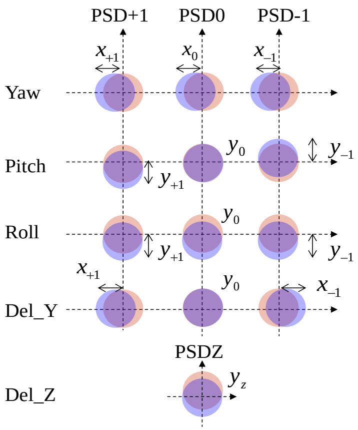


Fig. 2 Changes of beam position due to each error

$$\varepsilon_z = G\left(\frac{u_{+1}}{2L_{+1}} + \frac{u_0}{2L_0} + \frac{u_{-1}}{2L_{-1}}\right)\cdot\frac{1}{3} \quad (1)$$

$$\varepsilon_y = G\left(\frac{v_{+1}}{2L_{+1}} - \frac{u_{-1}}{2L_{-1}}\right)\cdot\frac{1}{2} \quad (2)$$

$$\varepsilon_x = G\left(\frac{v_{+1}}{2L_{+1}} + \frac{v_0}{2L_0} + \frac{v_{-1}}{2L_{-1}}\right)\cdot\frac{1}{3} \quad (3)$$

$$\delta_y = G\left(\frac{u_{+1} - u_{-1}}{2}\right)\cdot\frac{1}{\sin\theta} \quad (4)$$

$$\delta_z = G\frac{w}{2} \quad (5)$$

To understand and analyse multi-DOF motions in a PZT-driven nanostage and characterize those motions, system dynamics was considered, synthetically as shown in Fig. 3. We were confirmed that that the motion errors of the stage have relevance to the driving mechanism and the whole construction of the stage and the proposed multi-DOF motion measurement system could measure the dynamic properties of the stage such as natural frequency and damping ratios according to six-DOF directions, respectively.

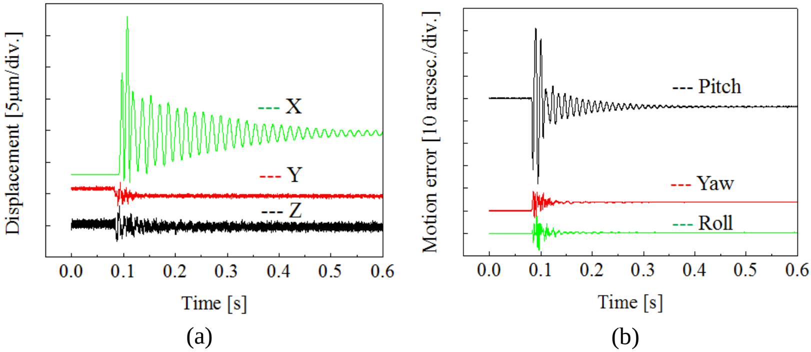


Fig. 3 Measurement result of multi-DOF motions by step response (X): translational (a) and rotational (b).

## 3 Conclusion

A five-DOF motion error and a single-DOF displacement were successfully measured and the relation between motion errors and dynamic characteristics of the stage in terms of frqeuency response was discused. The optical sensor showed a resolution of less than 0.03 arcsec. for angular, 20nm for linear errors, and 0.3nm for displacement along the traveling direction, respectively. As a result, the proposed optical system is expected to be applied for production evaluation of a high precision stage.

**Acknowledgement:**

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (No.20110018621) and partly by Development of Platform Technology for Machine Accuracy Simulation from the Korea government MKE and RISE.

**References:**

[1] ChaBum Lee, et al. Meas. Sci. Technol., Vol. 22, 105901, 2011.
[2] ChaBum Lee, et al. Proc. 26th ASPE Annual Meeting, 2011.
[3] Wei Gao, Precision Nanometrology: Sensors and Measuring Systems for Nanomanufacturing, Springer, 2010.
[4] Eugene Hecht, 4th Ed. Optics, Addison Wesley, 2009.