Development of a three-degree-of-freedom laser linear encoder for error measurement of a high precision stage

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In this study, a laser linear encoder with three degrees of freedom (3-DOFs) based on diffraction and interference was developed to measure the linear displacement and two angular errors of a linear moving stage. Parts of the linear motion errors induced from the two angular errors can be calculated by this prototype 3-DOF laser encoder. It was an effective method for online error calculation and compensation to improve precision stage performance. This new function was superior to other laser encoders. The verification results showed that the resolution is 20 nm. It detected displacements relative to an external grating scale with accuracy of about ±150 nm for a measuring range of ±1 mm, and detected the angular errors with related accuracy of about ±1 arc sec for a measuring range of ±100 arc sec. © 2007 American Institute of Physics.

The optical encoders generate their metrology signals by converting light beam intensity to modulations of grating scales. Such optical encoders can only measure one-dimensional displacement.1-7 Laser linear encoders, such as those manufactured by Renishaw, Heidenhain, or Sony, are the most common instruments for linear displacement measurements.1-3 The linear resolution of these commercial products is achieved to be in the nanometer range. Development of a measuring system with multidegree of freedom is important for the linear moving stage.8-11 The three rotational (εx, εy, εz) and three translational (δx, δy, δz) errors of the linear stage take effect of a component’s error on the position of the workpiece. Elimination of these component’s errors is important to improve precision stage performance. Our proposed three-degree-of-freedom (3-DOF) encoder can simultaneously measure displacement and two angular errors for the linear moving stage. Furthermore, the special optical design in the proposed encoder can measure two angular errors and calculate the Abbe error of the linear moving stage and is a useful instrument to be applied in the gantry-type linear stage for compensating the angular deviation between two moving axes.

Figure 1 presents the optical configuration. The laser source used is a He–Ne laser with a 632.8 nm wavelength and is oriented such that the emitted laser beam is linearly polarized at 45°. The zero-order diffractive ray is transmitted through a beam splitter (BS1) to a quadrant detector (QD). The position of the spot on the quadrant detector will be changed when the rotational errors εx and εz of the grating happened. One of the characteristics of the geometrical optics is that the parallel ray transmitted through the lens is focusing and focus is used to solve roll (εy) and yaw (εz) by means of Eq. (1).
The vertical velocity of the measuring tip and grating, and shift of relationship between displacement and phase. A frequency the frequency of the pler effect occur as soon as the grating moves. The actual frequencies of the two diffraction rays can be derived as

\[ f_{+1} = f_0 + \frac{v}{d_g}, \quad f_{-1} = f_0 - \frac{v}{d_g}, \]

where \( f_0 \) denotes the frequency of incident light, \( f_{+1} \) represents the frequency of the + first-order diffraction ray, \( f_{-1} \) is the frequency of the − first-order diffraction ray, \( v \) denotes the vertical velocity of the measuring tip and grating, and \( d_g \) represents the grating constant. Thus, the Doppler frequency shifts can be derived as

\[ \Delta f = f_{+1} - f_{-1} = \frac{2v}{d_g}. \]

Thus, the phase shifts can be derived as

\[ \Delta \phi = 2\pi \int_{0}^{\tau} \Delta f \, dt = \frac{4\pi L}{d_g}, \]

where \( \Delta \phi \) is the phase shift due to the beating signal and \( L \) is the grating displacement.

After the ± first-order diffractive rays passed through the polarized beam splitter (PBS1), the light beams become \( s \) polarized and \( p \) polarized of linear polarization. After the linear polarization beams passed through the quarter wave plates (QWP1 and QWP2), the light beams become circular polarized. Both of the transmitted and the reflected beams split by polarizing beam splitters (PBS2 and PBS3) and detected by the photodetectors (PD1, PD2, PD3, and PD4). The dc term is removed by differential amplification of the photodetectors. The ac components are the quadrature signals required to form a Lissajous circular pattern. The intensities of the Lissajous circular pattern can be derived as

\[ V_A = V_{PD1} - V_{PD2} = 8 \sin (\Delta \phi), \]

\[ V_B = V_{PD3} - V_{PD4} = 8 \cos (\Delta \phi), \]

where \( V_A \) and \( V_B \) represent voltages of the quadrature signals and \( V_{PD3} \) to \( V_{PD2} \) represent the voltages of the four photodetectors. The quadrature signals were sent to a signal processing card with signal compensation, subdivision, and counting function to compute the displacement.

Calibration tests for the two angular errors of the proposed encoder were first performed using an autocollimator. A grating with spaced 4 \( \mu m \) lines is used in this article. The angular measurement system detects the zero-order ray and focuses at the quadrant detector. The accuracy of yaw and roll angular measurements was made in direct comparison with the autocollimator. The autocollimator resolution is 0.1 arc sec for angular measurement.

Table I showed the verification results of yaw and roll of the proposed 3-DOF encoder. The related accuracy of yaw and roll were 1 arc sec for a calculated range of ±100 arc sec. Standard deviations (STDEV) of the yaw and roll measurements were about 0.2 and 0.7 arc sec for a calculated range of ±100 arc sec.

The proposed laser linear encoder with three degrees of freedom was also applied to measure the motion errors of a linear stage and was verified using the HP 5529A laser calibration system and the electronic level. In this experiment, three tests were performed by moving the stage along each axis with each step of 0.25 mm for a distance of 2 mm from the origin. These points were obtained from successive re-

<table>
<thead>
<tr>
<th></th>
<th>Sensitivity (arc sec/V)</th>
<th>Accuracy (arc sec)</th>
<th>STDEV (arc sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yaw</td>
<td>546.6</td>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td>Roll</td>
<td>549.7</td>
<td>1</td>
<td>0.7</td>
</tr>
</tbody>
</table>

FIG. 2. (a) Calibration results, (b) error difference, and (c) standard deviation of the linear moving stage.
angular errors between the 3-DOF encoder and electronic level is $<0.5$ arc sec. The error difference for the yaw angular error between the 3-DOF encoder and HP 5529A laser calibration system is $<0.2$ arc sec [Figs. 2(a) and 2(b)]. The standard deviation of angular error of the linear moving stage is 0.2 arc sec. The verification of the position of the proposed system is calculated by using IK220 (Ref. 12) signal processing card. The variation in starting position is about $-8$–$12$ nm [Fig. 3(a)]. Consequently, the resolution is estimated to be about 20 nm. The error difference for the position within the measuring range of $\pm 1$ mm between the 3-DOF encoder and HP 5529A laser is $\pm 150$ nm [Figs. 3(b)–3(d)]. The standard deviation of the position of the linear moving stage is 50 nm.

For a single-axis linear motion stage, it has three rotational ($\varepsilon_x$, $\varepsilon_y$, $\varepsilon_z$) and three translational ($\delta_x$, $\delta_y$, $\delta_z$) errors associated with their motion. These errors can be defined as occurring about and along the reference coordinate system’s axes, respectively. These errors will be a function of the position of the body in the reference frame. The homogeneous transformation matrix (HTM) is the technique to determine the effects of a component’s error on the position error of the tool point or the workpiece which are induced from the three rotational ($\varepsilon_x$, $\varepsilon_y$, $\varepsilon_z$) and three translational ($\delta_x$, $\delta_y$, $\delta_z$) errors. The errors in the position of a single-axis linear motion stage with respect to its ideal position is represented as

$$
E_{tot} = \begin{bmatrix}
\delta_x \\
\delta_y \\
\delta_z \\
1
\end{bmatrix} + \begin{bmatrix}
0 & -\varepsilon_z & \varepsilon_y & 0 \\
\varepsilon_z & 0 & -\varepsilon_x & 0 \\
-\varepsilon_y & \varepsilon_x & 0 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
a \\
b \\
c \\
1
\end{bmatrix},
$$

where $a$, $b$, and $c$ are the offset along the $x$, $y$, and $z$ axes.

Thus, the prototype 3-DOF laser encoder measured the $\delta_x$, $\varepsilon_x$, and $\varepsilon_z$ and used Eq. (8) to calculate parts of the total geometry errors. It was an effective method for online error compensation to improve precision stage performance. This advantage is superior to other laser encoders worldwide. In the future, a five-degree-of-freedom laser encoder will be designed and more powerful for online calculating the most linear motion errors.

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References:

1. http://www.renishaw.com