Reducing tilt errors in moiré linear encoders using phase-modulated grating

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A new hardware compensation method reducing displacement measurement errors, caused by tilt of the index scale in a moiré linear encoder, has been developed. In conventional moiré linear encoders, the detectors are aligned perpendicular to the line of the moiré fringes and this structure is very sensitive to an unwanted tilt of the gratings. In this article, a newly designed grating, called a phase-modulated grating, is developed to compensate for nonorthogonal errors. By using the phase-modulated grating instead of a conventional index, it is possible to reduce nonorthogonal errors of the moiré linear encoder. © 2000 American Institute of Physics.

I. INTRODUCTION

Linear encoders are small and inexpensive displacement measuring devices that can sense linear displacement in micron order in mechatronics systems such as CNC machines, industrial robots, microstages, and transfer mechanisms. Among various types of linear encoders, moiré encoders are widely used because they are relatively easy to manufacture and offer high resolution-per-cost ratio. Moiré linear encoders use moiré fringes generated by two gratings tilted at a small angle to each other, as a main scale and an index scale, and with a simple structure are able to measure extremely small displacements. However, they are very sensitive to a variation in the fringe spacing. The variation is caused by unwanted changes of tilt angles between the two gratings. The unwanted additional tilt angle change of the index scales results in comparatively large displacement errors in moiré linear encoders.

Research on how to deal with such errors has been conducted in two ways: with a software compensation method and with a hardware reconstructing method. The software compensation method calibrates system parameters by comparing experimental data with theoretical prediction. Research by Heydermann,1 Hanselman,2,3 Zhang,4 Wang,5 and Hagiwara6 falls into this category, where they corrected the errors with mathematical computations. However, this method cannot deal with the errors generated during the operation of the encoder. In order to alleviate this shortcoming, Engelhardt7 proposed an optical position encoder with a reconstructing system using a glass-based scale, a dedicated photodetector array, and a micro-optical imaging system for the application of high precision matching. However, the encoder is complicated in structure and difficult to manufacture.

In this study, a new hardware error compensation method with a simpler structure has been developed in order to reduce the errors caused by the unwanted additional tilt of the scales.

II. ERROR ANALYSIS

Moiré type linear encoders consist of the main scale, light intensity-detecting units, and signal processors. The main and index scales have repetitive transparent and opaque lines. The detecting units are composed of the light source, the index scale, and photodiodes. Figure 1 shows the moiré fringes generated by the two scales. With scale pitch \( p \) and angle of two scales \( \theta \), the spacing of fringe \( f \) can be expressed as:

\[
f = \frac{d}{\sin(\theta)}
\]
f = \frac{p}{2 \sin(\theta/2)}. \quad (1)

As the main scale moves by one scale pitch perpendicular to its lines, the moiré fringes move by one fringe period. By using the principle of displacement amplification, one can measure the displacement of an object precisely. As the fringes move, the detectors detect the changes of light intensity variations. Because the direction of the fringe movement cannot be determined with one detector, and there is the bias value of light intensity, at least four detectors should be stationed to give accurate and mutually orthogonal outputs. The signals from four photodetectors can be expressed as

\begin{align*}
I_1 &= V_0 + V_p \cos \phi, \\
I_2 &= V_0 + V_p \cos \left(\phi - \frac{\pi}{2}\right), \\
I_3 &= V_0 + V_p \cos \left(\phi - \pi\right), \\
I_4 &= V_0 + V_p \cos \left(\phi - \frac{3\pi}{2}\right),
\end{align*} \quad (2)

where \( \phi \) represents the phase of the moiré fringes, and \( V_0 \) and \( V_p \) the bias value and amplitude of light intensity, respectively. The four signals from Eq. (2) can be modified into two mutually orthogonal periodic signals with differential amplification as follows:

\begin{align*}
V_a &= \frac{I_1 - I_3}{2} = V_p \cos \phi, \\
V_b &= \frac{I_2 - I_4}{2} = V_p \sin \phi. \quad (3)
\end{align*}

The phase of the fringes \( \phi \) can be expressed by the following equation:

\[ \phi = \tan^{-1} \frac{V_b}{V_a}. \quad (4) \]

The relationship between the linear displacement of the main scale \( x \) and the phase of the fringes is linear and it can be expressed as

\[ x = \frac{p}{f} y = \frac{p}{2\pi} \Delta \phi. \quad (5) \]

To discuss the effect specifically, four index scales with the same pitch over the main scale are superimposed as shown in Fig. 2. The initial tilt angle between two scales is assumed to be \( \theta_0 \). When the index scale has an unwanted tilt angle \( \Delta \theta \), i.e., the angle between two scales changes to \( \theta_0 + \Delta \theta \), the spacing of the fringes is significantly changed as shown in Figs. 2(b), 2(c), and 2(d). These effects break the orthogonal relationship between the two signals of Eq. (3). Therefore, the error caused by the unwanted tilt angle is referred to as a nonorthogonal error.

From Eqs. (1) and (2), when the initial spacing of the

FIG. 2. Errors caused by tilt of an index scale (grating pitch \( p = 200 \mu m \), \( \theta_0 = 2^\circ \)).

FIG. 3. Simulated values of displacements during one pitch movement when there is tilt of an index scale (\( p = 200 \mu m \), \( \theta_0 = 2^\circ \)).
fringes $f_0$ varies with $f$, the phase of the fringes can be modified to $\phi'$:

$$\phi' = \tan^{-1}\left( \frac{V_b'}{V_a'} \right) = \tan^{-1}\left( \frac{\sin(\phi - 2\alpha)}{\cos(\phi - \alpha)} \right)$$

(6)

where $\alpha$ is the shifted phase of the fringes between two neighboring detectors. A variation of $\phi$ can cause a measurement error. The amount of the error can be easily obtained with Eqs. (4), (5), and (6). Assuming that scale pitch $p$ is 200 $\mu$m, initial tilt angle $\theta_0$ is 2°, and the main scale has one pitch movement, the simulation results when the main scale has one pitch movement are shown in Fig. 3.

The additional tilt angles of the index scale are 0.5°, 1°, and 1.95°, respectively, and the dashed line indicates the ideal case in which there is no additional tilt in the index scale. As Fig. 3 shows, small additional tilt angles of the index scale result in significantly large displacement errors. Therefore, it is necessary to stabilize the phase of moiré fringes in order to reduce displacement errors in moiré linear encoders.

III. ERROR COMPENSATION

To eliminate the “nonorthogonal” error, a new type of index scale named “phase-modulated grating” has been developed (Fig. 4). The phase-modulated grating has three thick lines that are thicker by 1/4 pitch than others at the positions of 1/4, 1/2, and 3/4. By superimposing the main scale with the phase-modulated grating, one can generate stairway shaped moiré fringes as in Fig. 5. The phase difference of the neighboring stairs is $\pi/2$.

The four photodetectors are arranged in the horizontal direction while they are arranged in the vertical direction in the conventional moiré linear encoders. Figure 6 shows the changes of the fringe spacing caused by the unwanted tilt, in clockwise and counterclockwise directions from the initial state, of the phase-modulated grating.

For each case, even if the spacing of the stairway shape fringes changes because of the unwanted tilts, the phase differences of neighboring fringe stairs are maintained by $\pi/2$. The displacement error due to the nonorthogonality can be greatly reduced this way because it has a simple design and is easy to manufacture, and can be produced at low cost.
IV. EXPERIMENTS

Figures 7 and 8 show a photograph and a schematic diagram of an experimental setup to show the validity of the proposed error compensation method. A fiber optic illuminator system illuminates a wide area uniformly. The light emitted from the light source goes through two scales and generates moiré fringes. The two scales are manufactured by an emulsion mask and have a pitch of 200 μm. All the scales are 20 mm by 20 mm in size. The light intensity variations are transformed to nearly sinusoidal electric signals by four photodiodes and they give information on the displacements. The conventional index scale and the phase-modulated grating can be replaced by each other under the same environmental conditions. For each case, measurement is carried out with the variation of the angle between scales, including the initial state. The angle of the two scales is set to 2° initially, and the spacing of moiré fringes has a value of 5.73 mm from Eq. (1).

Figures 9 and 10 show a comparison of Lissajous figures of a conventional system and the proposed system of two phase modulated output signals in the case of tilt angle $\Delta \theta = 0°$, 0.5°, 1°, and 1.95°.

In the case of $\Delta \theta = 0°$, a circle is obtained as shown. When there is a nonorthogonal error of the index scale, i.e., $\Delta \theta$ is not equal to 0°, it gives rise to elliptical Lissajous figures. For the case of the conventional system, curves are clearly distorted with the increase of the nonorthogonality (Fig. 9), but for the case of the proposed system, the curves are nearly in the shape of a circle (Fig. 10). Figure 11(a) shows the results of displacement tracking and Fig. 11(b) shows the interpolation errors in the case of $\Delta \theta = 0.5°$.

The proposed system results in a position error about five times lower than that in the conventional system. The maximum displacement errors of the two systems with some unwanted tilt angles are shown in Fig. 12. As the figure shows, the proposed encoder system with the phase-modulated grating is quite insensitive to the angular mis-
alignment. In the case of perfect alignment of the index scale, the maximum displacement errors are equally about 3 μm. They result from misalignment in manufacturing, imperfection between two scales, noise from amplifying circuits, photodiodes, and so on. The portions of displacement errors due to imperfection between two scales and measurement of the photodiodes are comparatively small. The misalignment is caused by the gap between two scales and the incorrect positioning of the components.

V. DISCUSSION

In this article, we designed a phase-modulated grating and substituted it for the index scale in conventional moiré linear encoders in order to compensate for nonorthogonal errors, which have relatively large effects on moiré linear encoders. We analyzed the nonorthogonal error mathematically and showed the computer simulation results. With the experiments, we confirmed that small changes of the angle between two scales result in relatively large displacement errors. For the case of encoders in which each scale has a pitch of 200 μm, the maximum displacement error reached 16 μm when Δθ=0.5°. However, in the case of the phase-modulated grating under the same environmental conditions, the maximum displacement error was reduced to 3 μm. The conclusions of this article are summarized as follows:

(i) The phase-modulated grating was designed to compensate for nonorthogonal errors in the moiré linear encoders; and

(ii) the moiré linear encoders that adopt the phase-modulated grating show improved accuracy and reliability when nonorthogonal errors were involved, and they had a simple structure and low cost.