Fast evaluation of pitch deviation and out-of-flatness of a linear scale by using a Fizeau interferometer

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A reflective-type scale 1-axis grating mirror with a pitch of 1.67 μm used in an interferential scanning-type 2-DOF linear encoder is evaluated by the Fizeau interferometer with measurement range of the 100 mm. The 2-DOF encoder produces 2-axis position signals based on interference between ±1st-order diffracted beams from the 1-axis grating mirror. Firstly, the Z-directional out-of-flatness $e_Z(x,y)$ of the 1-axis grating mirror is evaluated from the wavefront of the 0th-order diffracted beam reflected from grating mirror. The grating mirror is then tilted to align the axes of the 1st-order diffracted beams with that of the interferometer so that the X-directional pitch deviation $e_X(x,y)$of the grating mirror can be evaluated from the wavefronts of the 1st-order diffracted beams. Finally, the Z-directional out-of-flatness $e_Z(x,y$ and X-directional pitch deviation $e_X(x,y)$ were then verified by comparing them with the measurement errors of the 2-DOF linear encoder using the scale 1-axis grating mirror.

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1. Introduction

The 2-DOF linear encoder can measure not only displacement along the moving axis (X-axis) but also out-of-straightness of precision linear stage as shown in the Fig. 1. The graduations of the linear scale 1-axis grating mirror with a uniform period are read by the optical read so that the actual position of the moving table can be obtained.

This encoder is composed of a reflective-type scale 1-axis grating mirror with a pitch of g and an optical sensor head as shown in the Fig. 2 [1]. The optical sensor head consists of a Light source, four prisms, a non-polarizing beam splitter (BS), a reference grating mirror and a detector unit. The arrangement of the scale 1-axis grating mirror and the reference 1-axis grating mirror, which are identical except the scale length, is similar to that of the moving scale mirror and reference mirror of a Michelson interferometer [2], respectively. The detector unit is composed of two photo-detectors (PDs), PD X+1 and PD X−1.

The laser beam with a wavelength of λ emitted from the Light source is divided into two beams by the BS. One beam is projected onto the scale 1-axis grating mirror and the other onto the reference grating mirror. The ±1st -order diffracted beams from the two gratings with a diffraction angle of θ are bent by the prisms and superimposed

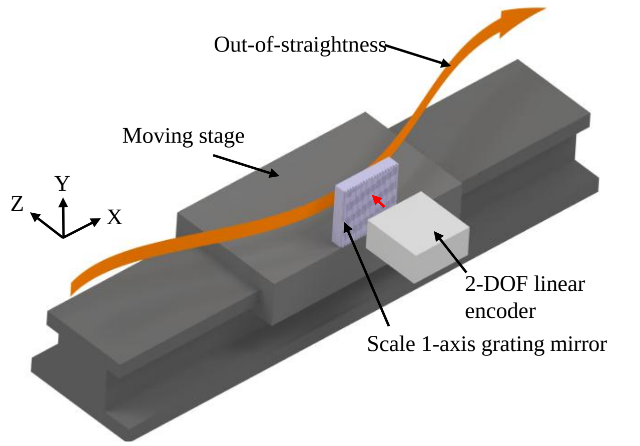


Fig. 1 Measurement of the X-directional position and Z-directional out-of-straightness of the precision linear stage using the 2-DOF linear encoder.

to generate interference signals. The prisms and the PDs are arranged in such a way that only the 1st-order diffracted beams can be received by the detector unit, in which the interference signal generated by the +1st-order diffracted beams is detected by PD X+1 and that generated by the -1st-order diffracted beams is detected by PD X−1, respectively.

Consequentially, the X-directional displacements Δx and Z-directional out-of-straightness Δz can be calculated from the intensities $I_{X\pm 1}$ of the interference beams.

On the other hand, the measurement accuracies of the 2-DOF linear

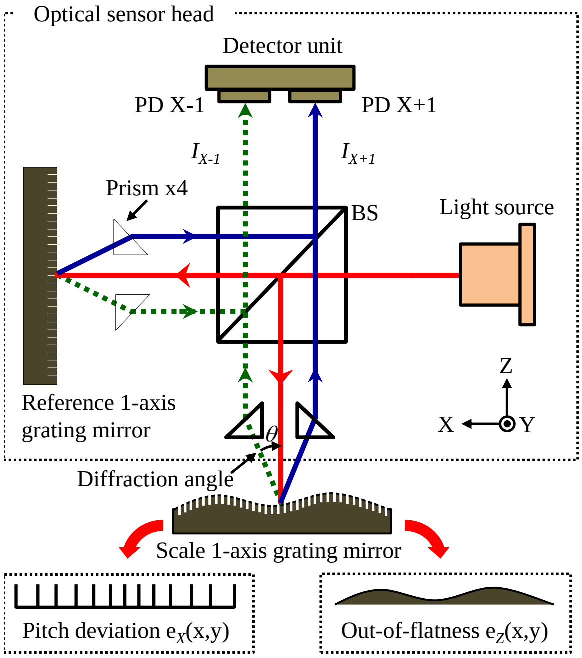


Fig. 2 Basic configuration of the linear encoder.

encoder are mainly determined by the X-directional scale pitch deviation $e_X(x,y)$ and the Z-directional out-of-flatness $e_Z(x,y)$ of the scale 1-axis grating mirror as shown in the Fig. 2 .

In this paper, the pitch deviation $e_X(x,y)$ and the out-of-flatness $e_Z(x,y)$ of the scale 1-axis grating mirror are calibrated from the wavefronts of the 0th-order diffracted beam, the X-directional ±1st-order diffracted beams from the scale 1-axis grating mirror, which are measured by a commercial Fizeau interferometer.

2. Principle

A Fizeau interferometer, which is typically used for measurement of out-of-flatness of a flat or smooth surface, is employed to evaluate not only the out-of-flatness but also the pitch deviations of a scale 1-axis grating mirror [3]. Let the X-directional pitch deviations and the Z-directional out-of-flatness of the scale 1-axis grating mirror be $e_X(x,y)$ and $e_Z(x,y)$, respectively [4]. Fig. 3 shows the evaluation procedure for the Z-directional out-of-flatness $e_Z(x,y)$. As can be seen in the figure, the wavefront of the 0th-order diffracted beam from the grating is measured by the Fizeau interferometer. The 0th-order phase output $I_0(x,y)$ can be expressed by:

$$I_0(x,y) = 2\pi\cdot\frac{2e_Z(x,y)}{\lambda} \tag{1}$$

where λ represents the wavelength of the light source in the Fizeau interferometer. The Z-directional out-of-flatness $e_Z(x,y)$ can thus be calculated as follows:

$$e_Z(x,y) = \frac{\lambda}{4\pi}\cdot I_0(x,y) \tag{2}$$

On the other hand, as shown in Fig. 4, the X-directional pitch deviation $e_X(x,y)$ of the scale 1-axis grating mirror causes a phase shift in the wavefront of the X-directional +1st-order diffracted beam. Meanwhile, an opposite phase shift is caused in the wavefront of the X-directional -1st-order diffracted beam. The two opposite phase shifts, which can be detected by the Fizeau interferometer, are employed to evaluate $e_X(x,y)$. Fig. 5 shows the measurement of the wavefront in the X-directional ±1st-order diffracted beam, which was included not only Z-directional out-of-flatness but also X-directional pitch deviation in the phase output. As can be seen in the Fig. 5(a), the

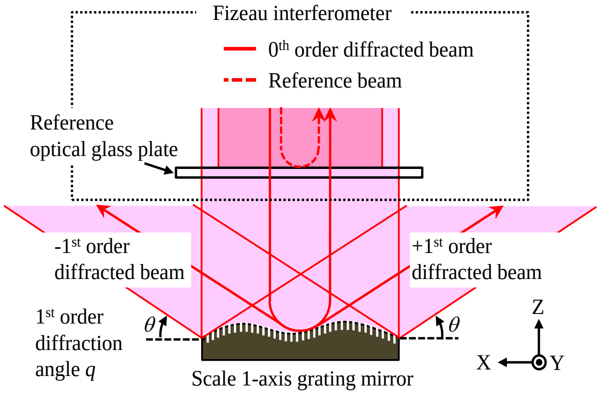


Fig. 3 Evaluation of the Z-directional out-of-flatness.

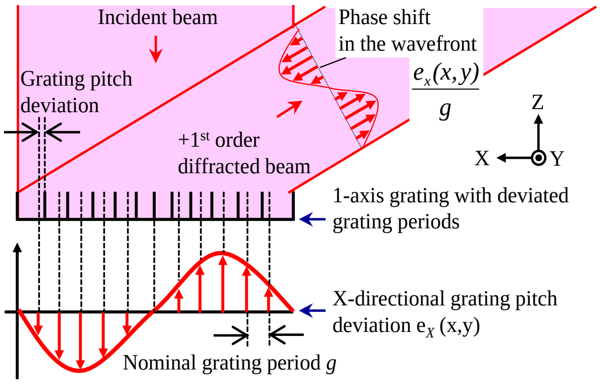
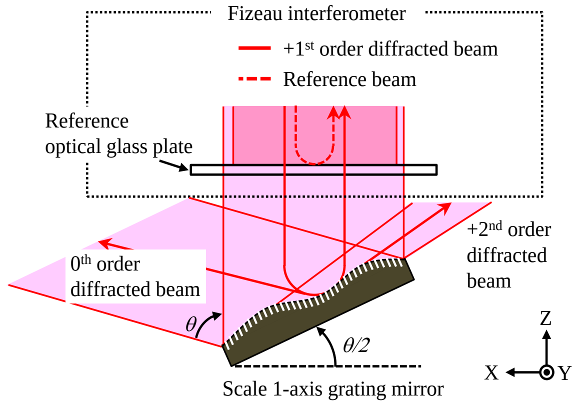
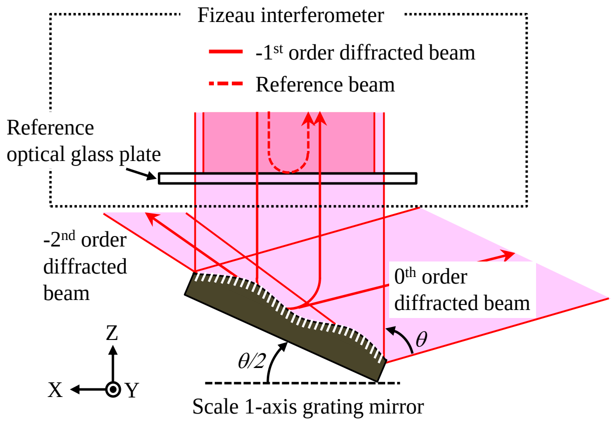


Fig. 4 Phase shift in the wavefront of the +1st-order diffracted beam caused by the pitch deviation.



(a) Measurement of the wavefront of the X-directional +1st-order diffracted beam



(b) Measurement of the wavefront of the X-directional -1st-order diffracted beam

Fig. 5 Evaluation of the X-directional pitch deviation.

scale 1-axis grating mirror is inclined to superimpose the X-directional +1st-order diffracted beams on the light beam from the reference optical glass plate of the Fizeau interferometer. The inclination angle is equal to half of the 1st-order diffraction angle. The wavefront of the -1st-order diffracted beam can also be measured by turnning the scale 1-axis grating mirror on the counter clockwise of $\theta/2$ as shown in the Fig. 5(b).

The X-directional ±1st-order phase outputs from the Fizeau interferometer $I_{X\pm 1}(x,y)$ can be expressed by:

$$I_{X+1}(x,y) = 2\pi \cdot \frac{e_X(x,y)}{g} + 2\pi \cdot \frac{2e_Z(x,y)}{\lambda} \cdot \cos\frac{\theta}{2} \tag{3}$$

$$I_{X-1}(x,y) = -2\pi \cdot \frac{e_X(x,y)}{g} + 2\pi \cdot \frac{2e_Z(x,y)}{\lambda} \cdot \cos\frac{\theta}{2} \tag{4}$$

where g and θ represent the nominal pitch of the scale 1-axis grating mirror and the ±1st-order diffraction angle, respectively. The X-directional pitch deviation $e_X(x,y)$ can be calculated as:

$$e_X(x,y) = \frac{g}{4\pi}\left\{I_{X+1}(x,y) - I_{X-1}(x,y)\right\} \tag{5}$$

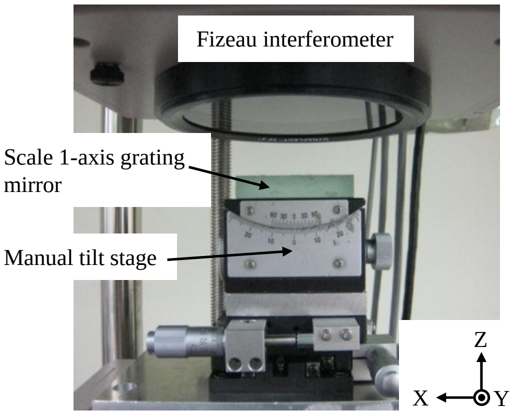
It should be noted that the inclination angles of the grating shown in Fig. 5 should be identical so that the term of $e_Z(x,y)$ in Eqs. (3) and (4) can be canceled in the operation shown in Eq. (5). The influence of the setting error of the inclination angle can be reduced by adjusting the manual tilt stage, on which the grating is mounted, to make the number of the interference fringes of the Fizeau interferometer minimum.

3. Experiments

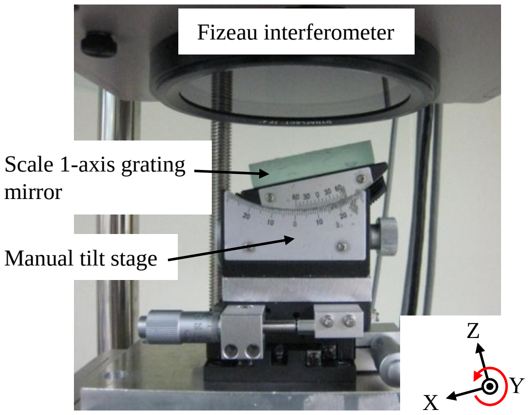
A commercial Fizeau interferometer, which had the wavelength of the 632.8 nm, was used in the experiment. The field of view of the interferometer was 100 mm in diameter. The resolution and accuracy of the Fizeau interferometer in the Z-axis were 0.05 nm and λ/20, respectively. The lateral resolutions in the XY-axes were 300 μm, which determines the measurement intervals of the wavefronts of the diffracted beams from the scale 1-axis grating mirror. A scale 1-axis grating mirror, which was fabricated with pitch of 1.67 μm in area of 45 mm x 45 mm, was used as the specimen. Fig. 6(a) and (b) shows the photographs when measuring the 0th order diffracted beam and the X-directional +1st order diffracted beam, respectively. Photographs showing other measurement procedures are omitted for clarity.

In each of the measurement, the inclination angle of the scale 1-axis grating mirror was adjusted by a manual tilt stage with the visual feedback from the fringe image of the Fizeau interferometer so that the influence of the setting error of the inclination angle could be removed. Fig. 7(a) shows the measurement result of the Z-directional out-of-flatness of a scale 1-axis grating mirror when measuring the 0th-order diffracted beam. Fig. 7(b) shows the measurement result of the X-directional pitch deviations when measuring the ±1st-order diffracted beam. The peak-to-valley values of the Z-directional out-of-flatness and the X-directional pitch deviations were 208 nm and 231 nm respectively. The out-of-flatness was mainly determined by that of the grating substrate. The pitch deviations were mainly caused by the fabrication process of the grating. It took approximately 3 minutes to finish all the measurements.

The results obtained by the proposed method were then verified by comparing them with the measurement errors of a 2-DOF linear encoder using the scale 1-axis grating mirror. Fig. 8 shows the experimental setup for evaluation of the measurement errors of the 2-

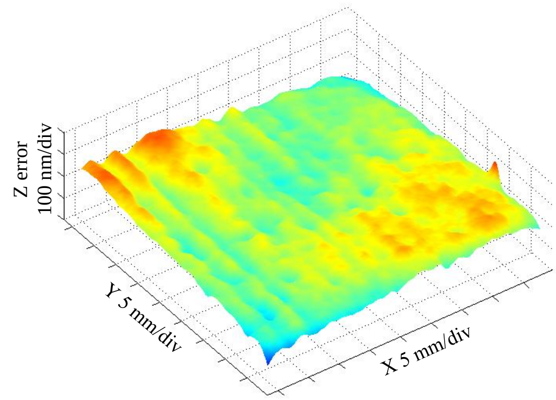


(a) 0th-order diffracted beam

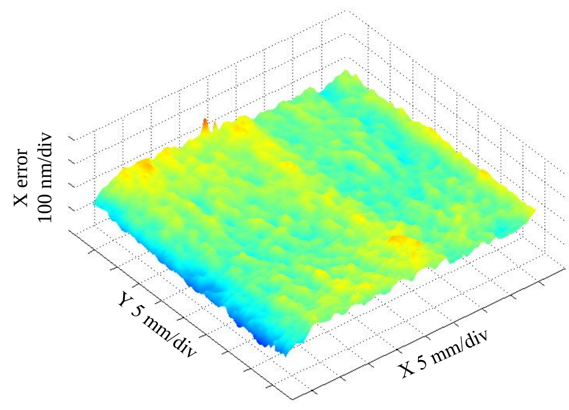


(b) +1st-order diffracted beam

Fig.6 Photographs of the measurement of the wavefronts of the diffracted beams.



(a) Z-directional out-of-flatness



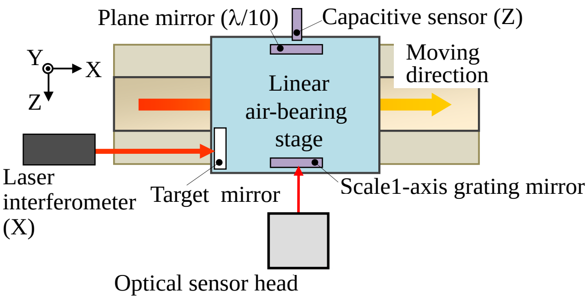
(b) X-directional pitch deviation

Fig. 7 Error maps of the scale 1-axis grating mirror.

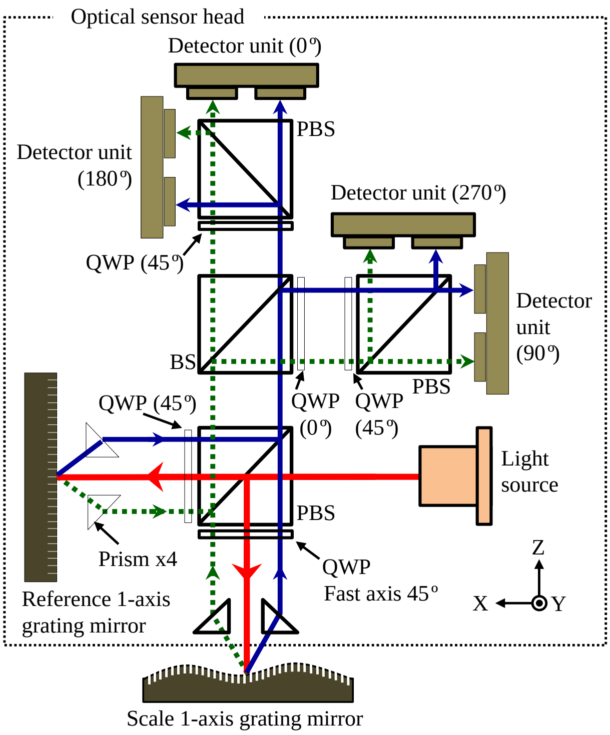
DOF linear encoder [5], which can measure not only X-directional displacement but also Z-directional out-of-straightness along the X-position of the linear air bearing stage. The laser interferometer (X) and the capacitive sensor (Z) were set to compensate X-directional displacement and Z-directional out-of-straightness of the linear air bearing stage with 2-DOF linear encoder. Fig. 9 shows the noise components in the compensated sensor outputs. The corresponding grating errors, which were extracted from the results shown in Fig. 9(a) and Fig. 9(b), are also plotted in the figures for comparison. It can be seen that the grating errors and the encoder errors had high correlations with each other, indicating that the grating errors are the main error sources of the encoder. Other factors influencing the accuracy of the encoder include assembling errors of optical elements in the optical sensor head, tilt error motions of the stage, which caused the differences between the grating errors and encoder errors shown in Fig. 9.

4. Conclusions

The Z-directional out-of-flatness and X-directional pitch deviation of the scale 1-axis grating mirror has been analyzed by using Fizeau interferometer in a short evaluation time. The X-and Z-directional error maps of the scale 1-axis grating mirror with a pitch of 1.67 μm



(a) Experimental setup



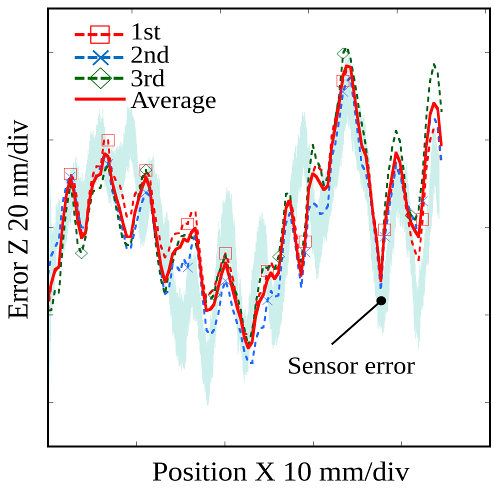
(b) Optical layout of the 2-DOF Linear encoder

Fig. 8 Experimental setup for evaluation of the measurement errors of the scale 1-axis grating mirror.

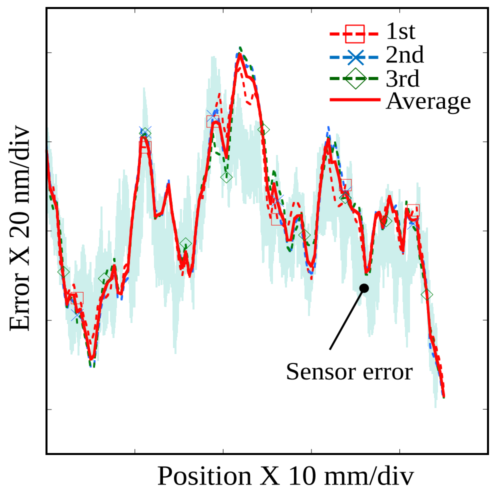
were obtained over an area of 45 mm x 45 mm. The evaluated grating has been employed in the 2-DOF linear encoder. Experimental results have confirmed that the measurement errors of the 2-DOF linear encoder were mainly caused by the corresponding errors of the scale 1-axis grating mirror.

REFERENCES

1. Linear encoder Catalogue, Heidenhain GmbH.
2. Steinmetz CR. "Sub-micron position measurement and control on precision machine tools with laser interferometry." Precision Engineering , Vol. 12, No. 1, pp.12-24, 1990.
3. Fizeau interferometer Catalogue, Zygo Corporation.
4. W. GAO, A. Kimura, "A fast evaluation method for pitch deviation and out-of-flatness of a planar scale grating," Annals of the CIRP, Vol. 59,No.1, pp.509-508, 2010.
5. Akihide Kimura, Wei Gao, Yoshikazu Ari, ZengLijiang, "Design and construction of a two-degree-of-freedom linear encoder for nanometric measurement of stage position and straightness," Precision Engineering, Vol. 34, No.1, pp.145-155, 2010.



(a) Out-of-flatness (Z-axis)



(b) Pitch deviation (X-axis)

Fig. 9 Comparison of the encoder errors with the grating errors