Concurrent measurement method for spindle radial, axial and angular motions using concentric grating interferometers
(2nd report: Performance evaluation of the optical sensor)

In this paper, we describe a concurrent measurement method for spindle radial, axial and angular motions using concentric circle grating interferometers. Three optical sensors, which consist of two interferometers, are fixed over the grating. One interferometer detects an interference signal between reflection lights from a fixed mirror and the grating for vertical displacement measurement. The other interferometer detects an interference signal between ±first order diffraction lights from the grating for lateral displacement measurement. From these measured displacements using three optical sensors, radial, axial and angular motions of the grating, i.e. the spindle, can be calculated concurrently.

1. Introduction
Conventional spindle motion errors measurement is error separation methods, which require artifact reference and displacement sensors, such as capacitive sensors. Radial motion error can be measured using a precise sphere or circular cylinder. 4-5. A concentric circle grating is also used for measuring the radial motion error. 6-9. The concentric measurement of radial, axial and angular motions can be realized using the reference artifact of two spheres linked with a bar 10. In a novel method for the concurrent measurement of five degrees of freedom spindle motion errors (=radial (2 degrees) + axial (1 degree) + angular (2 degrees)) using concentric grating interferometers, a concentric circle grating is installed on top of the spindle of interest, and it is used as the reference artifact. Three optical sensors are fixed above the concentric circle grating to observe the proper position of the grating. Because the concentric circle grating is not voluminous and not heavy, this method is effective for any spindle, and does not affect the spindle original rotational motion. Moreover, this method is suitable for maintaining the traceability against the meter definition because it uses laser interferometers.

2. Measurement Principle

![Fig.1 Basic principle of spindle motion errors measurement](image)

The basic principle of the proposed measurement method is shown in Fig.1. A concentric circle grating is set on the top side of the spindle of interest. Three optical sensors, A, B and C in the figure are fixed over the concentric circle grating, and observe the proper positions of the grating. The spindle rotation center must be almost aligned to the center of the concentric circle grating. In the figure, we assumed that the origin point is almost located at the center. The optical sensor A is set on the line along Y-axis, the optical sensors B and C are set on the line along X-axis.

![Fig.2 Schematic diagram of the optical sensor](image)

The optical sensor consists of a laser as a light source and two interferometers. The configuration of the optical sensor is shown in Fig.2. One interferometer observes an interference fringe between a reflection light from a fixed mirror (FM) and a 0th order diffraction light from the concentric circle grating. Another interferometer observes an interference fringe between +1st and -1st order diffraction lights from the concentric circle grating. In Fig.2, the output signals from vertical and lateral displacement is represent by

\[
I_{ax} (\Delta x, \Delta z) = E_1^\prime + E_2^\prime + 2E_1E_2 \cos \left[ \frac{4\pi}{\lambda} \left( \Delta z + \sqrt{\Delta x^2 + \Delta z^2} \tan \theta \right) \right] + L \left(1 - \sqrt{\tan^2 2\theta + 1}\right) \tag{1}
\]

\[
I_{ay} (\Delta x, \Delta z) = E_3^\prime + E_4^\prime + 2E_3E_4 \cos \left[ \frac{2\pi}{\lambda} \Delta z (\cos \theta_1 - \cos \theta_2) \right] + \frac{4\pi}{d} \Delta x \tag{2}
\]

where; \( E_{1,4} \), \( E_{2,3} \), \( \theta_1 \) and \( L \) are the amplitude of ±1st-order diffraction electrical field, the initial phase, the incident angle and the distance between the grating and PD1 and PD2, \( E_{1,2}, E_{3,4}, \theta_1, \theta_2, \theta_1, \theta_2 \) are the amplitude of the light reflected from FM and the
grating electrical field, the initial phase and ±1°-order diffraction angle, Δx, Δy and Δz are the displacement shift of the grating along the X-, Y- and Z-axes, d is the grating pitch and λ is the wavelength of the light source, respectively.

Equations (1) and (2) contain errors arising from the small incident angles θ2. However, the contributions from θ2 can be neglected in the case of the ultra precise spindle measurement. If λ = 633 nm, d = 2 μm, θ2 < 10 arcsec and Δz < 1 μm, then (2πλΔz) ≤ 10−1 order. This value is the same as Δx ≤ 50 pm; therefore, it can be neglected. For the condition of (λ = 633 nm, θ2 < 10 arcsec, √Δx2 + δy2 < 1 μm and L = 20 mm), the contributions from √Δx2 + δy2 tan 2θ2 and L(1 − √δz2 + δx2 + 1) in equation (1) are 90pm and 90pm, respectively; therefore, they can also be neglected. The output signals (IPD1, IPD2, IPD3 and IPD4) from photo diode PD1, PD2, PD3 and PD4 can be expressed as follows,

\[ I_{PD1} = E_{x1} + E_{y1} + 2E_xE_y\cos\left(\frac{4\pi x}{\lambda}\right) \]  
(3) \[ I_{PD2} = E_{x1} + E_{y1} + 2E_xE_y\sin\left(\frac{4\pi x}{\lambda}\right) \]  
(4) \[ I_{PD3} = E_{x2} + E_{y2} + 2E_xE_y\cos\left(\frac{4\pi y}{\lambda}\right) \]  
(5) \[ I_{PD4} = E_{x2} + E_{y2} + 2E_xE_y\sin\left(\frac{4\pi y}{\lambda}\right) \]  
(6)

From the optical sensor A, the lateral (yB) and the vertical (zB) displacements can be measured. From the optical sensors B and C, the lateral (xB and xC) and the vertical (zB and zC) displacement can be measured. Radial \( R_x \), \( R_y \), axial \( R_z \) and angular \( \theta_x \), \( \theta_y \), \( \theta_z \) motions can be derived from

\[ R_x = \frac{1}{2}(x_B + x_C) \]  
(7) \[ R_y = y_B \]  
(8) \[ R_z = \frac{1}{3}(z_B + z_A + z_C) \]  
(9) \[ \theta_x = \frac{1}{R}\left[z_z - \frac{(z_B + z_C)}{2}\right] \]  
(10) \[ \theta_y = \frac{2}{R}\left[(z_B - z_z)\right] \]  
(11) \[ \theta_z = \frac{1}{3}(R_x + R_y + R_z)\right] \]  
(12)

where \( R \) is the averaged distance of the interferometers A, B and C from the center, \( R_x \), \( R_y \) and \( R_z \) is the distance of the interferometers A, B and C from the center.

3. Preliminary experiment and discussion

3.1 Performance evaluation of the optical sensor

![Fig.3 Experimental setup](image)

In order to confirm the equation (1) - (4), and evaluate the optical sensors performance, we constructed the grating interferometer as shown in Fig.3. In the experiment, the concentric circle grating with a pitch of 2μm was set on the XZ axes PZT stage. A He-Ne laser (wavelength 633nm) was applied to the interferometer as a light source. Photodiodes PD1 and PD2 were detected the interference signal of vertical displacement when PZT was moved along the Z-axis, and photodiodes PD3 and PD4 were detected the interference signal of lateral displacement when PZT was moved along the X-axis, respectively. Figures 4 and 5 show the phase quadrature interference signal and Lissajous diagram of vertical and lateral displacements.

![Fig.4 Phase quadrature interference signal and Lissajous diagram from vertical displacement](image)

Fig.4 Phase quadrature interference signal and Lissajous diagram from vertical displacement

![Fig.5 Phase quadrature interference signal and Lissajous diagram from lateral displacement](image)

Fig.5 Phase quadrature interference signal and Lissajous diagram from lateral displacement

3.2 Crosstalk error estimation

In order to estimate term of the crosstalk error in the equation (1) and (2) for the ultra precise spindle measurements, we have plot graph relationship between Δz and Δx due to incident angle changed, which is shown in Fig.6. The crosstalk error can be neglected when the incident angle is less than 10arcsec.

![Fig.6 Relationship between Δz and Δx due to the incident angle](image)

Fig.6 Relationship between Δz and Δx due to the incident angle

The experimental and estimation results show that this method can measure the displacement of the grating with nanometer resolution without the crosstalk error. We can apply vertical and lateral displacements of three optical sensors for measurement radial, axial and angular motions of the spindle.

References
6) E.R. Marsh, Precision Spindle Metrology, (2008), P.120.