Investigation of an optical sensor for small angle detection

Yusuke Saito, Yoshikazu Arai and Wei Gao
Nano-Metrology and Control Lab
Department of Nanomechanics
Graduate School of Engineering, Tohoku University
Sendai, 980-8579, Japan
Tel.: & Fax: +81-22-795-6953 E-mail: saito@nano.mech.tohoku.ac.jp

Abstract
In this article, we describe the evaluation result of the characteristics of the angle sensor based on laser autocollimation method especially focused on the result about the evaluation of the relationship between the sensor sensitivity and measurement point of the target. The sensor consists of a laser diode (LD) as the light source, and a quadrant photo diode (QPD) as the position-sensing detector, and it requires a light-reflecting flat surface like a small plane mirror as a target. This optical system has advantages of high sensitivity, high resolution, quick response and the ability for 2-axis angle detection. Generally, the angle sensor only responds angular displacement of the target mirror, so the characteristics of the angle sensor such as sensor sensitivity are not influenced by the position of the target even if the target moves along with the optical axis. On the other hand, the sensor sensitivity could be changed according to the position of the target. Main error components that influence the sensor sensitivity are proposed and the optimal conditions of the optical system of the sensor are analyzed. The experimental result about evaluation of the working distance is also presented.

Keywords: Laser autocollimation method, sensor sensitivity

1. Introduction
Recently, precision components such as precision optical elements and semiconductor are widely used and this encourages the progress of the precise motion control. The key component of such precise motion system is the ultra-precision stages which are often applied in precision machine, semiconductor manufacturing machine and precision inspection device, etc. Therefore, the measurement of movement errors of the stages is essential for evaluating the performance of those machine tools.

The movement errors of the stage can be expressed as the positioning error and translational motion error (straightness) along the moving direction. The former error can be measured by using the laser interferometer or linear encoder, and the latter one is usually measured based on the straightedge. Additionally, the positioning error includes the angular motion errors that exist to cause unexpected Abbe-errors.

The simple way for measuring simultaneous two-axis angular motion errors such as pitch ($\Delta \theta_Y$) and yaw ($\Delta \theta_Z$) is feasible by using the laser autocollimation method with two-dimensional position-sensing detector [1, 2]. Since this method has the advantages of high sensitivity, quick response and high resolution, it can be satisfy the key requirements for applying to the ultra-precision profile measurement such as flatness measurement of large silicon wafers [3]. And this method can be applied for measuring the dynamic angular motion errors such as precision stages because of its fine measurement capability. For the purpose of measuring the angular motion errors precisely, it is necessary to evaluate the working distance of the angle sensor which determined as the distance between the angle sensor and the target reflector.
2. Principle of the angle detection

Fig. 1(a) shows the schematic view of the laser autocollimation method. The LD is used as a light source. When the target mirror has inclination angle $\Delta\theta_Y$, the corresponding optical spot displacement is occurred on the focal plane of the objective lens. The relationship between the incident angle $2\Delta\theta_Y$ and the optical spot displacement $\Delta d_{v,0Y}$ is expressed by the following equation:

$$\Delta\theta_y = \arctan\left(\frac{\Delta d_{v,0Y}}{2f}\right) \approx \frac{\Delta d_{v,0Y}}{2f}$$

where $f$ is the focal length of the objective lens, the $\Delta\theta_Y$ and the $\Delta d_{v,0Y}$ are assumed to be very small in the Eq. (1). It is possible to calculate the change of the tilt motion of the target mirror just by detecting the change of the spot position $\Delta d_{v,0Y}$ on the focal plane. As can be seen in this figure, the QPD is adapted as the position-sensing detector, so this optical system is able to measure two-directional angular displacements simultaneously.

Fig. 1(b) shows the schematic of the spot behavior on the QPD cells when the angle has changed. Assuming the laser beam has a circle shape and a Gaussian distribution of intensity, the spot size on the QPD can be obtained as follow equation [4]:

$$r_0 = K_f \frac{f\lambda}{D_i}$$

where $D_i$ and $r_0$ are the beam diameter and optical spot diameter defined as a full width at 1/e$^2$ maximum value (FW1/e$^2$M) of the beam intensity. And $f$ is the focal length of the objective lens and $\lambda$ is the wavelength of the LD. The $K_f$ is a Gaussian beam truncation ratio [4] and can be derived by the ratio of beam diameter and aperture size of the objective lens.

The QPD has insensitive area (gap) between PD cells in H and V directions. Now assuming there is only H-directional gap, the photocurrent of each PD cells are proportional to the optical spot receiving area on each PD cells, and the current conversion sensitivity of each PD cells will also be constant. Output from the QPD $Y_{out}$ can be expressed as follow equation:

$$Y_{out} = \frac{(I_A+I_B)-(I_C+I_D)}{I_A+I_B+I_C+I_D} \times 100\% = \frac{(S_A+S_B)-(S_C+S_D)}{S_A+S_B+S_C+S_D} \times 100\%$$

where $I_A$, $I_B$, $I_C$, and $I_D$ are the photocurrent of each PD cells, and $S_A$, $S_B$, $S_C$ and $S_D$ are the optical spot receiving area of each PD cells. Dividing by the total output value can compensate for the change in the intensity of incident light. When the target mirror has inclination angle of $\Delta\theta_Y$, the optical spot displacement $\Delta d_{v,0Y}$ occurs coincidentally on focal plane of the objective lens as expressed in Eq. (1). The difference between incident spot areas of cells A, B and C, D can be approximately expressed as $4r_0\Delta d_{v,0Y}$. Moreover, the entire area of an optical spot is $\pi r_0^2 - 4r_0g$, so the Eq. (3) can be rewritten as follows:

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(a) Principle of the laser autocollimation method

(b) Optical on the QPD ($\Delta d_{v,0Y}$-direction)

Fig. 1. Geometrical model for optical angle detection.
The sensitivity of the angle sensor $S_{\theta_Y}$ can then be roughly approximated as the ratio of incident angle $\Delta\theta_Y$ and sensor output $Y_{out}$, and is expressed as follow equation:

$$S_{\theta_Y} = \frac{Y_{out}}{\Delta\theta_Y} = \frac{8}{\pi} \sqrt{\frac{K \lambda}{D_t} - \frac{4g}{\pi f}} \times 100\%$$

(5)

It can be found that the sensitivity could be influenced by the gap size of the QPD, and the larger the gap size $g$ is, the higher sensitivity $S_{\theta_Y}$ can be obtained. On the other hand, it worth noting that the enlargement of the gap size reduces the optical spot receiving area on each PD cells, and it causes the decrease of signal/noise ratio of the sensor signal output.

3. **Analysis about the relationship between sensitivity and working distance**

A 2-axis angle sensor for evaluation of its fundamental output characteristics has been fabricated. Fig. 4 shows an example of the experimental setup for evaluation of the sensor sensitivity and its working distance. In this sensor, laser beam is emitted from LD and collimated through the collimate lens and $\phi2$ mm aperture. Then after being reflected by the plane mirror mounted on the 2-axis PZT driven tilt stage, the laser beam goes through the objective lens (triplet lens with $f = 25.4$ mm) and focused on the focal plane, forms a optical spot there. And the QPD with $10 \mu m$ gaps is used as its position-sensing detector. The target mirror can generate 2-directional tilt angular motions ($\Delta\theta_Y$, $\Delta\theta_Z$), and these motions are detected by the angle sensor and commercial autocollimator (PA102S, Nikon Corp.), simultaneously. The analog output from the commercial autocollimator is used as the angle reference for evaluation of the output of the angle sensor.

Fig. 2 shows the experimental result about output of the angle sensor. In this experiment, the sinusoidal signal is applied to drive the tilt stage, and the sensor outputs at different measurement point are evaluated. In Fig. 2, the horizontal axis is the applied angles measured by the commercial autocollimator and the vertical axis is the outputs from the angle sensor. The two sensor outputs ($x = 150$ mm, 350 mm) are linearized and the fitting line are plotted in
±15 arc-seconds measurement range. The sensor sensitivities are expressed as the inclination of the fitting lines. From this experimental result, the sensor sensitivity could be changed about 10% according to the position of the target mirror, i.e., the sensor output is influenced by the target movement. As expressed in Eq. (4), the sensor output is affected by the displacement $\Delta Y$ and the size of the optical spot on the QPD cells. So the main components affects the sensor output are analyzed. Fig. 3 shows the schematic diagram of the error components. The collimated Gaussian laser beam propagates through the air toward X-direction has the beam spreading because of the diffraction effect. The beam diameter $D_1$ at a measurement position $x$ is expressed as follow equation:

$$D_1(x) = D_0 \sqrt{1 + \left( \frac{8 \lambda x}{\pi D_0} \right)^2}$$  \quad (6)

where $D_0$ and $D_1$ are the FW1/e²M beam diameter, and the beam waist $D_0$ is assumed to be on the open end of the collimate lens. From Eq.(2) and Eq. (6), the diameter of the optical spot could be changed at different measurement position $x$. And another component is the defocus amount $\Delta x$. The spot displacement $\Delta d_1$ on the defocus plane is expressed as:

$$\Delta d_1(x, \Delta x) = \left( f + \frac{\Delta x}{f} \right) \tan(2\Delta \theta_x) \approx 2f'\Delta \theta_x$$  \quad (7)

When $x > f$ is effective, this component works for increasing / decreasing the output of the angle sensor depends on the sign of the $\Delta x$. Additionally, the optical spot is also enlarged by $\Delta x$. From Eq. (6), the enlarged optical spot size $r_1$ is calculated as follow equation:

$$r_1(x, \Delta x) = r_0(x) \sqrt{1 + \left( \frac{4 \lambda \Delta x}{\pi r_0(x)^2} \right)^2}$$  \quad (8)

The enlargement of the spot size $r_1$ against the gap size $g$ increases the optical spot receiving area on each PD cells, so the signal/noise ratio of the sensor signal output also improves. The sensor sensitivity $S_{\theta Y1}$ based on these two error components is calculated by substituting Eq. (7) and Eq. (8) to Eq. (4):

$$S_{\theta Y1}(x, \Delta x) = \frac{8 f'\Delta \theta_x}{\pi r_1(x, \Delta x)^2} - 4g$$  \quad (9)

The computer simulation has carried out to estimate the influence of these components and find the optimal optical conditions that minimize the change of the $S_{\theta Y1}$ against the measurement position of the target mirror. The simulation conditions are shown in Table 1. In this simulation, the optical system is an aberration-free system, the beam shape assumed to be a circle and only consider about Gaussian beam propagation (TEM₀₀ beam mode). The sensor sensitivities $S_{\theta Y1}$ at each measurement position ($x = 0$ mm - 500 mm) are calculated and took the average under the different combination of the optical conditions shown in Table 1. The deviation from the average sensitivity is determined as $V_{am,d}$. Fig. 5 shows the simulation result. The horizontal axis shows the defocus amount $\Delta x$ and vertical axis is the deviation $|V_{am,d}|$. The optical conditions are chosen as $f = 50.0$ mm, $g = 5$ μm, measurement range is ±15 arc-seconds and other conditions are same as shown in Table 1. From this result, when the initial beam diameter $D_0$ is larger, the influence of the beam spreading expressed Eq. (6) becomes smaller, and the influence of the defocus amount $\Delta x$ may dominate the change of the sensor sensitivity. When the initial beam diameter $D_0 = 3.0$ mm, the deviation $|V_{am,d}|$ is under 0.3 % over the range of $\Delta x$ from -100 μm to +100 μm. This result also indicates the tolerance of the QPD positioning is high when large $D_0$ is chosen for the initial diameter.
Table 1. Simulation conditions.

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<tbody>
<tr>
<td>Focal length of the objective lens</td>
<td>( f = 25.4 \text{ mm}, 50.0 \text{ mm}. )</td>
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<tr>
<td>QPD gap size and active area</td>
<td>Gap size : 5 ( \mu \text{m}, 10 \mu \text{m}. ) Active area : 150 ( \mu \text{m}\times150 \mu \text{m}. )</td>
</tr>
<tr>
<td>Condition of the incident beam</td>
<td>( D_0 : 1 \text{ mm}, 2 \text{ mm}, 3 \text{ mm}. ) ( \lambda : 633 \text{ nm}. )</td>
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<tr>
<td>Position of the target mirror</td>
<td>( X : 0 \text{ mm} - 500 \text{ mm} ) (calculation of each 50 mm).</td>
</tr>
<tr>
<td>Defocus amount</td>
<td>( \Delta x_1 : -100 \mu \text{m} - +100 \mu \text{m} ) (calculation of each 50 ( \mu \text{m}. )</td>
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4. Experimental results and discussion

Another angle sensor for evaluation of the sensor sensitivity against the measurement position is fabricated based on simulation results. To minimize the influence of the beam spreading, the \( \phi 2 \text{ mm} \) aperture is consisted before the objective lens. Fig. 6 shows the experimental results of sensor sensitivity about each direction. The average sensor sensitivity and the deviation are 3.19 \%/arc-seconds and 0.927 \% in \( \Delta \theta_Y \) direction, and 3.26 \%/arc-seconds and 2.02 \% in \( \Delta \theta_Z \) direction, respectively. The repeatability of this experiment is about 2 \%, so the deviation \(|V_{\text{am,d}}|\) is reduced as same level as repeatability.

5. Conclusion

The relationship between the sensor sensitivity and measurement point of the mirror is analyzed and discussed based on Gaussian beam propagation. The geometrical analysis and simulation result indicate that the influence of the beam spreading becomes smaller by large initial beam diameter \( D_0 \). And the defocus amount \( \Delta x_1 \) plays a roll for increasing / decreasing the sensor sensitivity. The design tolerance for positioning the QPD is also estimated by using the parameter \( \Delta x_1 \). Then another angle sensor is fabricated based on simulation results. From the experimental result, the deviation \(|V_{\text{am,d}}|\) is reduced up to 2 \%.

6. Acknowledgements

This research is financially supported by Grant-in-Aid for JSPS Fellows.

References