Optical diffractometer using area cameras for detection of diffraction beam positions and alignment of grating standards

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Abstract. The performance of an optical diffractometer (OD) was improved using an area camera and two alignment imaging systems. Since the area camera detected diffraction beam positions with higher dynamic range than a quadrant photodiode, the OD could measure the accurate positions of high-order ones having low intensity. The imaging systems enabled us to align the grating specimen and the rotation axis of the rotary table efficiently. Through experiments and uncertainty analysis, we showed improvement of the KRISS OD and evaluated the misalignment effect. When a 1D grating standard (pitch: 3000 nm) was measured, the expanded uncertainty (k=2) was less than 0.06 nm and a laser source having higher wavelength accuracy would be required to reduce the measurement uncertainty further.

1. Introduction

In nano-metrology, grating standards have been widely used to calibrate magnification of precision microscopes, such as a scanning electron microscope (SEM) and a scanning probe microscope (SPM). Therefore, they have a critical role to disseminate the meter-traceability in nanometre range. Two supplementary key-comparisons were also completed to check measurement capability of the national metrology institutes (NMIs) in calibration of 1D and 2D grating standards. Although precision microscopes adopting a metrological frame can measure both individual and average pitch values of grating standards, an optical diffractometer (OD) has been used as a main standard instrument for calibration service of grating standards in many NMIs, since average pitch value can be obtained with higher accuracy [1-4].

The Korea Research Institute of Standards and Science (KRISS) also developed an OD in the early of 2000, but it required two critical improvements [1]. One is detection of the diffraction beam position and the other is alignment of a specimen position. Since a quadrant photodiode, which was employed for detecting the diffraction beam position in the KRISS OD, had limited dynamic range, it could not measure the high-order diffraction beam having much lower intensity compared to the 0th-order one. Therefore, in the measurement of the grating standards having several micrometres pitch or the 2D gratings, we could not use large diffraction angle to decrease the measurement uncertainty. It was reported that measurement error occurred when the grating surface was not placed at the rotation axis during diffraction angle measurement [4]. Therefore, we need a new tool to check alignment condition of the grating with high confidence.

This paper presents performance improvements of the KRISS OD in the respect of measurement uncertainty and reliability. We explained the construction of the new KRISS OD shortly, and proved feasibility of the proposed methods through several experiments.

2. Optical diffractometer

The schematic of the KRISS OD is shown in Fig. 1. It uses two laser sources, which are a He-Cd (λ=325 nm) and a He-Ne (λ=633 nm) lasers, to extend measurable pitch range down to 180 nm and
also obtain more confident measurement results by comparing the pitch values measured using different laser sources. The other main components are several optical components adjusting the direction and size of the incident beam, a precision rotary table rotating a grating specimen, an area camera detecting the diffraction beam position, and two imaging systems for alignment of the specimen position.

Fig. 1. Schematic of the KRISS optical diffractometer for calibration of grating standards.

The laser beam was incident on a grating through an attenuator, a collimation lens (CL1), and a wedged beam-splitter. The incident beam was slightly focused on the specimen to reduce the beam size by adjusting the position and the focal length of the lens (focal length: 1000 mm). Using two tilting mirrors (M3, M4), the propagation direction of the incident beam was aligned to be perpendicular to the rotation axis and pass through the rotation center of the rotary table. Two laser sources could be switched easily using a tilt mirror (M2) attached on a magnetic indexing mount.

While rotating the specimen using the rotary table, the diffraction angle $\theta_d$ was acquired when the Littrow condition is satisfied, where the diffraction beam direction coincided with that of the incidence beam. To determine the Littrow condition accurately, an area camera was used as a null detector, and the center position of the diffraction beam was calculated using the center-of-gravity method. The camera was placed at the focal point of the collimation lens (CL2), of which focal length is 500 mm, to sense the diffraction angle accurately by satisfying the auto-collimating condition. In the beam position measurement, the area camera could obtain higher linearity and dynamic range than the quadrant photodiode by adjusting the gain and gate time of the camera automatically. The pitch value $p$ at 20 $^\circ$C is calculated using the well-known grating equation as

$$p = \frac{m \lambda}{2 n \sin \theta_i} [1 - \alpha(t - 20)],$$

where, $m$ is the diffraction order, $\lambda$ is the vacuum wavelength of the laser source, $n$ is the refractive index of air, $\alpha$ is the thermal expansion coefficient, and $t$ is the temperature of the grating.

For accurate diffraction angle measurement, the surface of the specimen was placed at the rotation center exactly using two imaging systems, since the misalignment causes serious measurement error [4]. Using the Imaging System1, we could monitor movement of the specimen, and align the specimen position in the X- and Z-axis to be stationary during the rotation. The specimen position in the Y-axis was also adjusted using the image acquired by the Imaging System2.

3. Experiments
To evaluate the performance of the KRISS OD, we measured a 1D grating standard having the nominal pitch of 3000 nm, and investigated variation of measured values due to misalignment in the direction of the Z-axis. When the grating surface was aligned with the rotation axis of the rotary table, the centre point of top edge line kept stationary during the rotation from 0 to 90 degrees as shown in Fig. 2(a). To satisfy this condition, we adjusted the position of the specimen in the X- and Z-axis.
iteratively monitoring the imaging system 1. The Y-axis position was aligned by checking the beam position on the specimen using the imaging system 2.

Using the He-Ne laser source, the diffraction beams could be obtained up to the 9th-order, and the diffraction angles were measured 10 times repeatedly after alignment of the specimen position. Since the \( \sin \theta_d \) term has linear relation with the diffraction order \( m \) as shown in Eq. (1), we estimated the performance of the KRISS OD using a linear regression between these terms. In Fig. 2(b), the analysis result showed highly linear relation \( (R^2 = 0.99999999915) \), and the residues were less than \( 1.5 \times 10^{-5} \).

\[
Y = 0.105471643386 \times -0.000000418735
\]

\[ R^2 = 0.999999999915 \]

![Fig. 2. (a) Images for the specimen alignment captured by the imaging system 1 at 0 and 90 degrees positions; (b) Linear regression of the \( \sin \theta_d \) term and the diffraction orders (error bars: standard deviations of the residues).](image)

Figure 3(a) shows variations of the measured pitch values for different diffraction orders, when the specimen position was misaligned intentionally in the Z-axis direction for \( \pm 0.5 \text{ mm} \). As the diffraction order increased, the standard deviations of the repeated measurements decreased, but the measured pitch values were deviated more largely due to the misalignment of the specimen position. These results were caused by the fact that the misalignment effect became eminent when the effective area of the specimen was deviated from the incident beam and the effective area increased as the increment of diffraction angle [4].

\[
d\theta \sin \theta_d = 0.105471643386 \times -0.000000418735
\]

\[ R^2 = 0.999999999915 \]

![Fig. 3. (a) Variations of the measured pitch values for multiple diffraction orders when the grating specimen was misaligned in the Z-axis (error bar: 1\( \sigma \)); (b) Pitch values of various diffraction orders calculated by averaging the results of the plus and minus diffraction orders.](image)

The uncertainty in the measurement of 1D grating can be evaluated according to the Guide to the Expression of Uncertainty in Measurement (GUM), and it is composed of several uncertainty sources as shown in Table 1. The expanded uncertainties \( (k=2) \) decreased from 0.12 nm to 0.055 nm according to the increment of diffraction order. In the low diffraction order case, the diffraction angle
measurement was a main uncertainty source, but its contribution decreased as the diffraction order increased. Therefore, for the 9th diffraction order, the measurement uncertainty was mainly caused by wavelength of the laser, and so the laser source should be replaced with a wavelength stabilized one to reduce the measurement uncertainty further.

Table 1. Uncertainty budget in the pitch measurement of 1D grating ($p = 3000$ nm) using the He-Ne laser source in the case of two diffraction orders ($m = 1, 9$).

| Source of uncertainty                     | Contribution ($m = 1$) | Contribution ($m = 9$) |
|-------------------------------------------|------------------------|------------------------|
| Vacuum wavelength of laser, $\lambda$    | 0.026 nm               | 0.026 nm               |
| Refractive index of air, $n$              | 0.002 nm               | 0.002 nm               |
| Readout of the rotation stage, $\theta_d$| 0.042 nm               | 0.015 nm               |
| Repeatability of angle measurement, $\theta_r$ | 0.021 nm           | 0.001 nm               |
| Thermal expansion coefficient, $\alpha$  | 0.009 nm               | 0.009 nm               |
| Temperature, $t$                          | 0.001 nm               | 0.001 nm               |
| Repeatability of pitch measurement       | 0.019 nm               | 0.002 nm               |
| Expanded uncertainty*(k=2)               | 0.12 nm                | 0.055 nm               |

*Level of confidence of approximately 95 %

Since the high-order diffraction beam positions could be measured accurately using the area camera having higher dynamic range than the quadrant photodiode, the pitch values were obtained with smaller uncertainty. This would be applied effectively also to the measurement of 2D gratings where each diffraction beam has low intensity. Among various alignments issues in the OD, the misalignment between the specimen and the rotation axis was reported as a critical uncertainty source, since it caused the first-order effect while other factors such as the specimen rotation about the x-, y, and z-axis were analyzed as the second-order ones [4]. Therefore, the imaging systems enabled us to align the specimen position efficiently and to increase reliability by checking the alignment condition precisely.

4. Conclusions

The performance of the KRISS OD was improved by replacing the quadrant photodiode with the area camera and employing two imaging systems. The area camera had higher dynamic range so that it could measure the positions of diffraction beams accurately even with large intensity difference. Using the images of specimen obtained by two imaging systems, the specimen surface and the rotation center of the rotary table could be aligned precisely. We measured a 1D grating standard of 3000 nm pitch to evaluate the performance improvement and the effect of misalignment. The improved system could detected the positions of all diffraction beams successfully, and the expanded uncertainty (k=2) was less than 0.06 nm. Through the precise alignment, we could reduce uncertainty source causing the measurement error of up to 0.15 nm in case of the misalignment of 500 $\mu$m. Therefore, the new KRISS OD can be used as an effective instrument for disseminating meter-traceability in nanometer range.

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