An Optical Head with Littrow Configuration for Measurement of the Pitch Deviation of a Diffraction Grating

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A method that utilizes positive and negative diffracted beams to measure pitch deviation in diffraction gratings demonstrates significant potential. However, conventional theory cannot measure pitch deviation when the grating's nominal pitch is narrower than the laser wavelength. In this paper, a new optical setup designed to overcome this limitation is presented. The setup uses laser autocollimation units to detect the diffraction angle of the first-order diffracted and reflected beams in a Littrow configuration. By applying arithmetic operations, pitch deviation can be evaluated while minimizing the effects of angular error and local slope in the grating. The basic characteristics of the setup have been evaluated using a grating with a nominal pitch of 556 nm and a laser with a wavelength of 785 nm.

1. Introduction

Precision positioning technology is becoming increasingly critical in various fields [1]. Optical linear encoders are indispensable for achieving ultra-precision positioning. These encoders rely on diffraction gratings as the measurement standard for length. Therefore, the accuracy of the grating pitch is crucial for maintaining the required precision. Conventional methods for evaluating scale gratings have several limitations. As a result, there is a need to develop techniques that can accurately measure pitch deviation. For this purpose, a method utilizing highly sensitive optical angle sensors based on laser autocollimation has been proposed to evaluate pitch deviation in scale gratings [2]. In this method, changes in the angles of positive and negative first-order diffraction beams are simultaneously captured. However, this approach is limited in its effectiveness when the grating pitch is narrower than the laser wavelength.

In this paper, we propose a theoretical extension of the conventional measurement method described above. The extended principle employs a laser beam made incident obliquely on the scale grating to obtain both the first-order diffracted beam and the reflected beam. These beams are captured by a pair of laser autocollimation units so that the evaluation of pitch deviation can be isolated from the influences of angular error motion and the local slope of the scale. The design and construction of the prototype optical system based on this extended principle, and some experimental results are reported.

2. Principle for measuring the pitch deviation

In the proposed method, A laser beam with wavelength λ is directed at a diffraction grating with a nominal pitch g in a Littrow configuration, where the incident angle θ_I equals the diffraction angle θ_D. The pitch deviation of the diffraction grating is evaluated by measuring the angular changes of the first-order diffracted beam and the reflected beam. Figure 1 illustrates a schematic diagram showing the changes in diffracted and reflected beams. If a pitch deviation $\Delta g(x)$ occurs in the pitch of the diffraction grating, the angle of the diffracted beam will shift by $\Delta\theta_g(x)$. Additionally, during scanning, local tilt errors $\Delta\theta s(x)$ of the scale grating and angular errors $\Delta\theta_R(x)$ of the stage may occur. Therefore, taking these factors into account, the diffraction grating equation can be expressed as follows [2]:

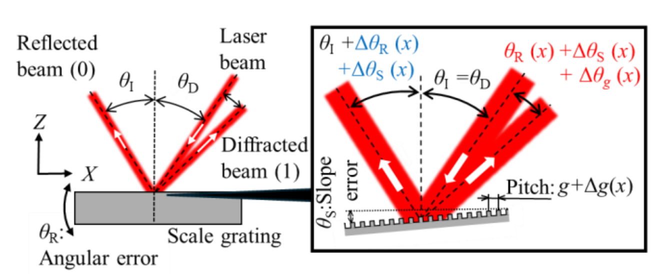


Fig. 1 Schematic diagram of the variations in the diffracted and reflected beam including local slope error and angular error

$$(g+\Delta g(x))\begin{bmatrix}\sin(\theta_\mathrm{I}+\Delta\theta_\mathrm{R}(x)+\Delta\theta_\mathrm{S}(x)) \\ +\sin(\theta_\mathrm{I}-\Delta\theta_\mathrm{R}(x)-\Delta\theta_\mathrm{S}(x)+\Delta\theta_g(x))\end{bmatrix}=\lambda \qquad (1)$$

The angular change caused by errors or pitch deviation is observed as a combined angular change in both the diffracted and reflected beams. Therefore, $\Delta\theta_\mathrm{I}(x)$ and $\Delta\theta_\mathrm{D}(x)$ represent the angular changes of the diffracted and reflected beams, respectively. By transforming Eq. (1), the following equation is obtained:

$$\Delta g(x)\cong\frac{\lambda}{\sin\left(\frac{\lambda}{g}+\frac{\Delta\theta_\mathrm{I}(x)-\Delta\theta_\mathrm{D}(x)}{2}\right)}-g \qquad (2)$$

By simultaneously analyzing the changes in reflection and diffraction angles, it is possible to detect the pitch deviation according to Eq. (2), thereby mitigating the effects of local slope and angular motion errors of the grating.

3. Development of the optical head and Experiment

3.1 Construction of measurement optical head

To evaluate the viability of the new method for measuring pitch deviations in scale gratings, a modified prototype optical system was developed and constructed. Basic experiments were conducted to evaluate the system's functionality. A photograph of the constructed optical system is presented in Fig. 2. This setup utilized a single-frequency semiconductor laser with a wavelength of 785 nm as the laser source. The laser was passed through an isolator, a polarizing beam splitter (PBS), a half-wave plate (HWP), and a quarter-wave plate (QWP) before being incident on a scale grating. A holographic scale grating with a nominal pitch of 0.556 μm was employed. In this case, the beam was incident at a Littrow angle of 44.95°. The diffracted and reflected beams were detected using a laser autocollimation unit (LAU) [3]. LAU enables rapid measurement by detecting angular variation with A dual-element photodiode (DPD).To calibrate the LAU, the grating was mounted on a PZT tilt stage. The angular displacement was measured using a commercially available laser autocollimator. Signals from the DPD were acquired by a PC through the DAQ system to assess the sensitivity during calibration and to calculate the angular displacement of the diffracted and reflected beams.

3.2 Basic characteristics experiment

At first, the calibration of the sensitivities of the laser autocollimation units for the diffracted and reflected beams. Sensitivities of the optical system were determined to be 0.7516%/arc-second and 0.7114%/arc-second, respectively. Subsequently. the diffraction grating was scanned using these sensitivities to detect changes in diffracted and reflected angles. The pitch deviation was calculated based on the detected angular changes using Eq. (2). This process was repeated in 100 μm increments to evaluate pitch deviation across the entire length of the grating. This scanning was conducted three times. And three additional scans in the reverse direction. The results shown in Fig. 2 indicate that pitch deviations on the order of 0.001 nm can be detected by the developed setup. Furthermore, the results exhibit a certain degree of reproducibility, confirming the experimental feasibility of pitch deviation evaluation.

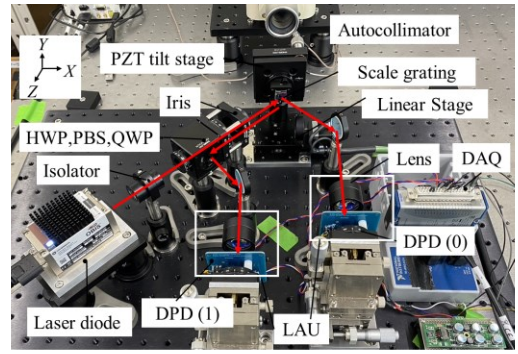
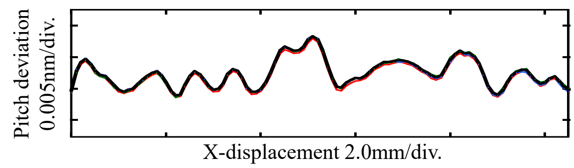
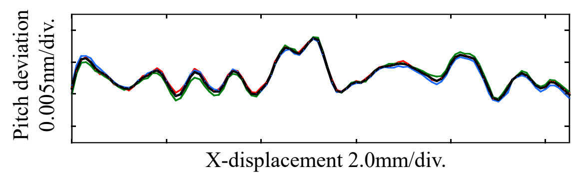


Fig. 2 Photograph of the constructed experimental setup



(a)



(b)

Fig. 3 Measured pitch deviation: (a) Scanning in the forward direction; (b) Scanning in the reverse direction.

4. Conclusions

In this paper, the principle for measuring pitch deviation has been extended to gratings with pitches shorter than the measurement wavelength. The method evaluates pitch deviation by detecting changes in the angles of the first-order diffracted beam and the reflected beam. Experimentally, pitch deviations as small as 0.001 nm have successfully been measured with good reproducibility. Further validation of these results will be addressed in future work.

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