Principle verification of two-axis displacement measurement system to compensating non-orthogonality error using single grating scale and Littrow configuration

Masaki Michihata[1,#], Souki Fujimura[1], Shuzo Masui[1] and Satoru Takahashi[1]

1 Department of Precision Engineering, the University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo, 113-5686, Japan
Corresponding Author / Email: michihata@nanolab.t.u-tokyo.ac.jp, TEL: +81-3-5481-6450

KEYWORDS: planar stage, linear scale, grating encoder, Littrow configuration, orthogonality

In this study, we introduced a novel measurement system designed to compensate for orthogonality in planar stages, effectively demonstrating its underlying principles. The system incorporates a single diffraction grating scale, strategically placed diagonally across the stage, and two interferometers aligned in a Littrow configuration. These interferometers are sensitive solely to stage displacement in the optical axis direction. By using Littrow configuration, the direction of measurement is determined with high accuracy, leveraging the pitch of the diffraction grating along with the optical wavelength of the laser, which facilitates orthogonality compensation. During our experiments, we successfully demonstrated that the interferometers, when aligned in the Littrow configuration, were capable of precisely measuring the displacement component of the stage in the optical axis direction. This configuration ensures that the measurements are not influenced by other displacement components, thereby providing accurate data. In our discussion, we highlighted the assessment of orthogonality and identified two crucial factors that significantly impact the system's accuracy. The first factor is the precise alignment of the Littrow configuration, which is essential for optimal performance. The second factor is the accuracy of the pitch of the grating scale, which directly influences the measurement precision. Both factors are critical for ensuring the system's reliability and effectiveness in compensating for orthogonality errors in planar stages. Overall, our proposed system offers a promising solution for enhancing measurement accuracy in various applications.

1. Introduction

In precision measurement, there is a growing demand for dimensional measurement systems that can achieve a wider measurement range and higher accuracy. To meet this demand, it is necessary to develop high-precision positioning technology. One of the most important devices is the plane stage. In particular, plane stages are indispensable for measuring 2.5-dimensional shapes and are also applied to 3-dimensional measuring instruments such as coordinate measuring machines (CMMs). To guarantee the accuracy of these stages, it is necessary to measure their motion accuracy with high precision. Addressing the motion error of plane stages has been the focus of numerous research efforts. In addition to geometric motion errors such as positioning accuracy, straightness, and rotation (pitch, roll, and yaw), the orthogonality of the stage is key. Orthogonality is recognized as one of the major sources of uncertainty. In general, it is difficult to significantly reduce non-orthogonality. It is more desirable if the measurement system of the stage can compensate for orthogonality errors. Therefore, in order to reduce errors due to non-orthogonality and improve overall measurement accuracy, it is important to advance measurement technology. Thus, accurate measurement of stage orthogonality is an important issue. Consequently, we have proposed a two-axis measurement system for plane stages that can compensate for non-orthogonality. The purpose of this study is to propose a concept for the measurement system and to verify it through experiments.

2. Principle

In this study, we propose a method for measuring displacements along two axes using a single grating scale as a reference plane. Conventionally, measuring displacements in two directions with either a linear scale or a reference mirror and interferometer requires two sets (X and Y), each aligned orthogonally to the other. It has been necessary to adjust the X and Y measurements while ensuring that each axis aligns with the stage motion axes. To address this issue, we propose using a single grating scale. The two interferometers are adjusted to be in a Littrow configuration with respect to the grating scale. Aligning the Littrow configuration ensures that the measurement axis angle achieves high accuracy relative to the surface of the grating scale. The angle depends on the scale pitch; recent advancements in scale pitch measurement technologies have achieved accuracies as high as 10^{-5}

to 10^{-6}.

The Littrow configuration imposes geometric constraints related to the spatial period of the diffraction grating and the optical wavelength. The relationship between the angle of incidence and the angle of diffraction in a reflective grating can be described by the following equation:

$$\Lambda(\sin\gamma + \sin\beta) = m\lambda \quad (1)$$

where λ is the light wavelength, Λ is the spatial period of the diffraction grating, γ is the angle of incidence, β is the diffraction angle, and m is the diffraction order. In a Littrow configuration, the diffracted light returns in the same direction as the angle of incidence, i.e., γ = β. Therefore, Eq. (1) simplifies to the following:

$$\sin\theta_L = m\lambda/2\Lambda \quad (2)$$

The angle θ_L is the Littrow angle. Suppose that light is incident on a tilted diffraction grating, satisfying the Littrow configuration with an incident angle θ_L. As illustrated in Fig. 1, when the diffraction grating is displaced, the position of the light illumination on the grating changes, altering the optical response. Initially, let us consider the case where the diffraction grating is displaced in the optical axis of the optical measurement system. At this point, the phase change $\Delta\phi_1$ of the returning light in the A-B plane can be expressed as:

$$\Delta\phi_1 = 4\pi\Delta L/\lambda \quad (3)$$

The displacement in the y direction can be determined by measuring the resulting phase change $\Delta\phi_1$. As depicted in Fig. 1(b), the displacement of the grating by δx causes the beam irradiation position to shift from P_0 to P_{0C}', also resulting in a change in the optical path length by $2\Delta L$. In addition, the phase change due to the change of irradiation position on the grating. Therefore, the phase change due to displacement in the direction normal to optical axis is,

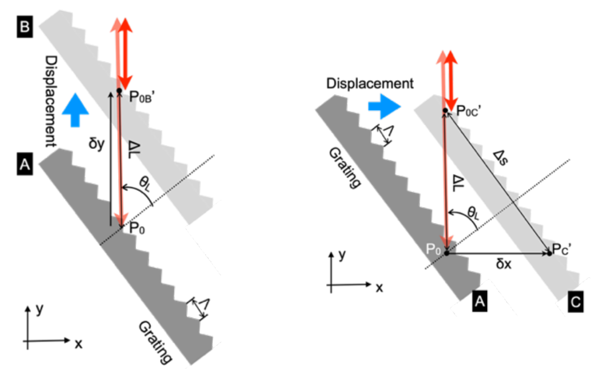
$$\Delta\phi_2 = 2\pi\Delta L(2/\lambda - m/\sin\theta) \quad (4)$$

The phase chance $\Delta\phi_2$ equal to zero, as derived from the relation in Eq. (2). Therefore, no phase change is observed for the displacement component in the x-axis direction in the xy-plane. In the Littrow configuration, the phase change of the diffracted light due to displacement in the direction perpendicular to the optical axis is offset by the phase change due to changes in optical path length and beam irradiation position on the diffraction grating. This property is particularly useful in displacement measurements, where pure axial displacement can be measured regardless of lateral displacement changes due to straightness, for example.

By using the Littrow configuration, only the stage displacement in the direction consistent with the optical axis direction of the laser interferometer can be measured, without being affected by straightness. Therefore, as shown in Fig. 2, by placing the grating scale at an angle to the stage under test and aligning the laser interferometer in the XY direction, only the XY direction can be accurately measured. The measurement direction of the interferometer is strictly determined by the Littrow angle. By correctly aligning the interferometer to the Littrow angle, orthogonality errors can be reduced. The wavelength stability and grating pitch period are considered as the error factors. Using a frequency-stabilized laser, a laser frequency stability of 10^{-9} to 10^{-11} can be obtained. The wavelength of the light is affected by the refractive index change of air, but at a wavelength of 1550 nm, a temperature change of 0.5°C results in a refractive index change of about 4.7×10^{-7}, a level still lower than orthogonality. The resolution and repeatability of grating pitch measurements are also high, reaching 10^{-7} and 10^{-6}, respectively. Using the proposed measurement system, it is possible to construct a highly accurate system with error derived from non-orthogonality less than 10^{-6}.

3. Conclusion

Focusing on the orthogonality associated with planar stages, we introduced the concept of a two-axis stage displacement measurement system to compensate for non-orthogonality errors and verified its basic principles (experiments are omitted in this paper). One grating scale is installed on the diagonal and the interferometer is placed in a Littrow arrangement with respect to the grating. This principle was verified experimentally[1]. It is possible to construct a highly accurate system with error derived from non-orthogonality less than 10^{-6}.



(a) Direction along optical axis. (b) Direction normal to optical axis.

Fig. 1 Geometrical relation to optical response in Littrow arrangement.

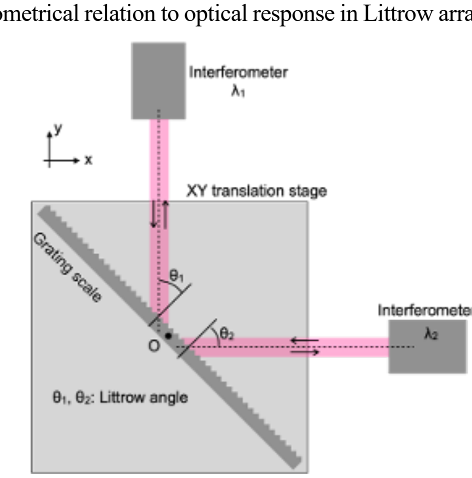


Fig. 2 Conceptual illustration of two-axis displacement measurement system utilizing single grating scale and Littrow configuration.

ACKNOWLEDGEMENT

This work was supported by Japan society for the promotion of science (JSPS) KAKENHI (No. 23H01313), Suzuki foundation, The Precise Measurement Technology Promotion Foundation, and Machine Tool Engineering Foundation.

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