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Novel instantaneous measurement method of straightness of a precision linear air-bearing stage

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Abstract
A novel compact method for simultaneously measuring straightness error of a moving linear air-bearing stage is proposed based on the collimator technique and a novel analysis method. The measuring principle and parameters of the system are analysed theoretically. A prototype laser encoder consisting of the stainless steel bar and the sensor is developed for two-axis position measurements. The stainless steel bar has a three dimensional micro-structured surface, which is a superposition of periodic sinusoidal waves in the X- and Z-directions with spatial wavelengths of 350µm and amplitudes of 0.5µm. The laser-based two-axis position sensor is used to detect local slope profiles of the grid surface, and an axial motion displacement volume and a radial displacement volume of the linear stage are calculated by using a slope signal equation and a position signal equation. The maximum displacement error is 3.306µm, and the minimum displacement error is 1.81µm. In addition, the instantaneous analysis method of measuring the straightness errors is proposed and verified by the experimental results.

Keywords: Precision positioning, Straightness, optical laser encoder, Precision linear air-bearing stage

1. Introduction

In accordance with the increasing market demand for ultra-precision technology, a high precision multi-degree-of-freedom displacement measurement technology has become important for industrial applications such as the field of manufacturing and inspection because physical quantities, such as linear and angular displacements, are key parameters for keeping and improving quality control of a production system. In addition, high accuracy stages have commonly been used in semiconductor processing, PCB drilling processing, micromachining processing, precision assembly processing, inspection processing, etc. It should be noticed that the term "straightness error" is generally used to refer to many aspects of engineering quality, such as work-piece straightness, motion straightness, etc. Optical measurements of straightness errors have been widely used in the field of engineering metrology. The straightness datum that can be measured by means of various optical accessories such as: autocollimators, alignment telescopes and optical theodolites are commonly adopted. Another method employs a laser beam to generate a reference line, which has the properties of small divergence and high intensity. Moreover, many other methods were developed with high alignment accuracy, such as the polarimetry method [1], the polarizing method [2], the optical compensation method, and the Zeeman laser interferometer method [3]. Recently, a laser diode was adopted for straightness measurement since it is small in size and low in power [4].

However, the mentioned measurement devices are not suitable to be installed on precise positioning machinery for on-line measurement as a result of heavy overall structure. Therefore, this research presents a novel compact method for simultaneously measuring straightness error of a moving linear air-bearing stage based on the collimator technique and on a novel analysis method.

2. Measurement principle and instrument configuration

Figure 1 shows a diagram of the measurement system. An incident beam from the laser diode is collimated by the collimating lens (CO). The collimated laser beam incidents to the polarization beam-splitting device. It should be noticed that the polarization beam-splitting device which is disposed in the light path of the incident light and comprises a polarization beam splitter (PBS) and a quarter-wave plate. The polarization beam splitter is used for guiding the incident light to pass the focus lens on the two-dimensional sinusoidal grating. The reflection light beam is reflected from the two-dimensional sinusoidal grating and reflected by the reflective mirror to pass the focus lens on the quadrant photo diodes (QPD).

Figure 2 shows the photograph of the measurement system. The reflective-type two-dimensional sinusoidal grating, wherein a profile equation of the reflective-type two-dimensional sinusoidal grating is expressed as:

$$h(x,z) = -A_x \cos\left(\frac{2\pi x}{P_x}\right) - A_z \cos\left(\frac{2\pi z}{P_z}\right) \qquad \text{Eq.[1]}$$

wherein $h(x,z)$ is the profile equation of the reflective-type two-dimensional sinusoidal grating, $A_{x,z}$ are sinusoidal amplitudes of an x-axis direction and a z-axis direction of the reflective-type two-dimensional sinusoidal grating separately, $P_{x,z}$ are sinusoidal wavelengths of the x-axis direction and the z-axis direction of the reflective-type two-dimensional sinusoidal grating separately, x and z indicate the location of the x-axis direction and the z-axis direction separately. In this study, the sinusoidal wavelengths of the x-axis direction and the z-axis direction of the reflective-type two-dimensional sinusoidal grating both are 350µm. The sinusoidal amplitudes of an x-axis direction and a z-axis direction of the reflective-type two-dimensional sinusoidal grating both are 0.5μm.

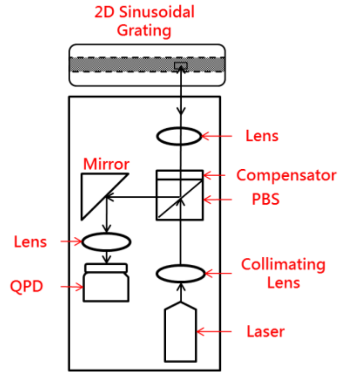

Figure 1. Diagram of the proposed measurement system

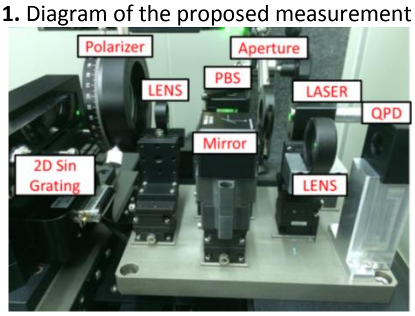

Figure 2. Basic principle of measurement system

Separately performing partial differentiation to x and z of the two-dimensional sinusoidal grating to obtain the slope equations of the x-axis direction and the z-axis direction of the two-dimensional grating as followed:

$$m_x(x,z) = \frac{\partial h(x,z)}{\partial x} = \frac{2\pi A_x}{P_x}\sin\left(\frac{2\pi x}{P_x}\right) \quad \text{Eq.[2]}$$

$$m_z(x,z) = \frac{\partial h(x,z)}{\partial z} = \frac{2\pi A_z}{P_z}\sin\left(\frac{2\pi z}{P_z}\right) \quad \text{Eq.[3]}$$

By mentioned equations, the slope equations of the x-axis direction and the z-axis direction of the two-dimensional grating merely relates to the data of the x-axis direction and the z-axis direction. Therefore, slope signals of the x-axis direction and the z-axis direction of the two-dimensional grating can be calculated individually. Because of it, we can apply the auto-collimation principle to measure the x-axis direction and the z-axis direction from QPD:

$$x = \frac{P_x}{2\pi}\left(\sin^{-1}\frac{P_x}{2\pi A_x}m_x(x,z)\right) \quad \text{Eq.[4]}$$

$$z = \frac{P_z}{2\pi}\left(\sin^{-1}\frac{P_z}{2\pi A_z}m_z(x,z)\right) \quad \text{Eq.[5]}$$

Therefore, an axial motion displacement volume and a radial displacement volume of the linear stage are calculated by using a slope signal equation and a position signal equation to calculate the sensing signals of the quadrant photodiode. Eventually, a straightness error of linear stage is obtained.

3. Experimental results of the proposed measurement system

The primary object of the study is to make an incident light from a light source disposed at a moving stage illuminating a two-dimensional sinusoidal grating positioned on a guiding rail, wherein a reflection light of the two-dimensional grating forms a light spot on a quadrant photodiode therefore making the quadrant photodiode generating a plurality of sensing signals. The position differences of the light spot are variable according to the movement of the stage thus further altering the intensity of the sensing signals of the quadrant photodiode.

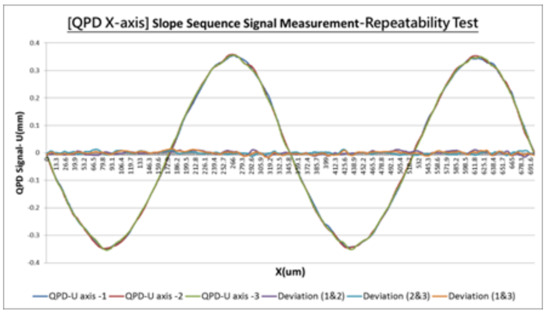

Figure 3. Sequence Signal Measurement –Repeatability Test of X axis.

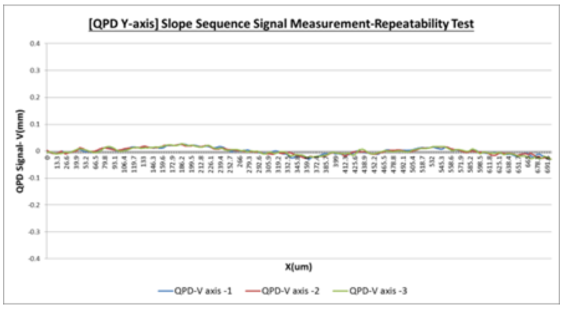

Figure 4. Sequence Signal Measurement –Repeatability Test of Z axis.

Figure 3 and Figure 4 shows the experimental repeatability results of the proposed measurement system. It should be noticed that the U and V axis are corresponding to the horizontal direction and vertical direction of the QPD. The maximum repeatability error is 17.013μm, and the minimum repeatability error is 0.83nm. The extracted slope signal datum could be inserted into the novel analysis model as above mentioned to decide the displacements of the X-axis and the Z-axis. The maximum displacement error is 3.306μm, and the minimum displacement error is 1.81μm. The experimental results show good verification with the instantaneous measurement method of the precision linear air-bearing stage.

4. Summary

In this research, the measurement device for linear stage is used for measuring the X and Z direction displacement of a linear stage includes a light source, a two-dimensional grating, a quadrant photodiode and a processor. The quadrant photodiode is positioned in light path of the reflection light and receives the reflection light for generating a plurality of sensing signals. The processor receives the sensing signals and utilizes the sensing signals to calculate a slope signal by a slope signal equation of the two-dimensional grating. Owing to simplified and rapid calculation, the measuring method for linear stage of present invention is suitable for measuring the displacement and the straightness error of the linear stage on line therefore instantaneously controlling the linear stage by information feedback. Moreover, the experimental results verified the instantaneous measurement method of the precision linear air-bearing stage.

References

[1] R.J. King and K.W. Raine 1981 Optical Engng **201** 39–43
[2] C. Yin and W.Z. Chen 1991 Optical Engng **304** 480–482
[3] S. Shimizu and H.S. Lee, N. Imai 1994 Int. J. Japan Soc. Prec. Engng **28** 273–274
[4] T.R. Armstrong and M.P. Fitzgerald 1992 Measurement Sci. **3** 1072–1076