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A Simple Low-Cost 2-D Optical Measurement System for Linear Guideways

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***Abstract*—**In this study, a simple 2-D measurement system based on optical design was developed to measure the motion errors of the linear guideway. Compared with the transitional methods about the linear guideway for measuring the motion errors, our proposed 2-D optical measurement system can simultaneously measure horizontal and vertical running straightness errors for the linear guideway.

The performance of the 2-D optical measurement system is verified by experimental results. The standard deviation of the 2-D optical measurement system is about 0.4μm in the measurement range of 100 mm. The maximum measuring speed of the proposed automatic measurement instrument is 1 m/sec.

***Keywords*—**2-D measurement, linear guideway, motion errors, running straightness.

I. Introduction

LINEAR guide ways are an important element in precision machinery, which is widely used in the automation, power transport, semiconductor, medical, and aerospace industries. The running accuracy of linear guide ways is divided into 5 classes, namely normal grade (N), precision (P), high precision (H), super precision (SP), and ultra precision (UP). Measurement systems for linear guide ways are divided into contact and non-contact types. Contact-type systems use a linear variable differential transformer (LVDT) and a dial gauge to measure N-, H-, and P-grade linear guide ways. Non-contact-type systems use an autocollimator and a laser interferometer to measure SP- and UP-grade linear guide ways. An LVDT or a dial gauge is often used to measure motion errors of linear guide ways because laser interferometers are costly. In the general measurement method, a contact-type system is used to measure the motion error between the base level of the measuring platform and the carriage.

The accuracy of the measurement results is affected by the base level of the measuring platform. The method uses manual manipulation and is time-consuming. Therefore, a high-precision measurement system for automatically measuring the straightness errors of linear guideways is proposed here.

In recent years, 2-D optical measurement systems have been used to measure multi-degree-of-freedom (DOF) errors [1], [2]. Lee et al. [3] presented an2-D optical measurement system that uses a laser beam, beam-splitters, a reflector, and quadrant detectors. The resolutions of the system are 0.048 arcsec and 26 nm. Kim et al. [4] presented a multi-dimensional motion measurement system that comprises a grating, three lenses, and detectors. A displacement of 6- DOF can be obtained. The resolutions of the system are 0.0133 arcsec and 60 nm. Fan et al. [5] used a DVD pickup heads to develop a high-precision straightness measurement system. Their system has a measurement range of 200 mm and an accuracy of 0.6 m. Liu et al. [6] presented a 4-DOF measurement system composed of a grating, two lenses, and detectors. The resolution of the system is 100 nm. Jywe et al. [7] presented a multi-dimensional motion measurement system that comprises an interferometer, two corner cubes, and three quadrant detectors. The resolution of the system is 25 nm and 0.06arcsec. Liu et al. [8] designed an optical path for a high-precision straightness measurement system with four corner cubes. The measurement system can measure two-dimensional errors and its accuracy is 0.5μm. Chen et al. [9] presented a 3-dimensional vibration measurement system with corner cubes and quadrant detectors; position errors can be obtained. The resolutions of the system are 100nm and 1000Hz. Hsieh et al. [10] designed an optical vibrometer based on multi-degree-of-freedom measurement. The accuracy of the proposed optical vibrometer is ±30 nm/200 nm and ±0.04 arcsec/0.1arcsec at 1000 Hz. Liu et al. [11] proposed a grating based multi-degree-of-freedom laser linear encoder. The accuracy of the system is ±0.6μm for straightness, ±0.8 arcsec for angular error, and ±1.2μm for linear displacement.

In the present study, the measurement system has three main advantages: (a) it can be used to automatically measure the horizontal and vertical straightness of linear guide ways; (b) it is a sample low-cost measurement system, and (c) it has a high resolution.

II. System Structure and Measurement Principle

A. Overall System Layout

The proposed 2-D optical measurement system is set-up on the precision linear positioning stage for measuring the motion errors of the linear guideway as shown in Fig. 1. The precision linear positioning stage integrates a precision granite table, a movable gantry stage, and a linear motor. The linear motor is the main linear driving system and is configured to drive a

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carriage, whose motion is automatically measured via an optical measurement system and a user interface. The development of the man-machine interface primarily involves hardware and software integration of the precision linear positioning stage for linear guideways and the development of an operation interface; the interface allows the precision linear positioning stage to be easily operated, to perform automatic measurement, and to process data rapidly.

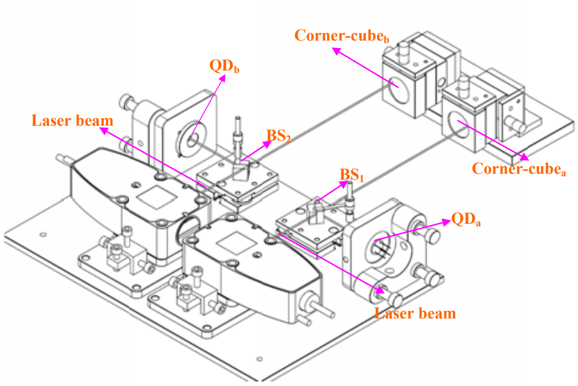

Fig. 1 Sketch of the 2-D optical measurement system

B. Principle for the2-D Optical Measurement System

The position deviations of the light spot in the corner cubes are shown in Fig. 2. After calculation and measurement, the horizontal straightness (ΔH) and vertical straightness (ΔV) that results from the linear motion of the linear guide way are determined as:

$$\Delta H = \frac{\Delta\delta_{ax}+\Delta\delta_{bx}}{2} \tag{1}$$

$$\Delta V = \frac{\Delta\delta_{az}+\Delta\delta_{bz}}{2} \tag{2}$$

The laser beam emitted by one of the laser units passes through BS1 and becomes an incident light beam that shoots to the corresponding corner cube. After being reflected by the three boundary surfaces of the corner cube, the light beam leaves the cube as a parallel collimated light beam, which is refracted by BS1 and then is projected onto QDa. By the same principle, the other laser beam follows a similar path into QDb. The corner cubes are the major reflectors in the system and have a resolution doubling function, increasing the resolution of the measurement system two-fold. The optical characteristics of the corner cubes are shown in Fig. 3. Therefore, the equations can be modified as:

$$\Delta H = \frac{\Delta\delta_{ax}+\Delta\delta_{bx}}{2} = \frac{X_{QDa}+X_{QDb}}{4} \tag{3}$$

$$\Delta V = \frac{\Delta\delta_{az}+\Delta\delta_{bz}}{2} = \frac{Z_{QDa}+Z_{QDb}}{4} \tag{4}$$

where X_{QDa} and X_{QDb}arethe reading values in the direction of the x-axis of QDa and QDb, respectively, and Z_{QDa} and Z_{QDb} are the reading values in the direction of the z-axis of QDa and QDb, respectively.

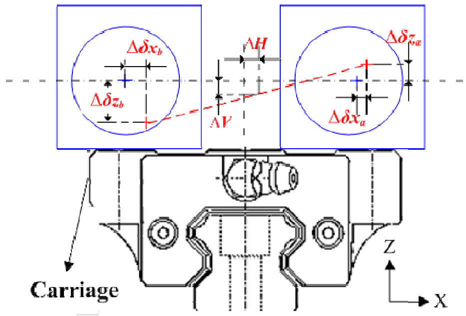

Fig. 2 Sketch of the position deviationof the light spotin the corner cubes

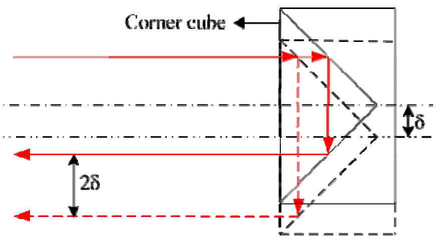

Fig. 3 Sketch of the increasing resolution

III. Discussion

A. Calibration Results for the Measurement System

The QDs are the main sensors in the proposed system. In order to transform voltage values into displacement values, the sensitivity of the QD must be obtained. The calibration results of the system are obtained using a laser interferometer (HP 5529A). The investigation consists of recording the output voltage from the QDs at measurement range from -50µm to 50µm in a step of 10µm. The sensitivity of the QDs are described in Table I. The sensitivity of QDs are about 86µm/v and 84µm/v in the measurement ranges of 50µm, respectively. In the three tests, the residual errors of QDa and QDb are about 0.2µm and 0.4µm, respectively.

TABLE I
Sensitivity of QDa and QDb

	Sensitivity of X	Sensitivity of Y	Errors of X	Errors of Y
QDa	86.7MM/V	86.4MM/V	0.2MM	0.2MM
QDb	84.7MM/V	84.4MM/V	0.2MM	0.4MM

B. Verification Results for the Measurement System

A linear guideway and the fixed end of the proposed measurement system were installed on the precision granite air-floating table. The moving end of the system was fixed on the carriage. The 2-D optical measurement system was verified using a laser interferometer (HP 5529A). Figs. 4 and 5 show the results of three straightness measurements. The standard deviation (STDEV) of the 2-D optical measurement system is about 0.4µm in the measurement range of 100mm. The precision linear positioning stage reduces measurement time and removes human error.

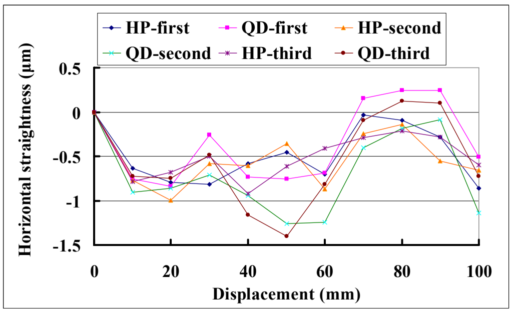

Fig. 4 Verification results of horizontal straightness

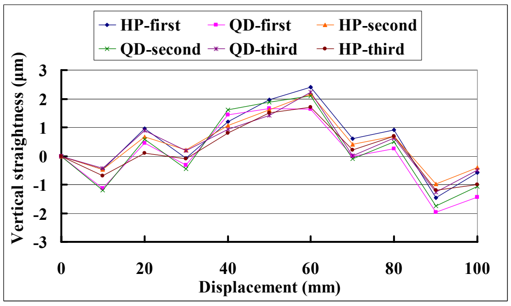

Fig. 5 Verification results of vertical straightness

C. Measurement Results for the Linear Guideway

Tests were repeated, the measurement parameters were set as follows. For the straightness measurement, the sampling frequency was 1000Hz, the measurement distance was 1000 mm, and the measuring pitch was6 mm. The results are shown in Fig. 6. The STDEV of the horizontal and vertical straightness measurement system are 0.9μm and1.2μm in the measurement range of 1000mm and the measuring time is 80s. The possible sources of error in the QDs can be due to fluctuation of collimated laser source, stray light and possible external environment vibrations. To reduce these effects the following precautions can be taken :(1) A well-regulated power supply is used for the collimated laser and this minimizes the fluctuation of light source intensity, (2) The fixture is designed so that the stray light and room light do cannot interfere with the light source intensity, and (3) The sampling rate of A/D card is increased to avoid the leakage effect.

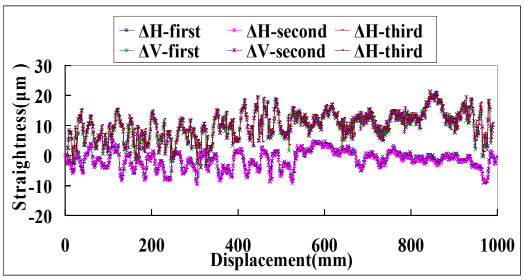

Fig. 6 Results of horizontal and vertical straightness measurements

IV. Conclusion

A simple low-cost 2-D optical measurement system was developed for linear guide ways. It was an effective method for on-line error measurement to improve linear guide way performance. This advantage is superior to other useful methods. In the future, a static/dynamic multi-function measuring device will be designed and more powerful for on-line measuring the motion errors of the linear guideway.

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