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Design and experimental verification of novel six-degree-of freedom geometric error measurement system for linear stage

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ABSTRACT

In this study, a novel and simple measurement system for simultaneously measuring the geometric errors in six-degree-of-freedom (6-DOF) for a moving linear stage of a machine tool is designed and validated. Compared to laser interferometer and laser Doppler systems, this new measurement system is less expensive and capable of multiple functions. The proposed measurement system comprises an optics module, composed of two reflectors and two cubic beam splitters; a sensing module, composed of three two-dimensional position sensitive detectors (PSDs); and a helium-neon (He-Ne) laser. Using skew-ray tracing and a first-order Taylor series expansion, the 6-DOF geometric errors of the moving linear stage, which include translation and rotation errors, are analyzed. A laboratory prototype system is built to verify the effectiveness and accuracy of the proposed measurement system. The experimental results show that the displacement uncertainty and the angular uncertainty of the proposed measurement system are less than 1.2 µm and 0.4″, respectively. Compared with the Renishaw laser interferometer XL-80 laser system, the translational accuracy and the rotational accuracy of the proposed measurement system are less than ±1 µm and ±0.2″, respectively, when the linear stage travels 6 mm.

1. Introduction

Many mechanical machines, such as three-axis machine tools, computer numerical control (CNC) machine centers and coordinate measuring machines (CMMs), are equipped with multi-axis linear stages. The height accuracy of the linear stage is used as the basis for linear motion in many industrial applications, such as precision assembly processing, semiconductor processing, micromachining, printed circuit board (PCB) drilling, and automated optical inspection [1–3]. It thus plays an essential role in a precision machine [4].

In the ideal case, a linear stage has a single degree of freedom when it travels along a straight line in a precision machine tool. Furthermore, we expect that it stops exactly at the precisely indicated position on a linear guide. In reality, both the linear axis and the rotary axis have six-degree-of-freedom (6-DOF) when they engage. For example, the six geometric errors associated with the movement of a linear stage along a linear guide consist of translation errors including the position error δ_z, straightness errors δ_x and δ_y in the x- and y-directions, respectively, and rotation errors around the three axes corresponding to pitch ε_x, yaw ε_y, and roll ε_z, as shown in Fig. 1 [5]. The 6-DOF geometric errors influence the linear stage performance when it is engaged; accordingly, there are several articles and research study reports on the measurement of geometric errors in machine tools. The measurement devices of geometric errors in machine tools can be classified into three basic types, i.e., commercial measuring devices, non-commercial measurement systems that apply interferometric technologies and non-commercial measurement systems that apply non-interferometric optical sensing technologies.

In recent years, commercial measuring devices for machine tools, such as the laser interferometer, the autocollimator and the laser Doppler vibrometer (LDV), have been developed and applied in industry widely to the measurement of the geometric errors of the linear stage. Measuring the geometric errors of the linear stage with one of the commonly used systems, the laser interferometer Renishaw XL-80, is a complex and time-consuming process. The system requires individual optical accessories and procedures to resolve a single geometric error for one step. For the three-axis machine, this complex procedure may require several hours or even a few days to measure the geometric errors. While the measurement is in progress, the production process is interrupted. Hence, using the conventional method to measure the geometric errors in machine tools requires costly measurement procedures [5,6]. Presently, the XD^{TM} laser, a commercially

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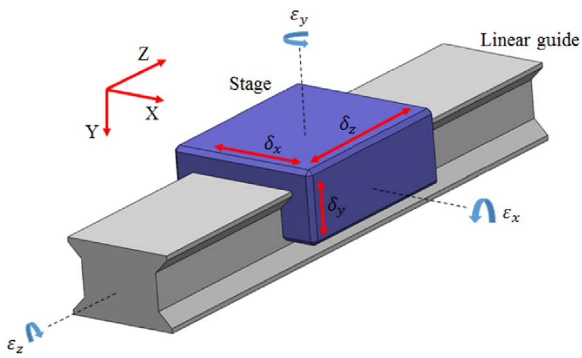

Fig. 1. Model showing 6-DOF geometric motion errors.

available precision laser measurement system from Automated Precision, Inc. (API) is capable of measuring multi-dimensional errors simultaneously. However, the XD^{TM} laser precision laser measurement system is much more expensive and much more complicated to implement.

The laser interferometer and grating interferometer methods are two other methods that could be used to measure the geometric errors in non-commercial measurement systems. These two methods are suitable for measuring the errors in the motions of the linear stages in industrial applications [7,8]. Fan et al. employed four laser Doppler scales and two quadrant photo detectors to simultaneously detect the positions and the rotations of an optical reflection device mounted on the top of a stage. Unfortunately, their system is costly and has a complex configuration [9]. Other scholars combined the laser interferometer with devices to measure the multiple degree-of-freedom (multi-DOF) error motions of a precision linear stage [10–12]. In addition, a laser linear encoder with multi-DOF based on diffraction and interference has been developed by several researchers [13–15]. On the other hand, in the measurement of the fields of rotary axes, Jywe et al. developed a novel, simple and low-cost technique to calibrate the 4 degree-of-freedom (DOF) errors of a rotary table [16,17].

Recently, several multi-DOF displacement measurement systems, using non-interferometric optical sensing technologies, have been proposed to simultaneously measure multiple geometric errors of the linear stage to speed up the calibration. These technologies were demonstrated to be superior to others in many aspects, including non-contact and non-interferometric measurement [4,18,19]. In the early years, Ni et al. developed a precision multi-DOF system for the simultaneous measurement of the straightness, pitch, yaw, and roll errors of the moving axes of a CMM [19,20]. Feng et al. also proposed a series of instruments, i.e., a single-mode fiber-coupled laser module, cube corner retro-reflectors and beam splitters, to measure the multi-DOF of the linear stage [21–24]. To improve the accuracy of miniaturized machine tools (mMTs), non-interferometric optical sensing technologies were also used to identify and correct the geometric errors of the mMTs. Therefore, optic multi-DOF measuring systems of the mMTs, composed of laser modules, lenses, reflectors and detectors, have been developed [24–26]. However the geometrical errors compensation is as important as the measurement. Researchers have built error compensation models based on the analysis of the influence of error crosstalk on the straightness error measurement using the prism expansion method and matrix optics [27,28]. The preceding papers describe several measurement technologies and systems, such as the laser interferometer method, the grating interferometer method, and the geometrical optics method, which have been applied to simultaneously measure multiple geometric errors. Most of them are expensive, complex and difficult to set up. In addition, non-interferometric optical sensing technologies have been demonstrated to be superior to the other technologies in many aspects, including non-contact measurement, resistance to electromagnetic interference (EMI), and compactness [18].

In this study, a novel and easily implemented system for simultaneously measuring the 6-DOF geometric motion errors of a linear stage using a simple structure is developed and verified. The methods used to determine the translation errors (i.e. position error δ_z, straightness errors δ_x and δ_y) and rotation errors (i.e. pitch, yaw and roll errors) are described in detail. This simple measuring system is inexpensive, has a simple optical configuration, and is very accurate. The system is composed of two reflectors, two cube beam splitters, three two-dimensional position sensitive detectors (PSDs) and a He-Ne laser. The entire system configuration, the theory of the proposed measurement system, and the capability of the system to detect 6DOF geometric motion errors are presented. The translation and rotation error measurement ranges are ± 3 mm and $\pm 0.6°$, respectively. The application filed of the proposed measurement system is aimed to the mMTs [24–26]. In the next section, the mathematical formulation, using skew-ray tracing and first-order Taylor series expansion analysis methods to calculate the laser spot positions on the PSDs, is presented.

Finally, we present the results of a series of experiments that illustrate the practicability and the effectiveness of the novel 6-DOF error measurement system for linear stage.

2. Measurement system setup and measurement method

A schematic of the proposed novel 6-DOF geometric error measurement system is shown in Fig. 2. The measurement system consists of two modules, a moving module and a fixed module. The fixed module comprises a laser source and three PSDs (PSD_A, PSD_B, and PSD_C), placed at various locations. The moving module is a synchronized mobile module composed of two beam splitters (BS_1 and BS_2) and two mirrors ($Mirror_1$ and $Mirror_2$); this synchronized mobile module is placed on the linear stage to be measured, which is moving in the z-direction. The fixed module is fixed at a location external to the measured linear stage for the 6-DOF geometric error measurement.

The proposed novel 6-DOF geometric error measurement system is based primarily on the geometric optics principle. The laser beam is directed into the PSDs through the synchronized mobile module. The orientation of $Mirror_1$ forms a 45° angle with the measured stage. The direction of the laser is changed by $Mirror_1$ and is incident onto BS_1; then BS_1 splits the laser into a reflected beam and a penetrated beam.

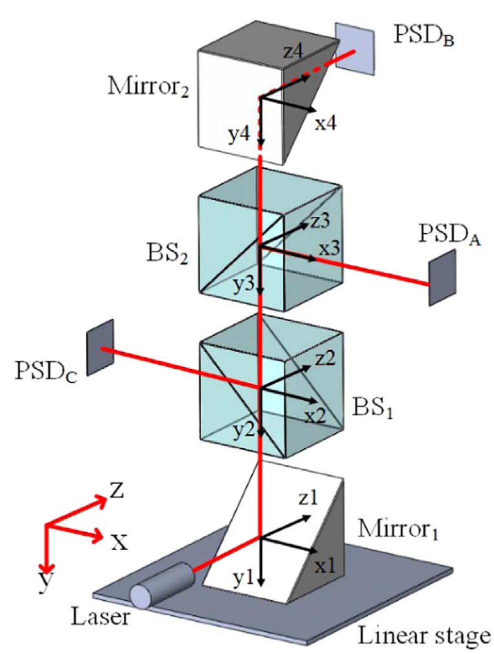

Fig. 2. Schematic of 6-DOF error measurement system.