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Simple and simultaneous measurement of five-degrees-of-freedom error motions of high-speed microspindle: Error analysis

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ABSTRACT

We have developed a simple and low-cost optical measurement system for the simultaneous measurement of the five-degrees-of-freedom error motions of high-speed microspindles. We demonstrated the usefulness of the system by using it to measure actual spindle rotation errors, and analyzed the major error factors. First, the measurement error due to the form error of the lens was analyzed by ray tracing. Second, we analyzed the measurement error due to a displacement of an irradiation laser point on a 3 mm diameter ball lens. Furthermore, we investigated the effect of the centrifugal force and the crosstalk problem of multiple laser beams. The results indicated that a form error of the rod lens significantly affected the measurement accuracy and that a change in the laser beam irradiation point of the ball lens due to a radial displacement had no significant effect on the measurement accuracy. Finally, we confirmed that, owing to the centrifugal force, the measurement accuracy decreased as the speed of rotation increased, and that there was no crosstalk that the reflected and transmitted laser beams in the X direction were detected by the photodiode in the Y direction for displacements within −10 to 10 μm.

1. Introduction

Small-sized machine tools are required to reduce energy consumption and installation area, especially when the microsized structures are to be machined. Furthermore, small-sized machine tools have the advantages of lower heat deformation, material consumption and vibration. The microsized structures include various microholes, micromolds, optical devices, microelectromechanical systems, and mechanical microparts. This miniaturization of machine tools and cutting tools in recent years [1–5] has led to an increased demand for small and high-speed rotation spindles. Moreover, the form accuracy and surface roughness of the workpieces are extremely dependent on the rotational accuracy of the microspindle, and hence, the need to evaluate microspindle rotation errors has increased.

It is, however, very difficult to evaluate the five-degrees-of-freedom error motions of high-speed microspindles by the conventional method [6–9], which simultaneously employs a master ball or cylinder and displacement sensors (for example, an electrostatic capacitance displacement meter). As illustrated in Fig. 1, the five-degrees-of-freedom spindle error motions comprise one axial (ε_Z), two radial (ε_X and ε_Y), and two angular ($\varepsilon_{\theta X}$ and $\varepsilon_{\theta Y}$) motions. The difficulties in evaluating these are due to the limitations in the measuring range, mechanical interaction, and frequency–response characteristics.

Reference pieces with a diameter of more than several 10 mm are used in the conventional method, such as the master ball or cylinder, since they must be large enough in order that the displacement sensors may measure them. They are therefore not appropriate for microspindles. High-speed microspindles can only accommodate small and lightweight reference pieces. Most high-speed microspindles can hold the tool shank with a diameter of less than 3 mm. Moreover, the displacement sensor must have a high bandwidth in order to measure the high dynamic motions of microspindles. For example, the bandwidths of most electrostatic capacitance displacement meters are less than 100 kHz, which corresponds to angular resolutions of 6° and 18° for nominal speeds of 100 and 300 krpm. This makes the measurement of the spindle rotation errors of microspindles very difficult.

To date, many studies have reported measurements of spindle-rotation errors [10–15], but the methods are not applicable to high-speed microspindles. Some optical [16,17] and laser Doppler vibrometry-based [18,19] techniques for measuring the rotation errors of high-speed microspindles have been reported in recent years. Although these techniques could not be used

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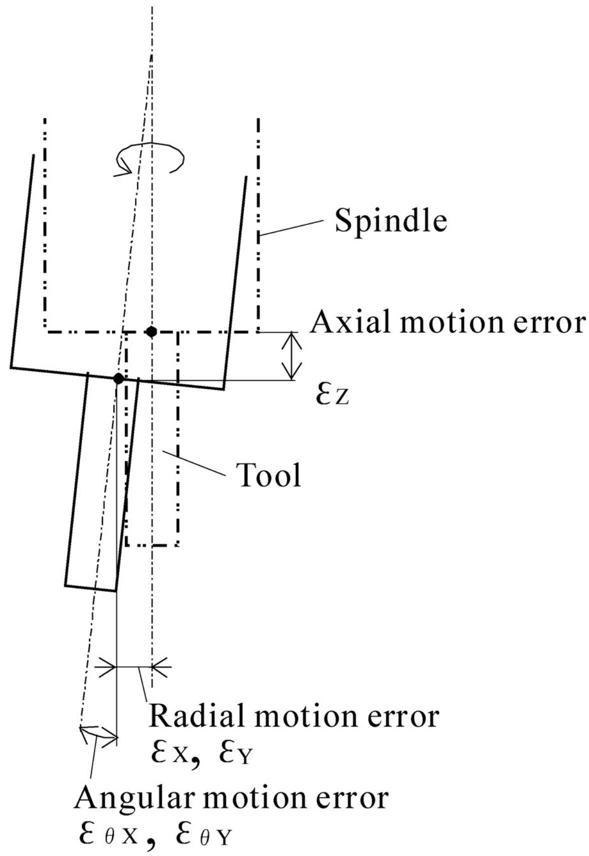
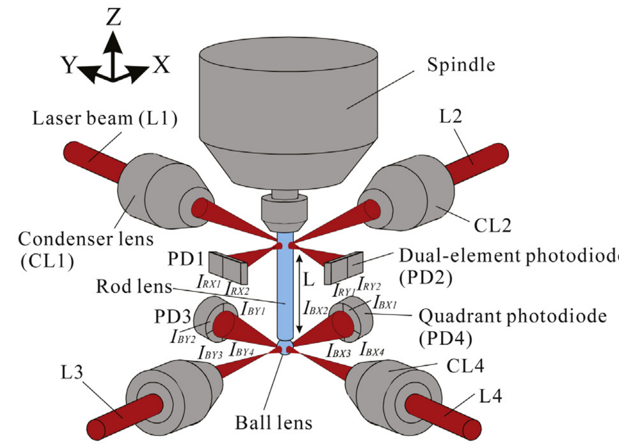


Fig. 1. Illustration of five-degrees-of-freedom spindle errors.

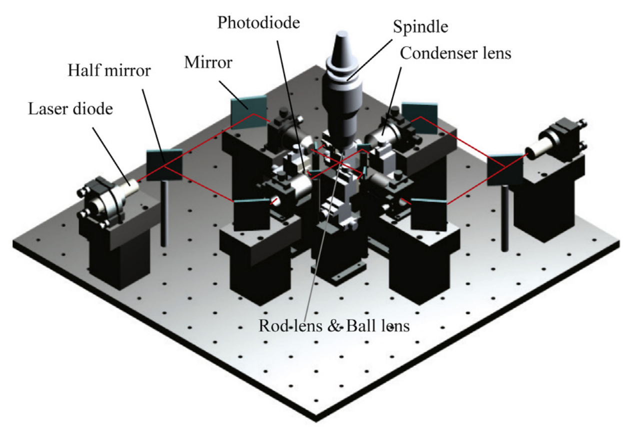
for the simultaneous measurement of five-degrees-of-freedom error motions, the chances are high that they might be used to measure such error motions by the application of multiple sensors. However, the techniques involve the challenge of optically configuring multiple optical instruments such as condenser lenses [16] by mechanical interaction. Moreover, the requirement of multiple sensors such as laser interferometers [17] and laser Doppler vibrometers [18,19] make the systems expensive.

We have therefore developed a simple and low-cost measurement system for the simultaneous measurement of the five-degrees-of-freedom error motions of high-speed microspindles [20]. The cost of this system is a fraction of that of a conventional system using multiple electrostatic capacitance displacement meters. The system consists of a rod lens, a ball lens, four divided laser beams, and multiple divided photodiodes. A spindle rotation error produces a displacement of the rod and ball lenses mounted on the chuck of the spindle, and the displacement is optically measured. We successfully optimized the design parameters of the system by means of ray tracing. Moreover, we fabricated a prototype and demonstrated its usefulness for the simultaneous measurement of the five-degrees-of-freedom error motions of high-speed microspindles by using it for actual measurements. Our experimental evaluation revealed a measurement resolution of 5 nm.

In this paper, the major error factors of the measurement are analyzed. The measurement error due to the form error of the lens is first analyzed by ray tracing, after which the measurement error due to the displacement of an irradiation laser point on a 3 mm diameter ball lens is examined. Finally, the effect of the centrifugal force and the crosstalk problem of multiple laser beams are analyzed.



(a) Schematic diagram



(b) Experimental apparatus

Fig. 2. Measurement system: (a) schematic diagram and (b) experimental apparatus.

2. Measurement principle

Fig. 2 is an illustration of the system used for the measurement of the five-degrees-of-freedom error motions of a high-speed microspindle. This measurement system is composed of a rod lens, a ball lens, four laser beams (L1, L2, L3, and L4), four-condenser lens (CL1, CL2, CL3, and CL4), two dual-element photodiodes (PD1 and PD2), and two quadrant photodiodes (PD3 and PD4). The 3 mm diameter ball lens is affixed to the end of the rod lens of diameter 3 mm, which is mounted on the chuck of the spindle. The stem of the rod lens is irradiated with two focused laser beams emitted by two laser diodes in the *X* and *Y* directions. The two dual-element photodiodes (PD1 and PD2) are opposite to the two-condenser lens (CL1 and CL2), and the rod lens is installed between the condenser lens and the dual-element photodiode in an orthogonal position. The laser beams that penetrate the rod lens reach the two dual-element photodiodes. The intensities of the laser beams detected by the two dual-element photodiodes are converted into voltages denoted by I_{RX1}, I_{RX2}, I_{RY1}, and I_{RY2}, as shown in Fig. 2(a). Similarly, the ball lens is irradiated with a laser beam emitted by the laser diode in the *X* and *Y* directions. The quadrant photodiodes (PD3 and PD4) are opposite to the condenser lens (CL3 and CL4), and the ball lens is installed between the condenser lens and the quadrant photodiode in an orthogonal position. The intensities of the laser beams detected by the two quadrant photodiodes are converted