Simple and Simultaneous Measurement of Five-Degrees-of-Freedom Error Motions for a Micro High-Speed Spindle

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Abstract

We present a simple and low-cost optical measurement system to measure simultaneously five-degrees-of-freedom error motions of high-speed microspindles. In this study, measurement error due to displacement of an irradiation laser spot on a 3 mm diameter ball lens is analyzed. The results show that the maximum error in the Z direction due to the 7 μm displacement of the laser spot in the X direction is about 0.15 nm, i.e., the change of the laser beam irradiation point of the ball lens caused by the radial displacement has little effect on the measurement accuracy.

1 Introduction

It is very difficult to evaluate five-degrees-of-freedom error motions for high-speed microspindles using the conventional method, which simultaneously employs a master ball or cylinder and displacement sensors. Because the reference pieces used in the conventional method, such as the master ball or cylinder, must be large enough to allow the displacement sensors to measure them, they are not appropriate for microspindles. In recent years, some optical techniques to measure high-speed microspindles have been reported, but these methods cannot be applied to a simultaneous measurement of five-degrees-of-freedom errors. We present a simple and low-cost measurement system to measure simultaneously five-degrees-of-freedom error motions of high-speed microspindles.

2 Measurement principle

Figure 1 shows an illustration of the measurement system of five-degrees-of-freedom error motions for a micro high-speed spindle. This measurement system is composed of a rod lens, a ball lens, four laser beams, four condenser lens, and multiple divided photodiodes. The ball lens of 3 mm in diameter is affixed at the end of the rod lens of 3 mm in diameter, which is mounted on the chuck of the spindle. The stem of the rod lens is irradiated with two laser beams emitted by two laser diodes in the X and Y directions. The two dual-element photodiodes (PD1, PD2) are opposite to the two condenser lens, 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, detected by the two dual-element photodiodes, are converted into voltage and are defined as I_{RX1}, I_{RX2}, I_{RY1}, and I_{RY2}, as shown in Fig. 1. 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, PD4) are opposite to the condenser lens, and the ball lens is installed between the condenser lens and the quadrant photodiode in an orthogonal position. The intensities, detected by the two quadrant photodiodes, are converted into voltage and are defined as I_{BX1}, I_{BX2}, I_{BX3}, I_{BX4}, I_{BY1}, I_{BY2}, I_{BY3}, and I_{BY4}, as shown in Fig. 1. Figure 2 (a) also shows a cross section of the rod lens irradiated by the laser beams in the XY plane. When the spindle rotates without rotation errors, the laser intensities measured by each element of each photodiode are equal ($I_{RX1} = I_{RX2}$, $I_{RY1} = I_{RY2}$). When the spindle rotates with rotation errors, the rod lens is shifted in the XY plane and the equality of the light intensity measured by each element of each photodiode is no longer assured. For example, if the rod lens is shifted in the +X direction, then $I_{RX1} = I_{RX2}$ and $I_{RY1} > I_{RY2}$ as shown in Fig. 2 (b). As a result, the direction and magnitude of spindle runout can be ascertained. The output signals, I_{RX} and I_{RY}, of the rod lens in the X and Y directions are defined by Eq. (1) :

$$I_{RX} = I_{RY1} - I_{RY2}, \quad I_{RY} = I_{RX1} - I_{RX2} \tag{1}$$

Similarly, the output signals, I_{BX}, I_{BY} and I_{BZ}, of the ball lens in the X, Y, and Z directions are defined by Eq. (2):

$$I_{BX} = I_{BY1} - I_{BY2} - I_{BY3} + I_{BY4}, \quad I_{BY} = I_{BX1} - I_{BX2} - I_{BX3} + I_{BX4}$$
$$I_{BZ} = I_{BX1} + I_{BX2} - I_{BX3} - I_{BX4} \tag{2}$$

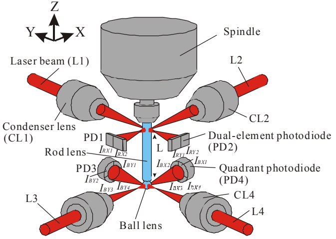
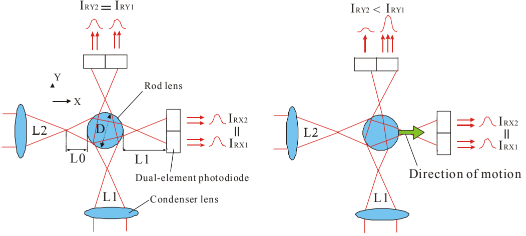


Figure 1: Optical measurement system



(a) Initial state (b) Displacement X

Figure 2: Measurement principle

Because of spindle errors, the output signals, I_{RX}, I_{RY}, I_{BX}, I_{BY}, and I_{BZ}, change when the rod lens and ball lens displace. The radial-motion errors are calculated using I_{BX} and I_{BY}, respectively, and the axial-motion error is calculated using I_{BZ}. The angular-motion errors are calculated using the I_{RX}, I_{RY}, I_{BX}, I_{BY} and the distance L between the laser-irradiated spots of the rod lens and the ball lens (Fig. 1). The distance L is 5 mm. Figure 3 shows the experimentally measured change in I_{RX} and I_{RY} as a function of the rod lens displacement in the ±X direction. The measurement resolution of this system is about 5 nm.

3 Error analysis

Due to the centrifugal force by the eccentricity between the spindle chuck and the rod (ball) lens, the rod lens bends. As the rotational speed increases, the measurement accuracy decreases. Also, when the rod lens and the ball lens displace, the measurement accuracy is affected by roundness of the rod lens and sphericity of the ball lens [1]. Moreover, when the ball lens displaces in the Z direction due to the axial-motion error under the condition that the ball lens displaces in the radial direction, the displacement of the laser irradiation point may affect the measurement accuracy because the output signal I_{BZ} changes in comparison with that under the condition that there is no displacement of the ball lens in the radial direction. For example, Fig. 4 (a) shows the 5 revolutions of measurement result of the radial-motion errors at a rotational speed of 150 krpm in the X direction by the measurement system shown in Fig. 5. A once-per-revolution sine curve of about 7 µm amplitude is included in the measurement data, because the eccentricity that is caused during chucking the rod lens on the chuck and adhering the ball lens to the rod lens exists between the spindle chuck and the ball lens. This sine curve is due to the install error of the ball lens, the error cannot be removed perfectly in the experiment. Therefore, this sine curve is finally removed by software (Fig. 4 (b)). Figure 4 shows the eccentricity of about 7 µm amplitude caused by alignment error. However, when the ball lens displaces in the Z direction under the displacement condition of about 7 µm of ball lens in the radial direction (Fig. 6 (b)), the displacement of the laser irradiation point may affect the measurement accuracy. Because the output signal I_{BZ} changes

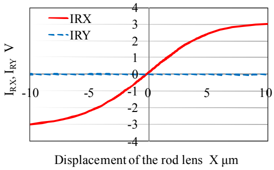
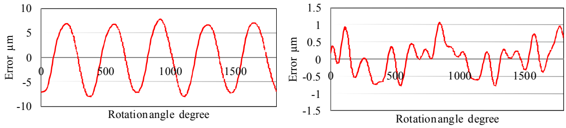


Figure 3: Output voltage I_{RX}, I_{RY}
(±X displacement of the rod lens)

although it does not change at the initial position of the ball lens (Fig. 6 (a)). This effect is analyzed using three-dimensions ray tracing method. First, random numbers with a Gaussian distribution are generated using the Box-Muller method, and the ray based on this distribution is radiated from the condenser lens. The rays are then traced through the optical system, and the intensities expected at each photodiode are calculated. Figure 7 shows the simulation result. The horizontal axis shows the displacement of the ball lens in the Z direction, and the vertical axis shows the difference of the measured value between Figs. 6 (a) and (b). The maximum error is about 0.15 nm. Therefore, the change of the laser beam irradiation point of the ball lens caused by the radial displacement has little effect on the measurement accuracy.



(a) Before compensation (b) After compensation

Figure 4: Measurement result of the radial errors at a rotational speed of 150 krpm in the X direction

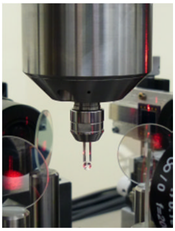
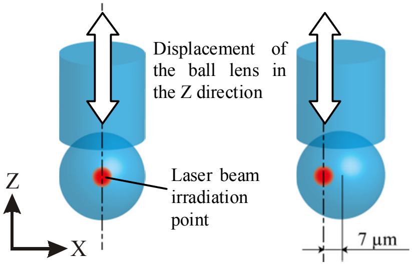


Figure 5: Measurement system for spindle error motions



(a) Initial state (b) Displacement X

Figure 6: Schematic diagram for evaluating the effect of the laser beam irradiation point of the ball lens

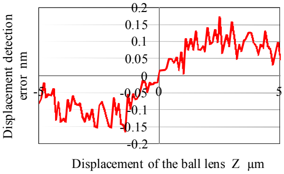


Figure 7: Detection error of displacement of ball lens along Z direction at X = -7 µm

4 Conclusion

We have developed the system to measure five-degrees-of-freedom error motions for a high-speed microspindle, and we revealed that the laser beam irradiation point of the ball has little effect on the measurement accuracy using ray tracing. This study was partly supported by a Grant-in-Aid for Young Scientists (B) from Japan's Ministry of Education, Culture, Sports, Science and Technology of Japan.

References:

[1] Murakami, H. et al., Proc. of the ASPE, (2011), pp.524-527.