A Comprehensive Technique for Measuring the Three-Dimensional Positioning Accuracy of a Rotating Object

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A method for measuring the accuracy of rotating objects was studied. Rotating axis errors are significant; such as the spindle error of a machine tool which results in increased surface roughness of machined work pieces. Three capacitance-type displacement sensors were used to measure the position of a rotating master ball. The sensors were mounted at the three orthogonal points on the spindle axis. The measurement data were analysed for rotating spindle accuracy, not only for the average roundness error but also for the spindle volumetric positional error during rotation. This method is simple and economical for industrial field use for regular inspection of spindles using portable equipment. The time taken for measurement and analysis using this method is only about two hours. This method can also measure microscopic amplitudes in 3-D directions of vibrating objects.

Keywords: Capacitance sensor; Rotating spindle accuracy; Volumetric positioning error

1. Introduction

The rotating error of machines can cause accidents by resonance as well as resulting in shortening the life of the machine. In the case of manufacturing machines, errors of spindle rotation greatly influence the surface characteristics of the work piece and result in a rough surface. This is because the distance between the work piece and tool will be changed slightly owing to the rotating spindle error producing a rough surface. Many studies of spindle vibration and measurement of rotating tool paths have been made to investigate spindle error and improve manufacturing surface quality. Kakino and et al. [1] suggested a procedure and the equipment necessary for measuring rotating spindle error as follows:

Determination of a reference circle using an eccentric cam or rotary encoder and the average circle of the rotating error measurement for each revolution.

Two sensors set up in the axial direction to measure the angular error and one sensor set up to measure the radial movement of the spindle.

The master ball or bar which is installed in the spindle as a reference may involve set-up errors which should be removed. However, most studies have been limited to the measurement of roundness error for a reference circular plane and workers using machine tools are measuring simply the total maximum roundness error for spindle rotation using a mechanical dial gauge and a master bar [2,3]. Figure 1 shows the typical methods for measuring rotating spindle accuracy described in the regulations [4] for machine tools and in other studies. However, the total errors measured for one rotation of a spindle shown in Fig. 2 include the parallel displacement error of the shaft in the axial and radial directions and angular errors, such as pitch, yaw and roll to the direction of rotation. Using the method described in Fig. 1(c), the 3D positioning error of the rotating spindle tip can be measured only at low speed because of the use of contact-type dial gauges.

In this study, to analyse the volumetric errors of the spindle, 3D positions of the rotating reference were measured using a master ball and three capacitance sensors for high-speed measurement. The 3D spindle positioning data for one revolution will be used to trace the rotating tool-tip path in a special angular division. This method will also be applied to the measurement of microscopic 3D displacement of various vibration points as well as to the measurement of the amplitude and direction of rotating objects for analysing vibration characteristics. The proposed system can be used as portable equipment in industry for rapid measurement and analysis using only a notebook PC.

2. Measuring System

2.1 Total System

Figure 3 shows the measuring system for a rotating spindle installed in a machine tool. A precision master ball mounted
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Fig. 1. Typical methods to measure the rotating spindle accuracy using dial gauges and master references. (a) Roundness error measurement. (b) Pitching and yaw error measurement. (c) 3D positioning error measurement.

Fig. 2. (a) Total volumetric positioning error for rotational motion. (b) Definition of 6 error components in a rotating axis.

Fig. 3. Overview of the experimental set-up installed in a machine tool.

Fig. 4. Installation of a master ball with a wobble plate in the spindle and three sensor mountings and an r.p.m. counter.

Fig. 5. A method of sensor calibration using a laser interferometer and a precision x,y-table for measuring ball displacement in two directions. Because the master ball will be placed in 3D space, calibration with a ball is required in two directions, tangential and normal for one sensor as shown in Fig. 5(a). The sensor output voltages and ball displacements were measured by moving the ball in the two directions using an x,y-table. For the measurement of the real displacement of the ball, a laser interferometer with 0.003 μm resolution was used. The 3D position of the master ball is determined from the three sensor output voltages and calibration data using an analytical method. Because the calculation for the master ball position in space includes many iteration procedures, in the

2.2 Sensor Calibration

on a shank was placed in the tool position. The roundness of the tungsten carbide master ball is better than 0.05 μm accuracy. To measure rotation speed and use it as a reference signal for the measuring time base, a gap sensor (r.p.m. counter) was set up at the ball shank. Fig. 4 shows the design of three sensor mounting plates installed in orthogonal directions, and an r.p.m. counter and a master ball to be set up in the spindle. The wobble plate, shown in Fig. 4, was used to minimise the initial set-up error of the ball shank during installation in the spindle. The rotating radius is adjusted and minimised at idling speed using the three precision spring bolts in the wobble plate and measuring the displacements of the master ball. This technique is required to reduce residual set-up error, in the measured data. Using the three capacitance displacement sensors in this study, a 0.1 μm resolution, 1 mm measuring range and a 3.5 kHz sampling rate are available. During measurement, sensor data and r.p.m. measurement signals are interfaced to a PC for calculation using an A/D converter and amplifiers. A hardware or software filter is necessary when using capacitance-type sensors to reduce the effect of noise on the measurement.