Precision Measurement of Cylinder Surface Profile on an Ultra-Precision Machine Tool

[1]J.C. Lee, [1]Y.J. Noh, [1]Y. Arai, [1]W. Gao, [2]C.H. Park

[1]Nano-Metrology and Control Lab, Department of Nanomechanics,
Tohoku University, Aramaki Aza Aoba 6-6-01, Sendai, 980-8579 Japan,
[2]Korea Institute of Machinery and Materials,
Sinseongno Yuseong-Gu, Deajeon, South Korea
Email: leejc@nano.mech.tohoku.ac.jp

Abstract. *This paper describes the measurement of the surface straightness profile of a cylinder workpiece on an ultra-precision machine tool which has a T-base design with a spindle, an X-slide and a Z-slide. The movement range of the X-slide is 220 mm and that of the Z-slide is 150 mm, which have roller bearings in common. Two capacitive sensors are employed to scan a cylinder workpiece mounted on the spindle along the Z-axis. The straightness error motion of the Z-slide is measured to be approximately 100 nm by the reversal method. The straightness profile of the cylinder workpiece is evaluated to be approximately 400 nm by separation of the motion error, simultaneously.*

Keywords: Measurement, Surface Profile, Error Motion, Straightness, Machine Tool, Slide, Reversal Method

1. Introduction

Ultra-precision machine tools are widely used in fabrication of various workpieces such as optical components with three dimensional microstructures. However, the motion error of the ultra-precision machine tool causes profile errors when fabricating the workpiece. It is thus necessary to measure the motion error of the ultra-precision machine tool for evaluation of the machine tool. Usually, a high precision gauge is needed for the measurement of the error motion. On the other hand, it is desired to measure the surface profile of the workpiece on the machine tool from the view point of machining efficiency [1-3]. For this purpose, it is desired to measure the motion error of the machine tool and the surface profile of the workpiece simultaneously [4-6]. In this research, a cylinder workpiece machined on an ultra-precision machine tool is used as the measurement target for simultaneous measurement of the error motion and the surface profile. To separate the two parameters from the sensor output, the reversal technique is employed. By using this method, both the error motion and the surface profile can be measured with a high precision. This paper presents the principle of the reversal method of using high-precision capacitive sensors. Experimental results on an ultra-precision diamond turning machine are also described.

2. Principle of measurement

The reversal method can be applicable for measurement of surface profile and error motion when the machine motion has a high repeatability [7]. The ultra-precision machine tool can satisfy this requirement because the motion of the machine tool slide is repeatable on the order of 10 nm. In this method, it is necessary to rotate the workpiece by 180 degrees and carry out two scans before and after the rotation (reversal). Fig. 1 shows the principle of the measurement by the reversal method. In the first scanning, two displacement sensors are employed to scan the workpiece before the reversal. The sensor outputs can be written as

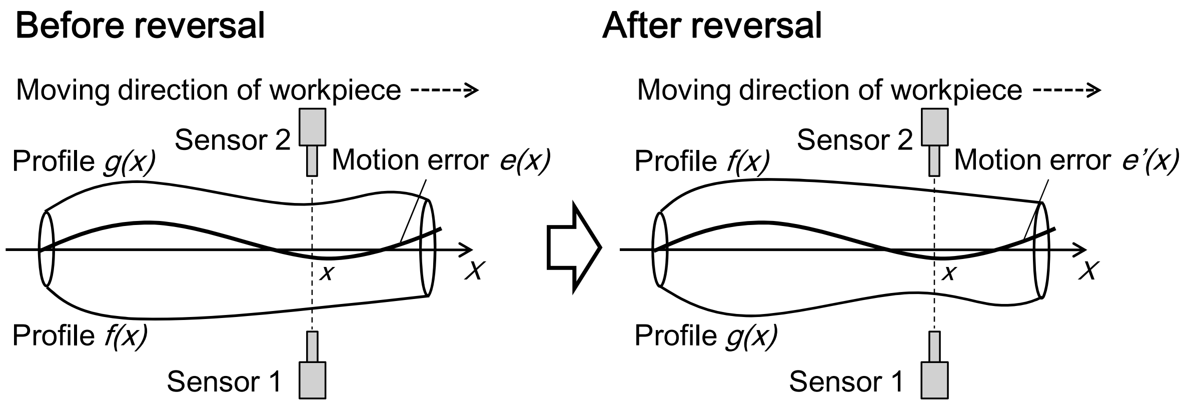

Fig. 1 Principle of the reversal method

$$m_{11}(x) = f(x) + e(x) \tag{1}$$
$$m_{21}(x) = g(x) - e(x) \tag{2}$$

where

m_{11}	sensor output of m_1 before reversal
m_{21}	sensor output of m_2 before reversal
e(x)	motion error of ultra-precision machine tool before reversal
f(x)	profile of the workpiece on the side of sensor 1
g(x)	profile of the workpiece on the side of sensor 2

When the workpiece is moved along the X-axis once again after the reversal, the sensor outputs are changed as follows

$$m_{12}(x) = g(x) + e'(x) \tag{3}$$
$$m_{22}(x) = f(x) - e'(x) \tag{4}$$

where

m_{12}	sensor output of m_1 after reversal
m_{22}	sensor output of m_2 after reversal
e'(x)	motion error of ultra-precision machine tool after reversion

From the above equations, the motion error e(x) and the surface profiles f(x), g(x) can be calculated as follows

$$e(x) = \left(m_{11}(x) - m_{22}(x)\right)/2 + \Delta e(x) \tag{5}$$
$$f(x) = \left(m_{11}(x) + m_{22}(x)\right)/2 + \Delta e(x) \tag{6}$$
$$g(x) = \left(m_{21}(x) + m_{12}(x)\right)/2 + \Delta e(x) \tag{7}$$

where

$$\Delta e(x) = \left(e(x) - e'(x)\right)/2 \tag{8}$$

Eq. 8 can be ignored because the motion of the ultra-precision machine tool has a high repeatability. Therefore, the motion error and profiles can be calculated in Eqs. (5)-(7) without considering Δe(x).

3. Experiments

Fig.2 shows the experimental system for measurement of the Z-slide straightness of an ultra-precision diamond turning machine and the surface straightness of the cylinder workpiece. Two capacitive sensors were employed in the measurement. Each of the sensors has a measurement range of ±50 μm, a resolution of 2 nm and a foot print of 1 mm. The sensor outputs were acquired by synchronizing them with the signal from a linear encoder which is used to the accurate position of the Z-slide. On the other hand, the Z-slide of the machine tool has a 150 mm stroke, a positioning resolution of 10 nm, and a positioning accuracy of ±50 nm. The air spindle has 50 nm rotational accuracies in the radial direction and the axial direction. Fig. 4 shows the results of the stability test, in which the machine tool was kept stationary. The test term was 10 min, and the sampling interval was 10 ms. As can be seen in the figure, the instability was measured to be 50 nm, which includes low-frequency components caused by thermal drift of the mechanical structure of the slide and long-term instability of the air pressure. The high-frequency components of the data came from the vibration of the machine tool. The cylinder workpiece was moved by the Z-slide for straightness measurement. The two capacitive sensors, which were kept stationary on the machine tool, scanned the both sides of the cylinder workpiece. After rotating the workpiece by 180 degrees, the workpiece was moved along the Z-axis once again. The length of measurement was 126 mm, the moving speed was 800 mm/min and the sampling interval was 180 μm. The reversal of the workpiece was carried out by the air-spindle. The straightness error of the Z-slide was measured to be approximately 100 nm. Fig. 6 shows the evaluated profiles of the cylinder workpiece by separation of the motion error. As shown in Fig. 6, the workpiece has a straightness error of approximately 400 nm.

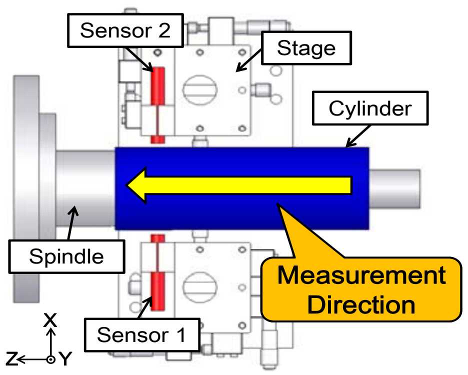

Fig. 2 Experimental system

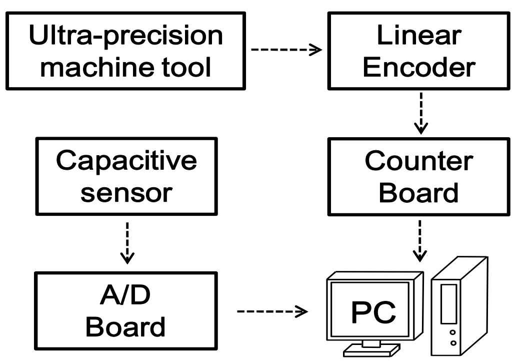

Fig. 3 Diagram of experimental setup

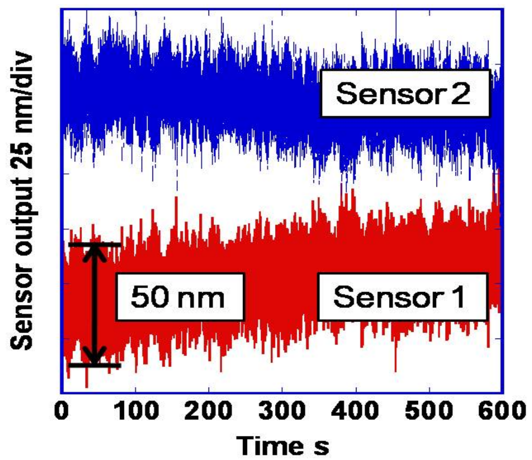

Fig. 4 Stability of sensor

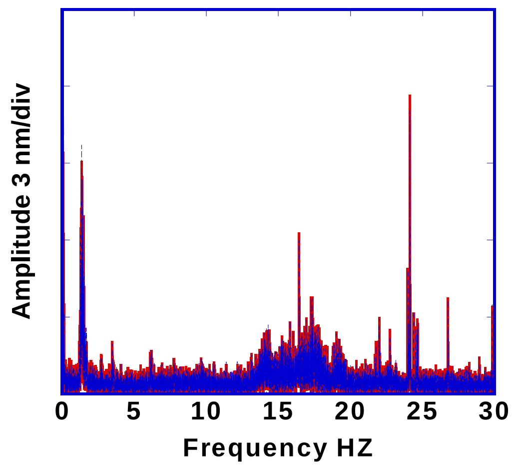

Fig. 5 Spectrum of the stability of sensor

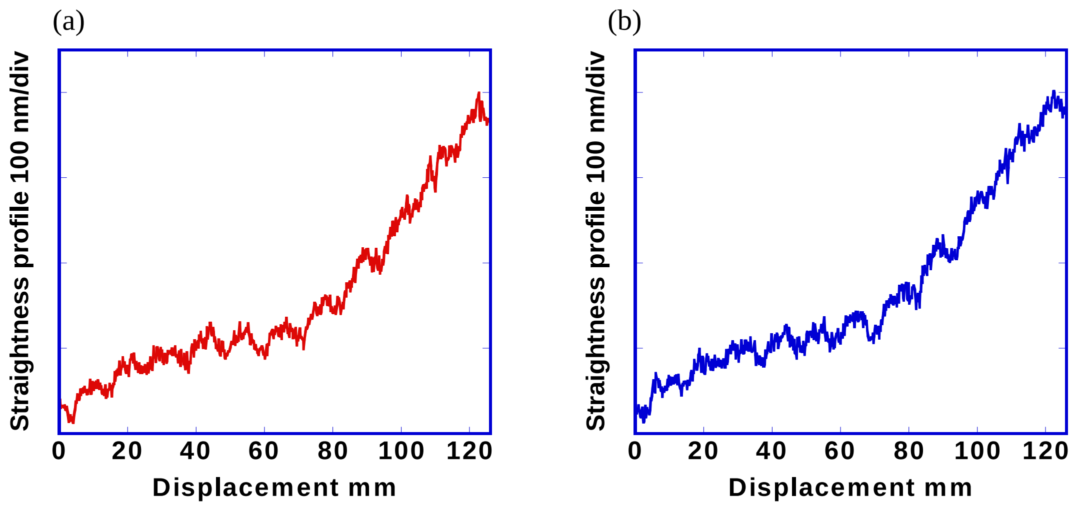

Fig. 6 Evaluated profile of cylinder: (a) profile of f(x) and (b) profile of g(x)

Conclusions

A measurement system that can measure the surface profile of a cylinder workpiece and the motion error of an ultra-precision machine tool at the same time has been established. It was confirmed that the straightness error of the Z-slide of the machine tool was approximately 100nm and the straightness profile of the workpiece was measured to be approximately 400nm.

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