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A Novel Calibration Method of Angular Misalignment in FTS-Based Diamond Turning

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With technological progresses in optics fields, such as VR and 3D sensing technologies, the demand for optical lenses with complex shapes, like freeform surfaces, has significantly expanded in recent years. Ultra-precision diamond turning is one of the main manufacturing methods for freeform optics. There are two tool motion mechanisms in freeform diamond turning: slow tool servo (STS), which moves the entire tool rest, and fast tool servo (FTS), which only drives the diamond tool tip. Especially, in FTS-based diamond turning, high-frequency and long-stroke FTS units driven by a separate control system from the machine tool controller are recently developed as a new trend. However, this kind of independent FTS control system causes a time delay between the machine tool instruction and the FTS tool motion. Even a small time delay on the microsecond scale can cause a large angular misalignment due to the high spindle rotation speed during FTS machining. In this study, a novel method was proposed to measure the time delay from the machined surface with microsecond scale accuracy and to compensate for the misalignment based on the measured time delay. To measure the time delay, a spherical dimple in the workpiece center and eight spherical dimples at an angular space of 45° on the outer region of the workpiece were machined by using the STS, and another eight spherical dimples were machined by using the FTS. The angular misalignment and time delay values were successfully obtained by comparing the measured positions of the spheres machined by the FTS and the STS. Based on the measured time delay, detected C-axis tool positions were corrected to be at the position after the time delay by considering the cutting velocity during machining, and the angular misalignment was reduced from 1.149° to 3.47×10^{-4}°. This proposed calibration method of angular misalignment for independent FTS unit is expected to significantly improve the accuracy of ultra-precision machining by FTS-based diamond turning.

1. Introduction

Technological developments in optical element manufacturing in recent years have made it possible to fabricate lenses with complex shapes such as aspherical and freeform surfaces [1]. Especially, freeform lenses can achieve high optical efficiency with a small number of optical components due to the flexibility of their shape design, and thus the freeform lenses have been used as components of head-mounted displays used in VR and AR technologies, etc., in recent years [2]. Improvement in accuracy and production efficiency of freeform lenses can achieve more contribution to those fields.

Ultra-precision diamond turning by using an independent fast tool servo (FTS) unit equipped with a voice coil, which enables high-speed and long-stroke machining, has a huge potential to realize more efficient manufacturing of freeform lenses [4]. However, the independent FTS unit is controlled by a dedicated control system separate from the machining tool controller. Therefore, there is a problem of time delay between the two control systems because the FTS tool movement is controlled after the command instruction of the machine tool controller. Since this time delay causes angular misalignment, there is a need for a method to measure the time delay precisely and compensate for the misalignment.

In this study, a novel calibration method of angular misalignment in FTS-based diamond turning was proposed. The effectiveness of the proposed calibration method was validated by measuring the time delay in the first cutting experiment and compensating for the time delay in the second cutting experiment.

2. Theory and Method

2.1 System Control Flow

As shown in Fig. 1, the X- C-, and Z-axes are moved by the machine tool controller, and the w-axis is moved by an independent FTS unit's controller in accordance with the movement of the X-axis and C-axis. In the FTS controller, the command generator calculates the tool stroke amount based on the output tool position coordinate values during machining. However, the problem of time delay occurs in FTS machining due to the use of two different controllers. The W-axis movement by FTS controller inevitably starts with a time delay because the FTS controller determines the w-axis tool stroke

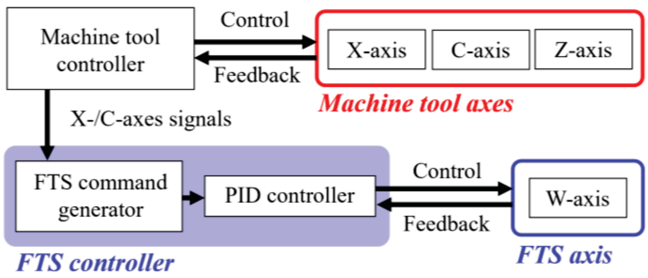


Fig. 1 Control flow of an independently controlled FTS.

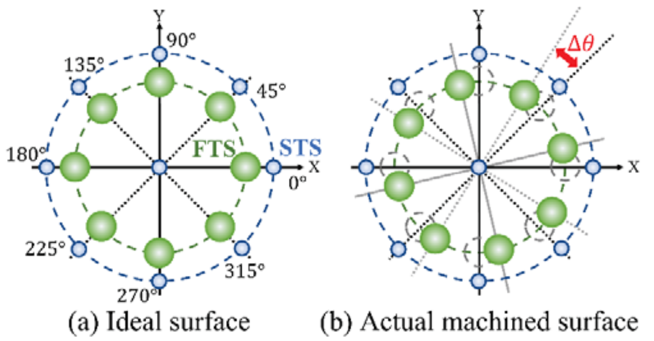


Fig. 2 (a) Designed surface and (b) actual machined surface for measuring the time delay.

amount and moves the tool after obtaining the machine controller's feedback data. The time delay caused by this signal processing is expected to be very small, on the microsecond scale. However, even a small time delay can cause a large angular misalignment due to the high spindle rotation speed during FTS machining. For example, if the rotation speed and time delay are 500 rpm and 100 µs, respectively, an angular misalignment of 0.3° will occur. This FTS-induced angular misalignment will lead to a form error which is much larger than the error produced in conventional slow tool servo (STS) machining, especially in the occasion when performing combination cutting with STS and FTS, or when the workpiece is not cylindrical form.

2.2 Designed Surface for Time Delay Measurement

To measure accurately the time delay from the machined sample surface, a surface was designed for STS and FTS maching as shown in Fig. 2. The green and blue spherical dimples are machined by STS and FTS, respectively. This designed surface consists of spherical dimples machined by FTS and STS at an angular space of 45° on the outside of the workpiece, and a spherical dimple machined by STS in the workpiece center. On the designed surface, spherical dimples are aligned in a line, as illustrated in Fig 3(a). However, on the actual workpiece surface, only the FTS spherical dimples are shifted to the rotational direction due to the time delay, as illustrated in Fig. 3(b). By measuring this angular misalignment $\Delta\theta$, the time delay value Δt can be obtained as follows:

$$\Delta t = \Delta\theta / 6s \ \#(1)$$

where s is spindle rotation speed. By conducting these calculations with every eight spherical dimples of FTS and STS placed at an

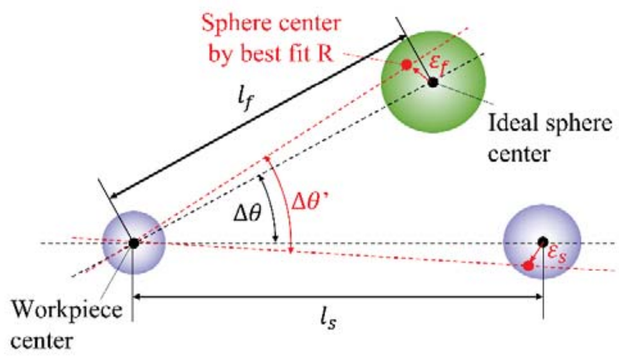


Fig. 3 Schematic of shifted angle change by spherical fitting error

angular space of 45°, the average misalignment and time delay values in the independent FTS-based diamond turning can be determined.

2.3 Measurement Accuracy of Time Delay

The position of each spherical dimple can be determined by fitting the sphere to the measured profile data. However, sphere center detection errors occur at the spherical dimples of FTS and STS in the outside region of the workpiece due to the form error of the machined surface. These sphere center detection errors cause changes in the positional relationships of the spherical dimples of FTS and STS, which lead to errors in the time delay measurement, as shown in Fig. 3. Hence, the parameters that can be adjusted to reduce the measurement error of the time delay need to be calculated theoretically.

According to Fig. 3, the measurement error of time delay Δt_ε caused by the sphere center detection error can be expressed as follows:

$$\Delta t_\varepsilon = \frac{\Delta\theta' - \Delta\theta}{6s} \#(2)$$

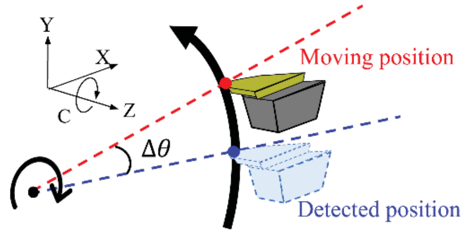
where $\Delta\theta'$ is the amount of shift in the cutting direction of the FTS dimple which is calculated when a sphere center detection error occurs. In this case, the maximum possible value of measurement error $\Delta t_{\varepsilon-max}$ is as follows:

$$\Delta t_{\varepsilon-max} = \frac{\sin^{-1}\left(\frac{\varepsilon_f}{l_f}\right) + \sin^{-1}\left(\frac{\varepsilon_s}{l_s}\right)}{6s} \#(3)$$

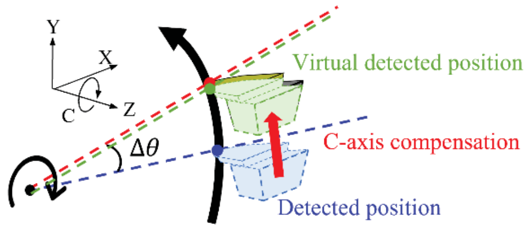
where l_f and l_s are the distances of the outer STS and FTS from center spherical dimple, and ε_f and ε_s are the detection errors of spherical dimples machined by STS and FTS, respectively. The above equation shows that the maximum measurement error is determined by the five variables l_f, l_s, ε_f, ε_s and s. By setting these five variables properly when determining the detailed conditions, a high-accurate measurement of time delays can be achieved.

2.4 Time Delay Compensation

By correcting the measured time delay during machining, precise machining without angular misalignment is possible with an independent FTS unit. To compensate for the time delay, a program, which redefines a detected C-axis coordinate value of tool position based on measured time delay, was applied to the FTS controller. As shown in Fig. 4(a), before the time delay compensation, the detected



(a) Detected and moving tool position



(b) Virtual detected position by C-axis compensation

Fig. 4 Schematic of (a) detected and moving tool position and (b) virtual detected position by time delay compensation

and moving tool positions are different due to time delay. However, by compensating for the detected C-axis tool position according to the following equation, the exact stroke amount at the position where the tool starts to move can be calculated.

$$c_{comp} = c_o + \omega \Delta t \#(4)$$

where c_{comp} and c_o are the values before and after compensation of the detected C-axis tool position, and ω is the angular velocity of spindle rotation.

By applying this correction to the detected C-axis value, a virtual detection position is set at the position where the tool starts to move, as shown in Fig. 4(b), and the command generator calculates the tool stroke amount based on this virtual detected position. The proposed compensation method is expected to reduce the angular misalignment caused by time delay.

3. Experimental Procedures

The time delay was measured and corrected by machining the designed surface with the fast tool servo FTS-5000 (AMETEK Precitech Inc.) attached to the NanoformX (AMETEK Precitech Inc.) ultra-precision diamond turning machine, as shown in Fig. 5. The FTS unit used in this study has a maximum stroke of 5 mm and a maximum frequency of 440 Hz. When machining FTS and STS spheres, the Z-axis and W-axis are fixed, respectively. The design surface parameters and the conditions of the cutting experiment are shown in Tables 2 and 3. Based on Equation (3), parameters related to the measurement accuracy of time delays have been adjusted. A round-nosed single-crystal diamond tool with a nose radius of 0.19 mm, a rake angle of 0°, and a clearance angle of 7° was used in the experiment, and an oxygen-free copper cylinder with a diameter of 50 mm was used as a workpiece. The cutting experiment was conducted twice, before and after the time delay compensation. In the first experiment, the time delay was measured, and the compensation

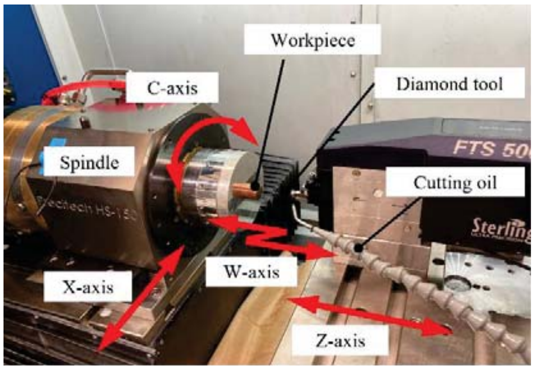


Fig. 5 Experimental setup of FTS-based diamond turning

Table 1 Parameters of designed form

	FTS	Center	STS
Curvature radius (mm)	11.3	1.13	0.19
Depth (mm)	2.6	2.6	1
Sphere location (mm)	R16	0	R18

Table 2 Cutting condition of each spherical dimple

	FTS	Center	STS
Rotation speed (rpm)	500	25	0.4
Feed rate (μm/rev)	1	1	0
Depth of cut (μm)	Rough: 2.6	Rough: 2.6	Fine: 1
	Fine: 1	Fine: 1	
Cutting area (mm)	R15~17	R0~0.1	R18
Coolant	Oil mist	Oil mist	Oil mist

process described in Section 2.4 was applied in the second experiment based on the measured time delay. A digital microscope VHX1000 (Keyence Co., Ltd.) and an ultrahigh accurate 3-D profilometer UA3P 5000H (Panasonic Co., Ltd.) were used to measure the machined surface.

4. Results and Discussions

4.1 Before Time Delay Compensation

Fig. 6 shows an enlarged view of the machined surface observed under a microscope. By comparing the position of the spherical dimple machined by FTS and STS, it is confirmed that the position of the FTS spherical dimple is angularly shifted by a time delay visually. Form error and position of each spherical dimple were measured by a 3-D profilometer. The average peak-to-valley (P-V) values for spherical dimples of center, FTS, and STS were 129 nm, 564 nm, and 96 nm, indicating that ultra-precision cutting was performed. Angular positions of the STS and FTS sphere dimples were calculated relative to the sphere dimple of the STS at 0°. The amount of the shift from the ideal position for each calculated angular position were shown in Fig. 7. These measured results indicated that the time delay during machining causes a large angular misalignment in the FTS machining, and the average angular shifted amount is 1.149°. Based on the measured shifted angle of the FTS spherical dimple, time delay value

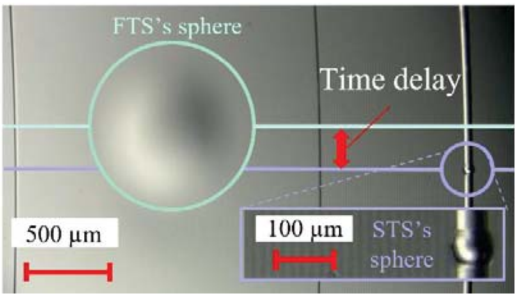


Fig. 6 Enlarged view of machined surface by microscope (Before time delay compensation)

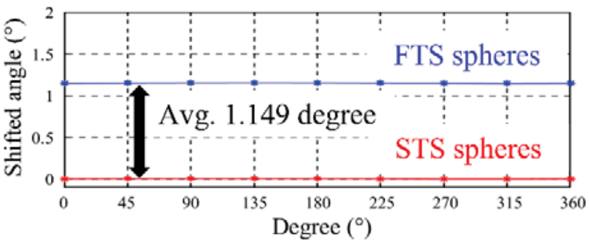


Fig. 7 Measurement results of shifted angle from each ideal position (Before time delay compensation)

was obtained from Equation (1). The mean value of the acquired time delay was 383.1 μs, with a standard deviation of 0.461 μs.

4.2 After Time Delay Compensation

An enlarged view of the machined surface applying time delay compensation is shown in Fig. 8. Compared with Fig. 6, it can be visually seen that angular misalignment has been improved. Average form errors were 216 nm, 517 nm, and 155 nm for spherical dimple of center, FTS and STS, respectively. Fig. 9 shows the results of the angular position deviation of each sphere from its ideal position. The average angular misalignment before compensation was 1.149° while it has been reduced to 3.47×10^{-4} ° after the compensation, indicating the effectiveness of the proposed compensation method. Based on these measured shifted angles, the residual time delay mean value after compensation was calculated. Calculated mean time delay values before and after time delay compensation were summarized in Table 3. Time delay mean value of 0.1 μs with a standard deviation of 0.226 μs after compensation, indicating that the proposed compensation method successfully corrected the time delay with an accuracy of less than 1 μs. The time delay after the compensation was reduced by 99.97 % compared to that before the compensation.

5. Conclusions

This study proposed a novel method to measure the microsecond level time delay in an independent FTS unit and then compensate for the angular misalignment according to the measured time delay. The parameters necessary to improve the measurement accuracy were clarified theoretically. Cutting experiments based on these parameters revealed that the time delay of the independent FTS unit used in this experiment was 383.1 μs with a standard deviation of 0.461 μs. Based on this measured time delay, the cutting experiment was reperformed under the same cutting conditions using the proposed time delay compensation method. After the compensation, the residual time delay was 0.1 μs, reducing the time delay by 99.97%. This proposed calibration method of the angular misalignment which is caused by the time delay of independent FTS unit is expected to improve the accuracy of ultra-precision machining by FTS-based diamond turning.

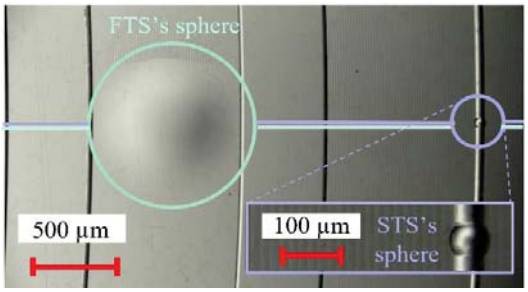


Fig. 8 Enlarged view of machined surface by microscope (After time delay compensation)

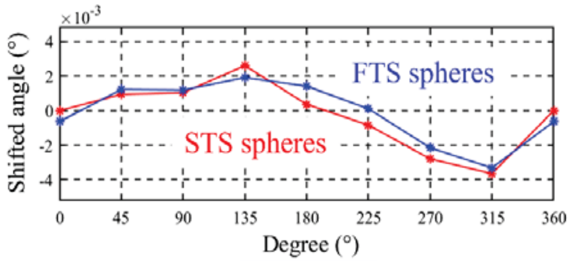


Fig. 9 Measurement results of shifted angle from each ideal position (After time delay compensation)

Table 3 Summary of measured time delay values

	AVG. (μs)	STD. (μs)
Before time delay compensation	383.1	0.461
After time delay compensation	0.1	0.226

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