https://doi.org/10.20965/ijat.2021.p0225

Paper:

Profile Measurement Using Confocal Chromatic Probe on Ultrahigh Precision Machine Tool

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[Received January 30, 2020; accepted September 25, 2020]

An on-machine measurement (OMM) system is an effective apparatus for achieving an efficient profile compensation and improving machining conditions in ultrahigh precision machining. Herein, we report a new OMM system with a confocal chromatic probe on a five-axis ultrahigh precision machine tool constructed using a real-time position capturing method. The probe and machine tool positions are captured synchronously using a personal computer to generate profile measurement data. Long- and short-term stability, micro step response, and repeatability tests using an optical flat indicates that the system has a precision of approximately ±10 nm. The profile measurement test using a reference sphere indicates that the precision of the OMM system deteriorated at a large slope angle of ±45°. However, the overall accuracy is estimated to be within ±100 nm at a slope angle within ±15°. The linearity test at various slope angles indicates that the decrease in reflected light from a mirror-like surface deteriorates the performance of the probe.

Keywords: on-machine measurement, ultrahigh precision machine tool, confocal chromatic probe

1. Introduction

Aspheric or free-form surfaces are widely used in precision optics for mobile phone cameras, telescopes, head-worn displays, neutron-focusing mirrors, etc. because such surfaces can improve the optics performance [1, 2]. To satisfy practical requirements in free-form machining, such as large diameters and complex structures, a fast or slow tool servo diamond turning on ultrahigh precision machine tools has been developed and is widely regarded as a promising technique because of its capacity to efficiently generate complicated surfaces with submicron accuracy and nanoscale roughness [3–5]. Cutting high-precision non-axisymmetric optical surfaces is beneficial but challenging. Although ultrahigh precision machining can process highly accurate and complex free-form surfaces, many factors may cause shape errors, such as axis straightness, scale interpolation error, thermal deformation, and vibration [6, 7].

To rectify these shape errors, it is crucial to measure the surface profile value of the machining workpiece during the compensation process [8, 9]. Many commercial profile metrology equipments for machining ultraprecision surfaces are available, e.g., contact or non-contact profilometers, laser interferometers, white light interferometer microscopes, and atomic force microscopes. However, the use of these off-machine measuring methods requires the removal of the workpiece from the machine tool, which may introduce setting errors and reduce the manufacturing efficiency. Hence, on-machine measurements (OMMs) and error compensation based on measurement results must be performed. Several methods can be used to perform OMMs, for example, scanning tunneling microscopy, atomic force microscopy, auto focus laser probing, sapphire microprobing, dispersed reference interferometry, and white-light interferometry [10–18]. Recently, in non-contact measurement methods, confocal chromaticity has become more noticeable owing to the high measurement accuracy and stability afforded [19–21]. The measurement principle of a confocal chromatic probe is that chromatic aberrations are generated through shite-light illumination, and only the light focused on the object is reflected by the confocal optics, from which the maximum intensity wavelength is detected by a spectrometer to obtain displacement information.

In our previous studies, we developed the OMM system of an ultrahigh precision machine tool using a confocal chromatic sensor and a real-time position capturing system [22]. Using this system, we measured the optical flat and demonstrated periodic displacements during X-axis motion. However, we did not achieve a precise synchronization between the confocal chromatic sensor and the scale data from the machine tool.

In this study, we constructed a new synchronization mechanism between a confocal chromatic probe and the scale data of a machine tool such that the precision, accuracy, stability, and repeatability of the system can be evaluated effectively.

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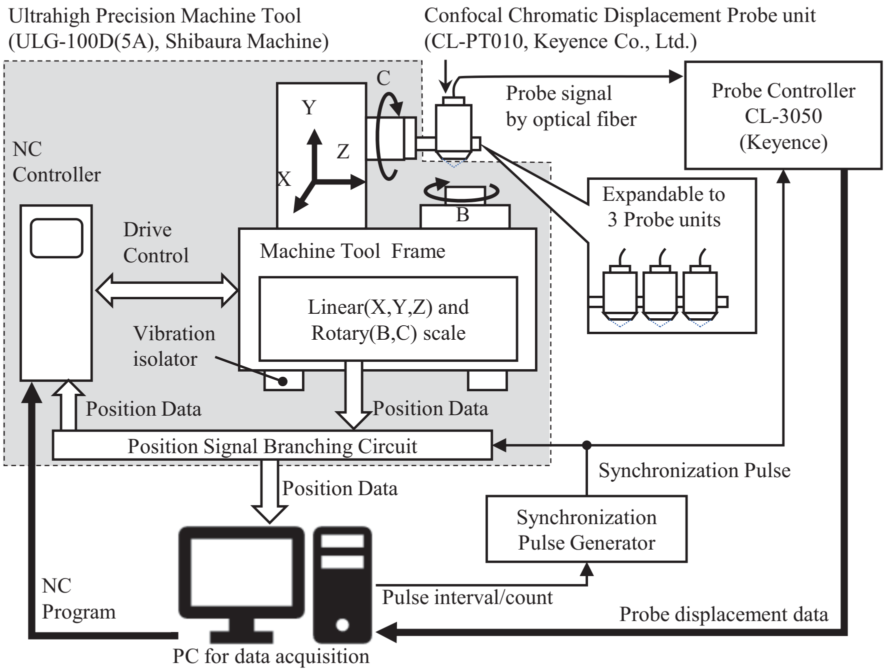


Fig. 1. Configuration of on-machine measurement system.

2. Configuration of OMM System

Figure 1 shows a diagram of the OMM configuration, which comprises four main parts: an ultrahigh-precision machine tool, a confocal chromatic sensor, a synchronization pulse generator, and a personal computer (PC). We used the OMM system to obtain the machine tool position data, measure the workpiece profile, and evaluate the motion accuracy of the machine tool.

The five-axis ultrahigh precision machine tool (ULG-100D (5A), Shibaura Machine Co., Ltd.) used in these experiments comprises three linear axes (XYZ) guided by V–V rollers with a 0.1 nm resolution linear scale driven by linear motors. The X- and Z-axes move along the horizontal direction, whereas the Y-axis moves along the vertical direction with motion ranges of 450, 350, and 150 mm, respectively. The two rotational axes (B, C) of the tool are pneumatic bearings with rotary encoders of $1/100{,}000°$ resolution driven by direct-drive AC servo motors. The machine tool was placed in a double constant temperature chamber. The outer and inner chamber temperatures were controlled to $23 \pm 0.5°$C and $23 \pm 0.01°$C, respectively. In addition, the machine was equipped with a pneumatic vibration isolator. The data of five-axis encoders were sent to the branching circuit and then passed on to the NC controller for machine tool motion control, whereas the position data were captured by the trigger signal and subsequently transferred to the PC [23]. The captured linear encoder data sent to the PC had a resolution of 1 nm only.

The confocal chromatic sensor was composed of a confocal chromatic displacement probe (CL-PT010, Keyence Co., Ltd.) and a probe controller (CL-3050, Keyence Co., Ltd.). The white light source was transmitted from the probe controller to the displacement probe by the optical fiber, and the white light focused by a chromatic dispersive lens exhibited different focal points based on its wavelength. When the light was scattered or reflected on the measurement surface, the spectra of the reflected/scattered light corresponded to the height of the surface. Subsequently, the reflected/scattered light was transmitted back to the probe controller through a chromatic dispersive lens and optical fiber. The probe controller analyzed the reflected/scattered light using a spectrometer and determined the central wavelength to calculate the displacement. The probe displacement data were captured by the trigger signal and subsequently transmitted to the PC. The working distance of the probe was 10 mm, and the focal depth corresponding to the measurement range was ± 0.3 mm. The spot diameter of the probe was 3.5 μm, the linearity was within ± 0.09 μm, the resolution of the probe was 1 nm, and the maximum measurable slope angle was $\pm 45°$ according to the specification data sheet provided by the manufacturer.

The PC in the OMM system obtained two types of position data, i.e., the five-axis coordinates $(X_M, Y_M, Z_M, B_M, C_M)$ of the machine tool and the displacement Y_P measured by the probe. The rotational positions of the B and C axes were not used in this experiment.

We generated the point cloud data $\boldsymbol{W}$ of the measured surface of the workpiece from the three-dimensional coordinates $\boldsymbol{M}$ of the machine tool and probe displacement coordinates $\boldsymbol{P}$ based on the equations below.

$$\boldsymbol{M} = (X_M, Y_M, Z_M) \quad \text{(1)}$$

$$\boldsymbol{P} = (0, -Y_P, 0) \quad \text{(2)}$$

$$\boldsymbol{W} = \boldsymbol{M} + \boldsymbol{P} = (X_M, Y_M - Y_P, Z_M) \quad \text{(3)}$$

We used one displacement probe in this experiment, and the direction of the probe data $\boldsymbol{P}$ was opposite to that of Y_M.

A trigger pulse generator was used to send synchronization pulses to the branching circuit and probe controller to capture the position and displacement data simultaneously. Subsequently, they were transferred to the PC and rearranged using a time stamp.

In our previous studies, we constructed an OMM system using the same machine tool and confocal chromatic sensor; however, a synchronization mechanism was not used. Therefore, a detailed profile data analysis or motion accuracy evaluation was not possible [22]. The position capture precision in terms of time delay was estimated to be ± 1 μs since the capturing clock cycle of the branching circuit was 1 μs. When the machine was moving at a velocity of 100 mm/min, 1 μs corresponded to 1.6 nm, which appeared to be sufficiently precise for this experiment.

3. Experiments

We used a glass optical flat as a reference flat and a silicon nitride hemisphere as a reference sphere to evaluate the measurement performance of the developed OMM system.

Four experiments were conducted using the reference flat to verify the system stability against vibration, noise, and temperature change, as well as its submicrometer step response, repeatability, and the machine tool straightness. The reference flat had a diameter of 101.6 mm and a flatness of 31.64 nm ($\lambda/20$, whereas $\lambda = 632.8$ nm). To confirm the flatness error distribution of the reference flat, we measured it using a Fizeau laser interferometer (Verifier QPZ, ZYGO). The peak-to-valley form deviation was 34.76 nm.

Two experiments were conducted using the reference sphere to verify the profile accuracy and linearity at the sloped surface. The reference sphere, which was made of silicon nitride, had a radius of 5.55675 mm. Furthermore, the form accuracy measured using a three-dimensional high precision profilometer (UA3P, Panasonic Production Engineering Co., Ltd.) was less than ± 100 nm for a slope angle within $\pm 45°$ and less than ± 50 nm within $\pm 30°$.

3.1. Short-Term Stability Test

A reference flat was set on the B-axis rotational table, and its surface was measured using the probe set on the Y-axis; subsequently, the stability of the measurement was tested. The first test was a short-term stability test. A measurement time of 5 s was started 1 h after the apparatus was set up. We compared the Y-axis position data and the displacement probe data when the machine tool was stationary to verify the short-term stability and vibration level. The sampling period of the probe was 128 ms, whereas the axis position sampling period was 10 ms. **Fig. 2** shows the results of the short-term stability test.

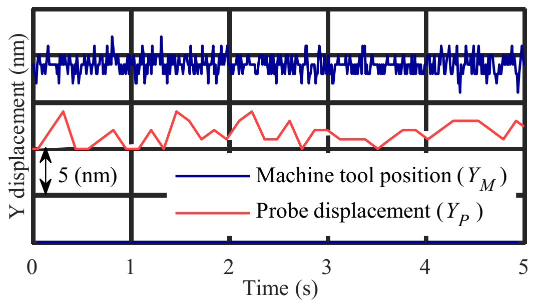


Fig. 2. Short-term stability test.

The standard deviations of the Y-axis position and probe displacement were 1.0 and 1.2 nm, respectively. Moreover, the amplitude error was 1 nm in the time period of 5 s. This indicates that the OMM system has a stability of approximately 1 nm. The effect of floor vibration or machine tool position control error was estimated to be less than or equal to this level.

3.2. Long-Term Stability Test

The thermal expansion of a machine tool due to temperature fluctuations affects the accuracy of the OMM system; occasionally, large workpieces must be measured over a long time period (more than several hours). Therefore, we evaluated the stability of the measurement accuracy and temperature fluctuations over a long period.

To verify the long-term temperature fluctuation stability, all the axes of the machine tool were maintained stationary for 24 h. We used the output value of the OMM displacement probe in the Y-axis direction of the machine to evaluate the long-term stability. The setup of the reference flat and the sampling period were the same as those detailed in Section 3.1. Three temperature sensors were placed to measure the temperature variation. T_1 was measured in the inner chamber air outlet. T_2 was measured at the exhaust of the cooling fan of the probe controller, which was located inside the outer chamber. T_3 is the temperature outside the outer chamber.

Figure 3 shows the long-term measurement results. The displacement drifted approximately 200 nm in 24 h.

Figure 4 shows the temperature changes. Within approximately 5 h after the start of measurement, the displacement appeared to be affected by temperature changes during probe installation. After 5 h from the start, some correlations might appear between the T_2, likely due to the heat generated by the probe controller and the temperature drift inside the outer chamber. Such drifts may be reduced if the probe controller is placed inside the inner chamber; however, it was impossible because of space limitations.

3.3. Micro Step Motion Test

A micro step motion test was conducted to verify the motion characteristics of the machine tool and probe. The step interval was set to 5 s, and the step height was set to

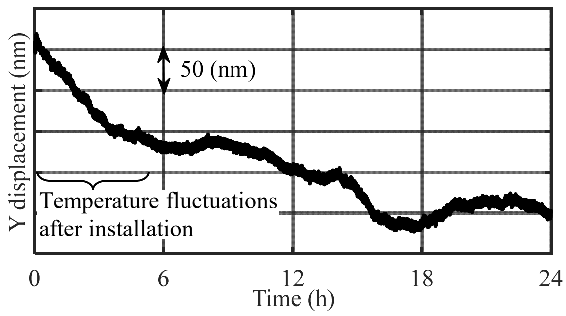


Fig. 3. Long-term stability test for 24 h.

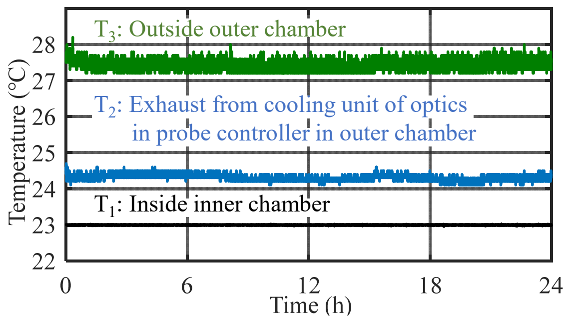
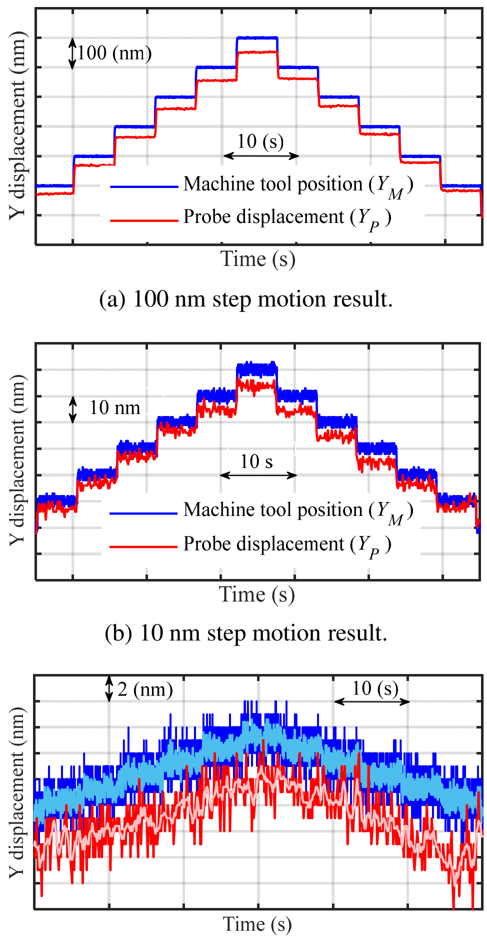


Fig. 4. Temperature fluctuation for 24 h.



(a) 100 nm step motion result.

(b) 10 nm step motion result.

(c) 1 nm step motion result (light blue: five-point moving average of Y_M; pink: five-point moving average of Y_P).

Fig. 5. Micro step response test without synchronization (blue: Y position of machine tool Y_M; red: probe displacement Y_P).

100, 10, and 1 nm. The feed rate was 10 mm/min. The setup of the reference flat and the sampling period were the same as those described in Section 3.1.

As shown in **Fig. 5**, with step heights of 100, 10, and 1 nm, reciprocating motions were observed as motion commands. At a 1 nm step motion (**Fig. 5(c)**), because of the probe fluctuations, a step-like response was not observed, but the 10 nm reciprocation motion was observed. At 100 and 10 nm step motions, a clear step-like response was observed. Hence, the machine tool and the probe responded to a motion command of a few nanometers. The experiments described in Sections 3.1–3.3 did not involve a synchronization pulse generator because those experiments did not require an exact synchronization.

3.4. Profile Measuring Accuracy and Repeatability Test by Reference Flat

The profile measurement accuracy and repeatability depend on the machine tool motion accuracy and probe stability. The reference flat was measured using the OMM system based on a synchronization pulse. The reference flat was set on the B-axis, and the probe measured a unidirectional straight line of 100 mm along the X- and Z-axes on the reference flat (**Fig. 6**). The reference flat was measured five times to verify the repeatability of the system. The feed rate was 10 mm/min. The position sampling was synchronized, and the sampling period was 100 ms.

Figures 7(a) and **(c)** show the results of the X- and Z-axes direction measurement results. The horizontal axis shows the position of the X- or Z-axis, and the vertical axis shows the profile of the measured surface by subtracting the probe data (Y_P) from the Y-position data (Y_M).

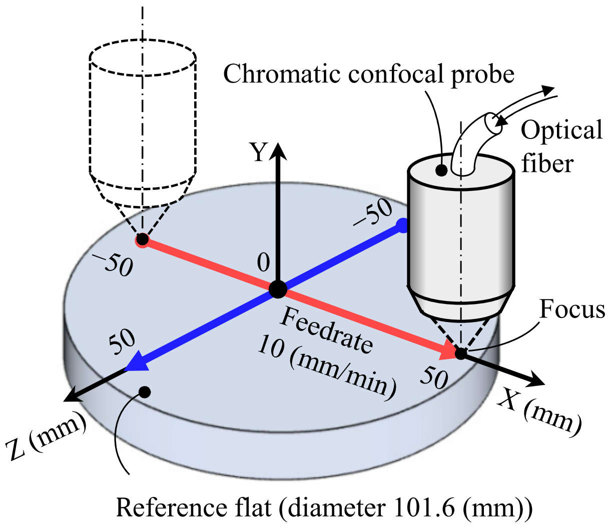
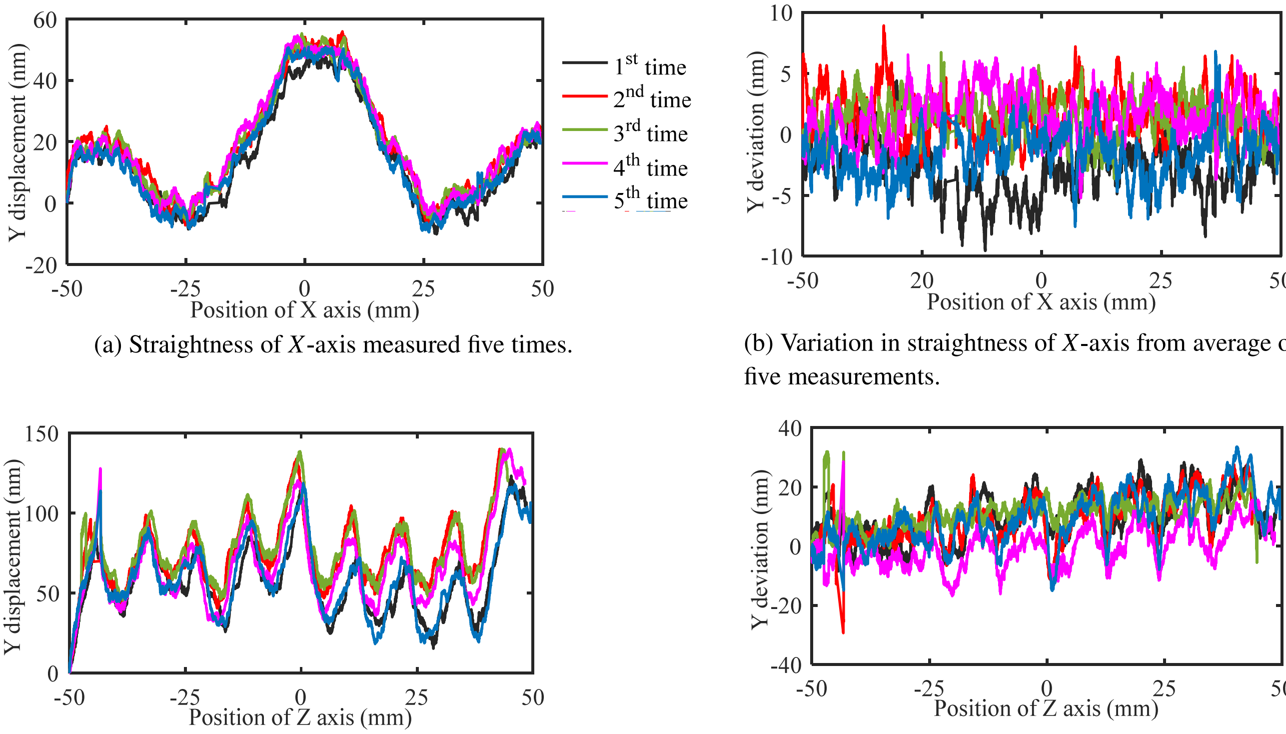


Fig. 6. Straightness and repeatability test along horizontal (X- and Z-)axes of machine tool using a reference flat.



(a) Straightness of X-axis measured five times.

(b) Variation in straightness of X-axis from average of five measurements.

(c) Straightness of Z-axis measured five times.

(d) Variation in straightness of Z-axis from average of five measurements.

Fig. 7. Straightness test along horizontal (X- and Z-)axes and its repeatability.

Spike noise that was presumed to originate from dust particles was eliminated. The results show that it exhibited periodic displacements. Because the reference flat profile did not include such periodic displacements, these periodic displacements were likely due to the waviness on the axis of the ultrahigh precision machine tool. The precision criterion for the machine tool was 100 nm; therefore, this periodic displacement did not suggest the fault of an ultrahigh precision machine tool.

To estimate the repeatability of the system, deviations from the average were calculated. Average curves were obtained by applying smoothing spline fitting to the average of five measured data. The deviation was calculated by subtracting the average curves from the measured data. The deviation results are shown in **Figs. 7(b)** and **(d)**. Based on these results, the overall straightness of the measurement was ±50 nm for a 100 mm displacement along the X- and Z-axes. The standard deviation (σ) of the repeatability was $\sigma_x = 2.7$ nm for the X-axis and $\sigma_z = 8.6$ nm for the Z-axis. From these results, we conclude that the standard deviation of the OMM system repeatability for the X- and Z-axes of the ultrahigh precision machine tool was less than 10 nm.

3.5. Form Accuracy Test by Reference Sphere

The reference sphere was measured using the OMM system to evaluate the accuracy of the system. Two-axis simultaneous motion control was involved, and the measurement was performed on inclined slope surfaces;

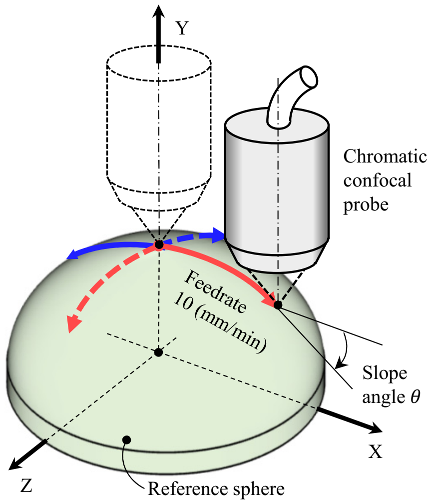
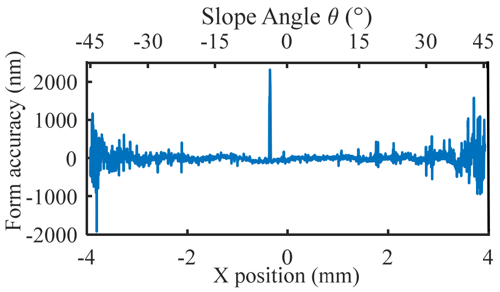
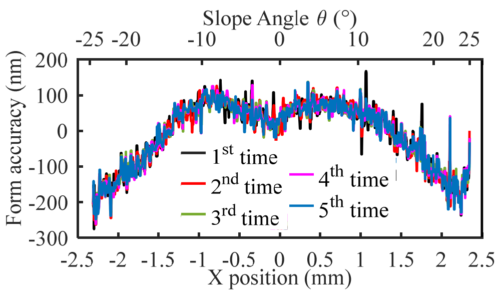


Fig. 8. Profile measurements using silicon nitride reference sphere.

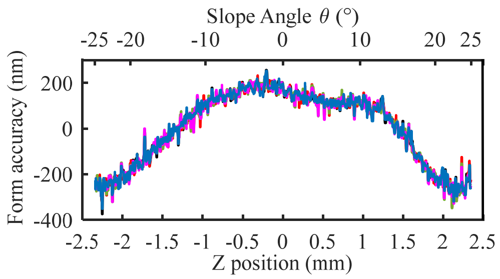
hence, it was similar to the actual optics metrology. The reference sphere was fixed on the B-axis of the machine tool. As shown in **Fig. 8**, the measurement was performed along the X- or Z-axis. The feed rate was 10 mm/min, and the measurement range of the slope angle θ was $\pm 45°$, which corresponded to X or $Z = \pm 3.929$ mm. The position data of the machine tool and probe displacement were synchronously captured, and the probe displacement data were subtracted from the Y position data to generate the



(a) Profile error data from measuring reference sphere at slope angle within ±45° along X-axis.



(b) Profile error data from measuring reference sphere five times at slope angle within ±25° along X-axis.



(c) Profile error data measuring reference sphere five times at slope angle within ±25° along Z-axis.

Fig. 9. Profile measurement accuracy test results using reference sphere and its repeatability.

profile data. The measured data were fitted to the circle curve with the designated radius of the reference sphere using the least-squares method. The error data were obtained by subtracting the fitted circle data from the measured data. The sampling period was 20 ms.

Figure 9(a) shows the result of the profile error measured along the X-axis direction. Except for the spike, which was likely caused by a dust particle or a pit in ceramic material, the profile error amplitude increased as the position of X approached ±3.929 mm. This was likely because the slope angle of the measured point increased, and the chromatic confocal probe became noisy because it was more difficult to obtain reflected light when the slope angle was large and the measured surface was mirror-like.

Figures 9(b) and **(c)** show the measurement results on the reference sphere with a range of ±25°, which corresponded to X or $Z = \pm 2.348$ mm. The profile accuracy of this region was ±300 nm. The profile accuracy was ±100 nm for the X- and Z-axes, which can be maintained in the range of ±15°, corresponding to X or

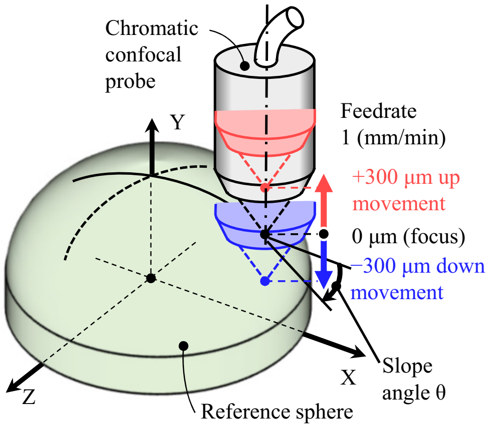


Fig. 10. Linearity measurement over ±300 μm vertical travel (upward/downward) on slope angles of 0°, ±15°, ±30°, and ±45° using reference sphere.

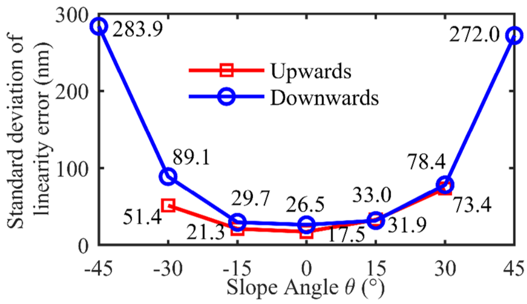
$Z = \pm 1.438$ mm. When the angle of the measurement was 15° or less, the measurement result corresponded to the shape accuracy of the reference sphere.

Although the confocal chromatic displacement probe had a focusing lens with a large numerical aperture and according to the manufacturer's data sheet the measurable slope angle was ±45°, the measuring stability and precision may deteriorate at a large slope angle and a mirror-like surface.

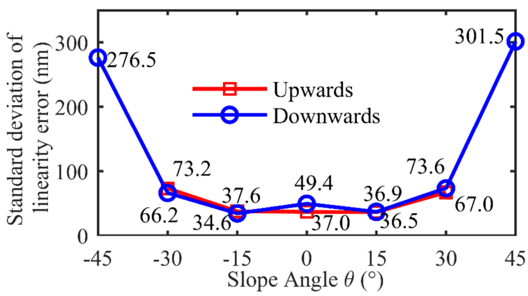
3.6. Probe Stability and Precision Test at Different Slope Angles

As indicated in Section 3.5, the performance of the confocal chromatic probe at a large slope angle deteriorated. To evaluate this, tests were conducted at different slope angles using the same reference sphere. A linearity test using the Y-axis of the machine tool was performed at different positions of the reference sphere, where the slope angles were 0°, ± 15°, ±30°, and ±45° in the X- and Z-directions. At a certain slope angle, the Y-axis oscillated at a feed rate of 1 mm/min within the measurement range of the probe (±0.3 mm) (**Fig. 10**). The position sampling was synchronized, and the sampling period was 20 ms. This experiment provided stability and linearity data over the Y-axis of the machine tool, from which we estimated the stability and precision (linearity) of the probe at a large slope angle.

The measurement path pattern was stopped at the first measuring point for 1 min, moved 300 μm vertically along the $+Y$-axis direction, returned to the measuring point after 5 s of stopping, moved 300 μm vertically in the $-Y$-axis direction after stopping for 5 s, returned to the measuring point after stopping for 5 s, and then moved to the next measuring point. If the probe precision is perfect, then the Y-axis position data and probe displacement will have a complete linear correlation. Therefore, the measured data were fitted by a straight line, and the error from the fit line was calculated. The standard deviation of the error was calculated for each slope angle and for the

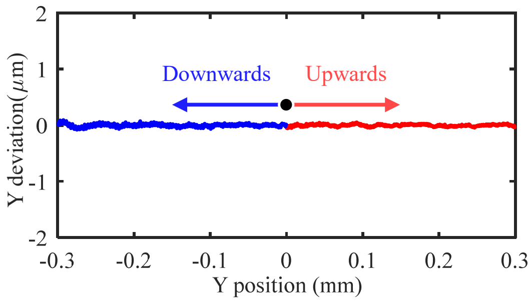


(a) On XY ($Z = 0$) plane.

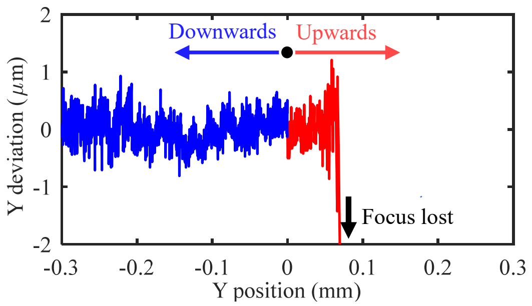


(b) On ZY ($X = 0$) plane.

Fig. 11. Standard deviation (σ) of linearity error in $\pm$300 μm vertical travel (upward/downward) on slope angles of 0°, $\pm$15°, $\pm$30°, and $\pm$45° using reference sphere.



(a) Slope angle $\theta = 0°$ on XY plane.



(b) Slope angle $\theta = 45°$ on XY plane.

Fig. 12. Residual deviation of linearity test at $\theta = 0°$ and 45°.

$+Y$- and $-Y$-directions.

The results are summarized in **Fig. 11**. From 0° to 30°, the standard deviation of the linearity error was within 100 nm. At 45°, the standard deviation was approximately 300 nm.

In addition, as shown in **Fig. 12**, when the Y-axis was moved in the Y-direction at 45°, the probe could not provide valid data at 45°. This was likely because the small pits or dust particles on the surface reflected insufficient light for detection.

4. Conclusion and Discussion

An OMM system was constructed, and its stability, repeatability, and accuracy were evaluated.

The stability of the system for the short term was estimated to be within $\pm$1 nm, which implies that the vibration isolation and machine tool motion control demonstrated good stability. Concerning long-term stability, a drift of 100 to 200 nm over 24 h might occur, which may be reduced by improving the temperature stability of the probe controller. In addition, the step response test indicated that the minimum system response resolution was well below 10 nm, i.e., 2 to 5 nm.

Based on the repeatability test with the reference flat, the overall straightness of the measurement was $\pm$50 nm for a 100 mm displacement along the X- and Z-axes. Because the straightness test data indicated repeatable waviness, the deviation was estimated to be within $\pm$10 nm.

The result of the accuracy test using the reference sphere indicated that the confocal chromatic probe demonstrated some limitations in terms of precision on surfaces with large slope angles. When the slope angle was within $\pm$15°, the accuracy was estimated to be within $\pm$100 nm; and within $\pm$30°, $\pm$300 nm. This result was not consistent with the catalog specifications provided by the manufacturer; therefore, a precision test at a large slope angle was performed.

The accuracy test at various slope angles indicated that the standard deviation of linearity was within $\pm$100 nm when the slope angle was within 30°. However, at $\pm$45°, the deviation was approximately $\pm$300 nm, and the probe lost its signal occasionally.

The overall precision of the OMM system was $\pm$100 nm for a slope angle within $\pm$15°. For slope angles within $\pm$45°, an accuracy of $\pm$300 nm can be obtained, but the probe might not be stable. This performance is not ideal as a metrology system; however, this OMM system is useful for various ultrahigh precision machining when the surface slope angle is not extremely large. In addition, the confocal chromatic probe is a non-contact type probe with an extremely small spot size; it is useful in measuring soft materials or microstructures.

The overall accuracy was affected by both the probe linearity and motion accuracy of the machine tool. Based on the stability and repeatability test, the repeatability of the ultrahigh precision machine tool can be within $\pm$10 nm. Therefore, the accuracy of the OMM system can be improved by introducing a compensation method or a differential metrology using a reference surface.

The stability, repeatability, and accuracy verification tests conducted in this study did not fully describe the motion error of the ultrahigh precision machine tool. For a more detailed motion precision analysis, three probes must be attached to the system to measure multiple degree-of-freedom motion errors (e.g., pitching, rolling, etc.) of the system when necessary. We will attempt to improve the accuracy of the OMM system by motion error correction and perform compensation machining in the future.

Acknowledgements

The authors would like to thank the Advanced Manufacturing Support Team of the RIKEN Center for Advanced Photonics for their support in the machining of the jigs and plates used in this study.

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