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Non-contact calibration of resin gauge for assessing measurement errors of X-ray CT

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Abstract
X-ray computed tomography (X-ray CT) is widely used for non-destructive three-dimensional inspection of industrial parts. For measurement applications, the accuracy of X-ray CT must be validated using reference gauges calibrated with traceability to the SI unit. We have developed a resin gauge with embedded spheres, whose center-to-center distances are calibrated using X-ray CT with an uncertainty of 3 µm. To improve the calibration uncertainty of the resin gauge to less than 1 µm, an optical non-contact calibration system is being developed. This study reports verification results for the measurement repeatability of the optical calibration system.

Dimensional, Measurement, X-ray, Calibration

1. Introduction

X-ray computed tomography (X-ray CT) is a powerful tool for measuring the external and internal geometrical features of industrial parts without destruction. To ensure accurate three-dimensional (3D) measurements, it is necessary to evaluate the length measurement accuracy of X-ray CT at various positions and in various directions within the measurement volume using a reference gauge [1]. We have proposed a new gauge with spheres embedded in resin, as shown in Fig. 1 [2], and are developing an optical non-contact measurement system for this gauge. The target calibration uncertainty using this system is less than 1 µm. In this study, the optical calibration system under development is introduced, and its measurement repeatability is evaluated.

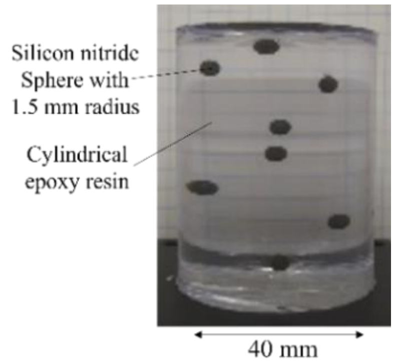

Figure 1. Resin gauge for assessing measurement errors of X-ray CT

2. Overview of the optical calibration system for a resin gauge

The center-to-center distances between the embedded spheres of the resin gauge are calibrated using the optical calibration system shown in Fig. 2. The resin gauge is placed on the X and Z stages of the system, and the center positions (x_c, z_c) of the spheres embedded in the resin gauge are measured. To acquire images of the spheres within the field of view of the telecentric microscope, the resin gauge is moved by the X and Z stages. The positions of the X and Z stages are measured by laser interferometers. The microscope is focused on the sphere by moving the Y stage. The gauge is then rotated by 90° around the Z axis, and the center positions ($x_{c(90°)}$, $z_{c(90°)}$) of the spheres are measured. From the center positions (x_c, z_c) and ($x_{c(90°)}$, $z_{c(90°)}$) of the spheres, the distances between them are calculated. By improving the structure of the optical calibration system reported in [3], Abbe errors are reduced in the current system.

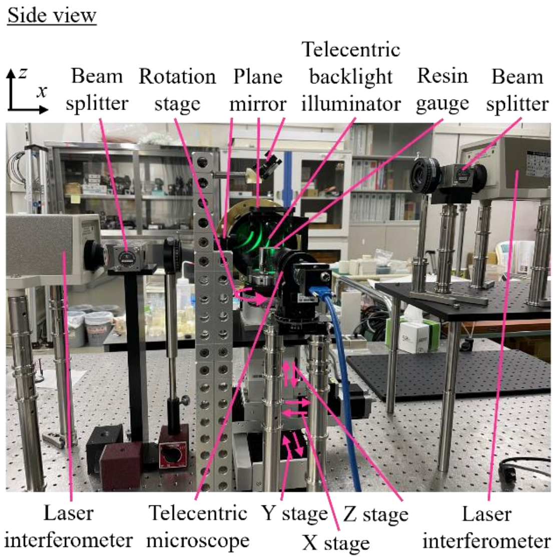

Figure 2. Optical calibration system for a resin gauge

To calibrate the resin gauge, it is necessary to evaluate the calibration uncertainties. The dominant calibration uncertainties of the resin gauge using the current system under development include repeatability, uncertainty due to the calculation method of the sphere center position, uncertainty due to thermal expansion of the resin gauge, geometric errors of the optical calibration system, and uncertainty due to refraction within the resin gauge.

3. Verification

To verify the repeatability of measurements of the sphere center positions using the optical calibration system, the sphere center positions of a 30 mm gauge, shown in Fig. 3, were measured repeatedly. In this gauge, ruby spheres with a diameter of 3 mm are fixed to carbon fiber–reinforced polymer (CFRP) support rods. The center positions of the spheres were measured 10 times at the original position and at the position after rotation, respectively.

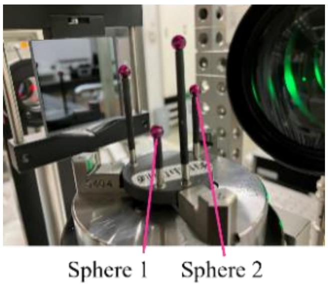

Figure 3. Gauge for the measurement repeatability verification 4of the optical calibration system

4. Results and discussion

Figures 4 and 5 show the deviations of the measured values from the average values of x_c, $x_{c(90°)}$, z_c, and $z_{c(90°)}$ for sphere 1 and sphere 2. Table 1 summarizes the measurement repeatability, expressed as standard deviation (SD) and peak-to-valley (PV), of the center positions of sphere 1 and sphere 2. The measurement repeatability (SD) of x_c and $x_{c(90°)}$ was within 1.0 µm, and that of z_c and $z_{c(90°)}$ was within 2.1 µm.

Through the verification experiment, it was confirmed that reducing Abbe errors in the measurement system improves the repeatability of the system. Before improvement of the instrument structure, the measurement repeatability (SD) of x_c and $x_{c(90°)}$ was within 1.7 µm, and that of z_c and $z_{c(90°)}$ was within 2.8 µm. Because the spheres of the gauge used for the verification are supported by CFRP rods, fluctuations due to thermal expansion of the gauge can be smaller than sub-micrometer.

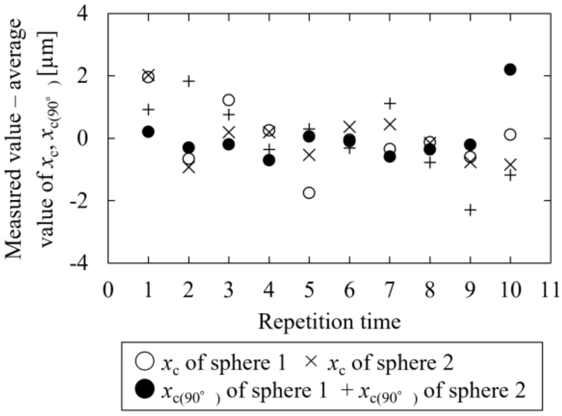

Figure 4. Deviations of the measured value from the average value of x_c, $x_{c(90°)}$

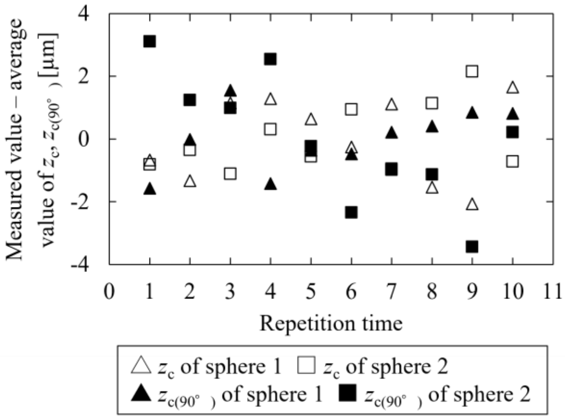

Figure 5. Deviations of the measured value from the average value of z_c, $z_{c(90°)}$

Table 1 Measurement repeatability of sphere 1 and 2's center positions

	Measurement repeatability [µm]
x_c	SD: 1.0 µm (Sphere 1), 0.8 µm (Sphere 2)
	PV: 3.7 µm (Sphere 1), 2.9 µm (Sphere 2)
z_c	SD: 1.3 µm (Sphere 1), 1.1 µm (Sphere 2)
	PV: 3.7 µm (Sphere 1), 3.3 µm (Sphere 2)
$x_{c(90°)}$	SD: 0.8 µm (Sphere 1), 0.8 µm (Sphere 2)
	PV: 2.5 µm (Sphere 1), 2.4 µm (Sphere 2)
$z_{c(90°)}$	SD: 1.0 µm (Sphere 1), 2.1 µm (Sphere 2)
	PV: 3.1 µm (Sphere 1), 6.5 µm (Sphere 2)

To achieve the target calibration uncertainty in this study, further improvement is required. The lasers fluctuated with an SD of 0.2 µm due to air turbulence and temperature drift. In addition, the measured values may vary because the rigidity of the laser mounts in the current system is still low. The measurement repeatability of z_c and $z_{c(90°)}$ was lower than that of x_c and $x_{c(90°)}$. This may be because the position of the mirror used to measure the position of the Z stage fluctuates in accordance with the stage movement during measurement. Therefore, it is necessary to reduce fluctuations due to instability of the laser units and the mirror setting.

5. Summary

The measurement repeatability of the optical calibration system under development for the resin gauge was verified. The measurement repeatability was within an SD of 2.1 µm. To achieve the target calibration uncertainty, it is necessary to further improve the measurement repeatability by stabilizing the laser units and the mirror setting and by reducing other contributions to uncertainty.

References

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