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Development of a compact gear measuring machine based on modified line-of-action scanning for high-precision tooth profile measurement

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Abstract

The accuracy of the tooth profile in cylindrical involute gears is crucial for ensuring reliable performance in many industrial applications, and dedicated gear measuring machines (GMMs) are widely used for this purpose. Conventional GMMs are based on the principle of involute generation, in which the probe scans along the line of action tangential to the base circle. To measure both the left and right flanks, however, the probe must be laterally offset along the line of action. This offset enlarges the overall machine size, while the increased movement of the Z-axis column reduces structural rigidity and can significantly degrade measurement accuracy. In this study, a measurement principle that adapts conventional line-of-action scanning based on the theory of involute generation is proposed to reduce the required lateral offset. While the scanning approach along the line of action is retained, the angle of the line of action is individually adjusted for the left and right flanks. This modification allows the measurement regions for both flanks to be substantially coincident, thereby reducing the required XY measuring range of the machine. The downsizing of the gear measuring machine provides significant benefits, including enhanced stage rigidity and reduced manufacturing cost. However, the proposed approach changes the orientation of the line of action, so that the normal direction of the tooth surface does not necessarily coincide with the sensitivity direction of the probe. In this paper, the probe characteristics with respect to the sensitivity direction were experimentally evaluated to clarify their influence on tooth profile measurement. To validate the modified line-of-action scanning, we developed a GMM. The measurement accuracy was evaluated using a master gear calibrated by a coordinate measuring machine operated as Japan's national standard. Experimental results showed that the tooth profile deviations measured by the proposed GMM agree with those obtained by a national standard CMM within ±1 µm, demonstrating its potential as a practical and high-precision solution for industrial gear inspection.

Gear measuring machine, involute gear tooth, line of action, probe characteristics, calibration, master gear

1. Introduction

Gears are essential mechanical components used for power transmission in automobiles, power generators, aircraft, marine vessels, medical equipment such as CT scanners, and construction machinery. To improve transmission efficiency, enhance durability, and reduce noise, the geometric deviations of gear teeth must be minimized. Large gears additionally require high structural rigidity because they cannot be easily replaced or repaired. For such gears, the surface profile of tooth flanks must be manufactured with micrometer-level accuracy.

Advancing the geometric accuracy of gears requires reliable methods for measuring the tooth-flank geometry. In industry, dedicated gear measuring machines—configured as a polar-coordinate system consisting of three orthogonal linear axes (X, Y, Z), a rotary table (θ), and a probing system—are commonly employed for this purpose [1-2]. Figure 1(a) illustrates the basic measurement principle for an involute cylindrical gear. The workpiece is rotated while the probe is translated along the tangent to the base circle (the line of action) in synchronization with the gear rotation. This motion reflects the involute generation theory. The tooth profile deviation is detected as the probe displacement from its theoretical position.

To measure both the left and right flanks of the gear, the probe must travel a long distance along the line of action. However, this long travel can lead to motion errors in the Z-column. To suppress these errors, the measuring machine must be designed with high structural rigidity, which is a major factor contributing to the high cost of large-gear measuring systems.

M. Yuzaki proposed a measurement approach in which the rolling angle of the base point A on the involute profile is shifted by $\pm\alpha_t$—where the positive sign corresponds to the right flank and the negative sign to the left flank—to define different lines of action for the two flank measurements [3]. Here, α_t denotes the transverse pressure angle of the gear under test. In this method, the probe is controlled in the orthogonal X- and Y-directions in synchronization with the gear rolling angle ε, as illustrated in Figure 1(b). Similar to conventional gear metrology, the probe scans along the line of action. In the conventional measurement principle, the line of action is parallel to the X-axis of the machine coordinate system. In the proposed method, the orientation of the line of action is modified by adjusting the transverse pressure angle $+\alpha_t$ and $-\alpha_t$ for the left and right flanks.

Because a smaller probe-travel range is sufficient for large gears, reducing the required probe travel makes it possible to design a more compact measuring system, which contributes to lower manufacturing cost. In addition, the smaller travel range facilitates a high-rigidity structure, an advantage that is particularly important for large-gear measuring machines.

Furthermore, conventional methods sometimes fail to evaluate small internal gears—such internal gears are used in

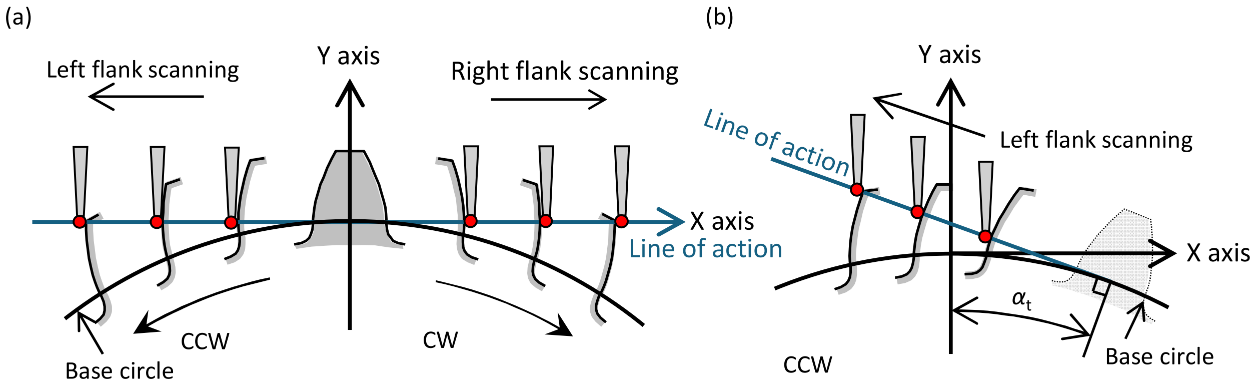

Figure 1. Schematic of involute gear profile measurement:(a) Traditional measurement principle, requiring a large probe travel due to different measurement regions on the left and right flanks. (b) Measurement principle based on modified line-of-action scanning for the left flank.

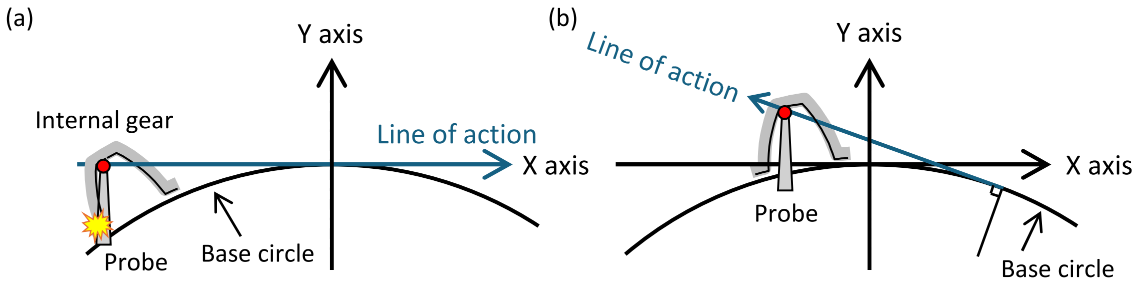

Figure 2. Schematic of internal gear profile measurement: (a) Traditional measurement principle, where probe interference is an issue and a special probe is required. (b) Modified line-of-action scanning, in which probe interference is avoided.

micro-actuator components for electric vehicles, medical evaluate small internal gears—such internal gears are used in micro-actuator components for electric vehicles, medical equipment, and communication devices—because of probe interference. The proposed method overcomes this limitation, making it possible to measure these internal gears without probe collisions, as shown in Figure 2.

However, in the modified line-of-action scanning approach—a compact gear measuring method—the line of action is not aligned with the surface normal of the tooth flank. When a probe with unidirectional sensitivity is used, the probe characteristics influence the measurement accuracy of tooth form deviation and thus become a source of measurement error. A similar mismatch between the surface normal and the line of action also exists for helical gears in conventional measurement systems.

In this study, a probe calibration device was developed, and the relationship between the tooth-flank contact angle and the probe characteristics was evaluated. A compact gear measuring machine equipped with a probe calibrated using the developed system was constructed, and the validity of the proposed approach was confirmed through comparative measurements against a master gear calibrated with a coordinate measuring machine operated as Japan's national standard.

2. Evaluation of probe characteristics

A probe calibration system was developed to evaluate the characteristics of GMM probes. In this study, two commercially available probes (1. TD-1R/Zero, Tokyo technical and 2. SP80H, Renishaw) were selected as representative probes, and their characteristics were evaluated using the developed system. Figure 3 shows the configuration of the system. It consists of a laser interferometer (Renishaw, XL-80), a piezoelectric stage (THK Precision, PS1L80-700U), a spherical measurement target (ruby sphere, ϕ8 mm), and the probe under test. The measurement beam of the interferometer is aligned with the motion axis of the piezo stage within five arcminutes. The measurement beam of the interferometer is adjusted so that its central axis passes through the center of the target sphere. The sensitivity direction of the probe under test is aligned with the motion axis of the piezo stage. The target sphere is moved in steps over a range of ±100 µm in 10 µm increments. By comparing the outputs of the probe and the laser interferometer, the sensitivity (gain) of the probe is calibrated. Because the probe is used to measure both the left and right flanks of a gear, the calibration is performed for both directions by changing the probe contact direction accordingly. The calibration system satisfies Abbe's principle, and the stage displacement is measured in real time using a laser interferometer. The alignment between the interferometer beam and the motion axis was adjusted within five arcminutes, resulting in a cosine error below 1 nm. In addition, the probe contacts the same point on the spherical target during calibration, the influence of the probe tip form is negligible.

In actual gear-tooth measurements, the surface normal of the tooth flank does not coincide with the probe's sensitivity axis.

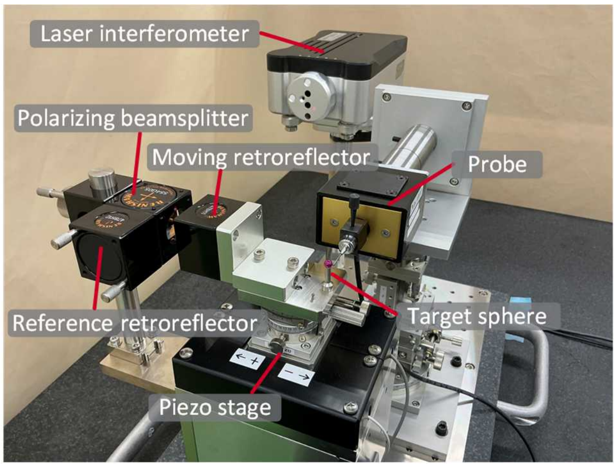

Figure 3. Probe calibration system

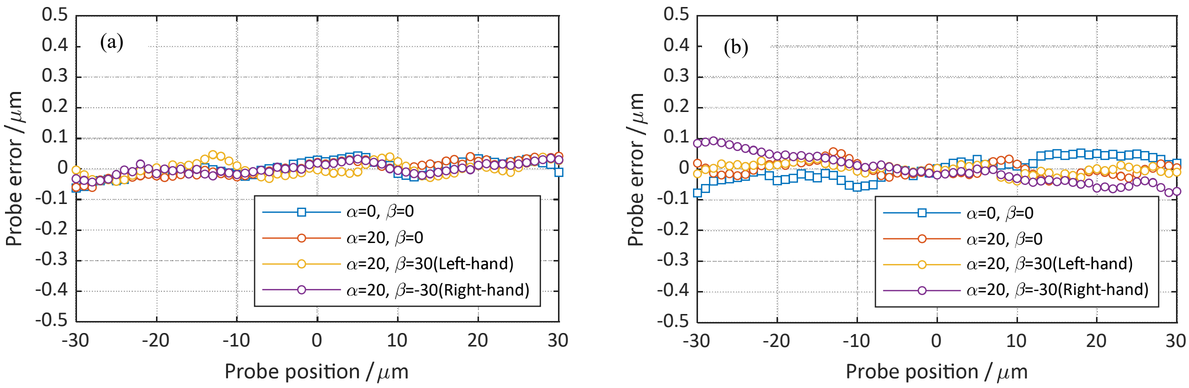

Figure 4. Evaluation results of the probe (TD-1R/Zero, Tokyo Technical): (a) left tooth flank and (b) right tooth flank

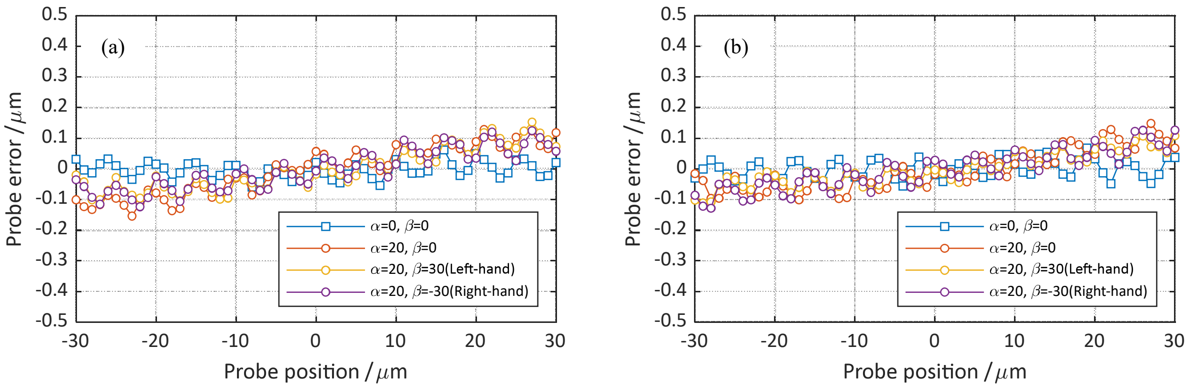

Figure 5. Evaluation results of the probe (SP80H, Renishaw): (a) left tooth flank and (b) right tooth flank

Therefore, probe characteristics were evaluated for spur and helical gears with a pressure angle of α = 20°, helix angles β = 0°, ±15°, and ±30°. The probe was brought into contact with the target sphere at positions corresponding to the expected surface-normal directions, starting from the equator of the sphere as a reference position. The probe characteristics were evaluated by scanning over ±30 µm in 1 µm increments and comparing the probe output with that of the laser interferometer. Figures 4 and 5 shows the evaluation results.

The evaluation results for the TD-1R/Zero and the SP80H are shown in Figs. 4 and 5. In each figure, (a) corresponds to the left tooth flank and (b) to the right tooth flank. The combination $(\alpha,\beta) = (0,0)$represents the condition in which the motion axis of the piezo stage (the sphere normal) is aligned with the probe sensitivity axis, i.e., the state used for probe calibration. The results clearly show that the probe characteristics vary depending on the pressure angle and the helix angle. Nevertheless, within the evaluation range of ±30 µm, the probe error remains within ±0.2 µm for both probes.

The probe characteristics are influenced by the difference between the tooth-surface normal direction, which changes with the pressure angle and the helix angle of the gear, and the fixed probe sensitivity axis. For high-accuracy measurements, it is therefore meaningful to apply different probe sensitivity coefficients depending on the target gear. The probe sensitivity calibrated under the condition (α, β) = (20°, 0°) was applied in the subsequent GMM measurements. The influence of the probe gain error on the evaluated tooth profile deviation depends on the amount of tooth profile modification and becomes larger for gears with larger profile modifications.

3. Experimental validation of the proposed scanning method

To validate the modified line-of-action scanning method, a general-purpose gear measuring machine (GMM) was developed. Figure 6 shows the developed GMM. The machine is

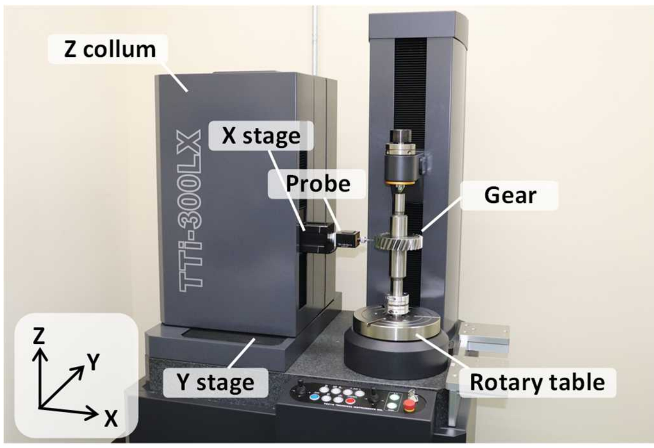

Figure 6. General-purpose gear measuring machine (GMM) developed for the modified line-of-action scanning method

Table 1 Master gear specifications

Gear type	Helical gear (right-hand)
Module	4 mm
Number of teeth	30
Normal pressure angle	20°
Helix angle on reference cylinder	20°
Face width	30 mm
Base circle diameter	119.0809 mm

equipped with three orthogonal linear axes with travel ranges of 180 mm (X), 130 mm (Y), and 370 mm (Z). The Z-axis column is mounted on the Y-axis stage, and the X-axis is installed on the developed. Figure 6 shows the developed GMM. The machine is equipped with three orthogonal linear axes with travel ranges of 180 mm (X), 130 mm (Y), and 370 mm (Z). The Z-axis column is mounted on the Y-axis stage, and the X-axis is installed on the Z-axis column. The X-, Y-, and Z-axes are constructed using commercially available linear motion guides, linear motors, and linear scales. The rotary θ-axis is also composed of commercially

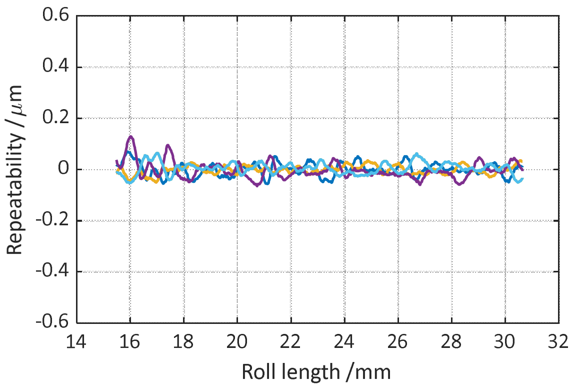

Figure 7. Repeatability of tooth No.1 at orientation 1

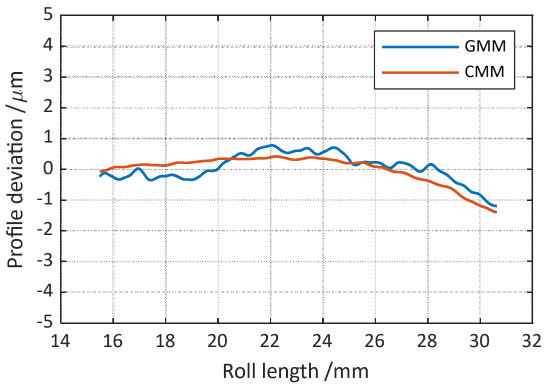

Figure 9. Comparison between GMM and CMM for tooth No. 1

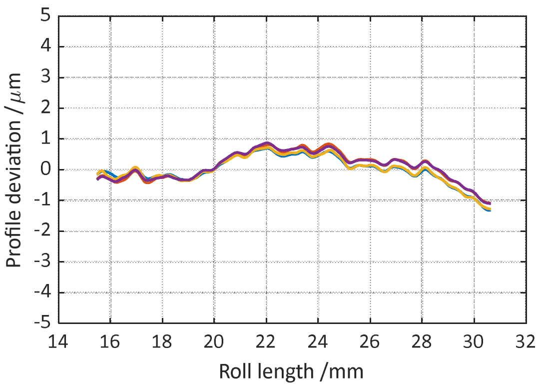

Figure 8. Reproducibility among four orientations for tooth No.1

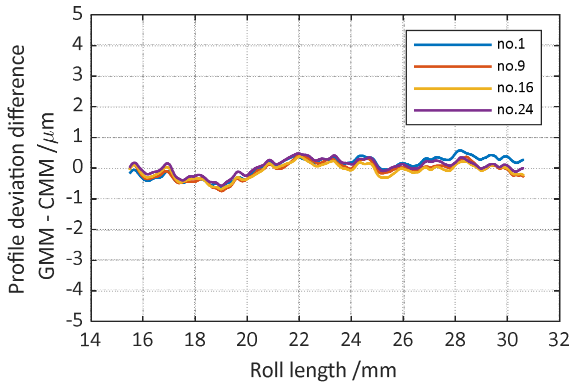

Figure 10. Difference curves between the GMM and the CMM for teeth Nos. 1, 9, 16, and 24

available rolling bearing and a direct-drive motor. As the probing system, the TD-1R/Zero probe evaluated in Section 2 was mounted on the machine. The measurements were conducted under laboratory conditions with the temperature controlled at 20 °C ± 0.5 °C, a probing force of approximately 0.05 N, and 480 points along each profile.

Table 1 shows the specifications of the master gear used for the evaluation. The master gear was mounted on the rotary axis of the GMM in four orientations, equally spaced at 90°. The averaging over four orientations was performed to reduce the influence of mounting eccentricity. Since the mounting error affects both the traditional and the proposed methods but is not related to the modification of the line of action, the mean profile over the four orientations was used for the comparison. Other error sources, such as probe errors and stage motion errors, are not cancelled by this averaging and remain in the results. For each orientation, six repeated measurements of the gear tooth profile were performed. The obtained tooth profile was then determined as the average profile over all orientations.

The measurement results for selected teeth (Nos. 1, 9, 16, and 24), which are approximately evenly spaced on the 30-tooth gear, on the left flank of the master gear are presented. Figure 7 shows the repeated measurement results for tooth No.1 at orientation 1. The standard deviation of the residuals from the mean curve was 0.025 µm, indicating high repeatability. Figure 8 shows the dispersion of the mean curves obtained from the four orientations for the same flank. The standard deviation among the orientations was 0.081 µm, demonstrating high reproducibility. These results confirm that sub-micrometer repeatability and reproducibility can be achieved even without employing an ultra-precision stage or applying error compensation techniques.

Next, to evaluate the validity of the obtained tooth profile deviation curves, the same tooth flank was measured using a coordinate measuring machine (CMM) operated as Japan's national standard. The expanded uncertainty of the CMM for tooth profile measurement is 0.4 µm (k = 2). Figure 9 compares the tooth profile deviation curves for tooth no.1 measured by the developed GMM and the CMM, and Fig. 10 shows the corresponding differences between the four selected teeth (Nos. 1, 9, 16, and 24). The maximum root-mean-square (RMS) value among the difference curves was 0.42 µm, and all difference curves were within ±1 µm. These results indicate that the tooth profile deviations measured by the proposed GMM agree with the CMM measurement within ±1 µm, even without using high-precision stages or advanced compensation methods.

By adopting higher-precision stages, such as air slides and air spindles, and by applying various compensation techniques for scale errors, motion errors, and workpiece mounting eccentricity, further improvement in measurement accuracy is expected.

4. Conclusion

A general-purpose gear measuring machine (GMM) based on the modified line-of-action scanning method was developed and experimentally evaluated. The probe characteristics were investigated, showing that the probe response depends on the pressure angle and the helix angle through variations in the tooth-surface normal relative to the fixed probe sensitivity axis. Comparisons of the master gear measurements with a coordinate measuring machine (CMM) showed good agreement. The proposed GMM can measure tooth profile deviations with an accuracy better than 1 µm using a simple and practical system.

References

[1] Goch G 2003 Gear metrology *CIRP Ann.* **52** 659–95
[2] Goch G, Guenther A, Peng Y and Ni K 2023 Gear metrology – an update *CIRP Ann.* **72** 725–51
[3] Yuzaki M 2011 Gear measuring machine by "NDG method" for gears ranging from miniature to super-large metrology *Gear Technol.* **March/April** 55–60