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Comparison of Metrology-Grade Squareness Error Measurement Methods

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Keywords： Self-calibration, Squareness error, Reversal method, Holeplate.

ABSTRACT

This study compares two metrology-grade methods for measuring squareness errors in three-axis machine tools: the Swing Round Method (SRM) and the Reversal Method (RM). The experiment utilized a holeplate with standard size transfer functionality as a geometric error analysis reference, comparing the measurement results of these two methods. The experimental results show that the measurement differences between the two methods remain consistently within 1 arcsecond, meeting the precision requirements of machine tools with an accuracy of 20 μm. Additionally, the study examined the consistency of external calibration and self-calibration RM measurements for the squareness of the holeplate, confirming that the holeplate used in the experiment is sufficiently stable and suitable as a reference object. The study further found that while external calibration and SRM can provide high-precision measurements, they involve higher costs or more complex procedures. In contrast, the RM method offers greater flexibility, although it may introduce larger measurement errors. Future research could explore the application potential of these methods in ultra-precision machining and develop hybrid measurement techniques to reduce measurement uncertainties and further enhance measurement accuracy efficiently.

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INTRODUCTION

Error assessment is crucial for analyzing characteristics in various measurement domains. In contact-based measurement methods, numerous studies have employed tactile probes and multiple spheres to comprehensively evaluate motion errors [Lin, 2023; Hsieh, 2024]. With the advancement of Industry 4.0, the demand for on-machine, in-line, and in-process measurements has significantly increased. This trend highlights the growing importance of 2D dimensional reference standards for online measurement. By utilizing a tool library, tools can be exchanged and converted into 3D measurement probes, enabling multi-axis machines to directly measure 2D dimensional standards after processing. The measurement results can be instantly transmitted for tasks such as health monitoring, real-time compensation, or further processing. Moreover, multi-axis machines can perform measurements during the machining process, enhancing efficiency and accuracy. According to ISO 10791-6 standards (2014), linearity and squareness errors are critical parameters for machine tool assembly inspections. Traditional methods, such as those by Evans (1996) and Mokroš (2001), rely on square rulers and linear displacement devices. However, the significant weight of square rulers poses challenges in factory environments, particularly for single-person operations. To address these limitations, alternative methods have been explored. One effective solution is the use of a specially designed holeplate, equipped with standardized holes for precise squareness error measurements. It provides a stable and reproducible reference for geometric error analysis, making it highly suitable for applications involving coordinate measuring machines (CMMs) and machine tools. Calibration can be achieved through high-level calibration, which uses certified external references for high accuracy but at a higher cost and time investment, or self-calibration, which is more cost-effective and flexible but may introduce some uncertainty. The holeplate represents a promising approach to balancing precision and practicality, addressing the challenges of traditional methods while supporting the evolving needs of modern manufacturing. Miura et al. (2019) employed a hole plate to assess the performance of CMMs and introduced a Monte Carlo simulation technique to estimate uncertainty via computational modeling. By identifying and correcting geometric inaccuracies, the precision of CMMs and machine tools can be enhanced. In summary, the holeplate proves to be an effective and versatile tool for addressing geometric error measurement challenges in modern manufacturing. Its ability to provide precise squareness error measurements, stable and reproducible references, and support for both high-level and self-calibration methods.

Over the years, methodologies for measuring and calibrating geometric errors in machine tools and CMMs have significantly evolved. For example, Evans et al. (1996) introduced innovative techniques for parts measurement without externally calibrated artifacts. Their methods led to the development of calibration-based vertical measurement approaches, improving industrial measurement accuracy and reliability. However, these approaches primarily address calibration rather than real-time application challenges. Similarly, Mokroš and Hain (2001) proposed a self-calibration procedure for large square standards, achieving an expanded uncertainty of less than 1 arcsecond within a 1200 mm measurement range. Despite its precision, the substantial weight of large standards limits its practicality in industrial settings. Liu et al. (2018) advanced geometric error identification for machine tools by introducing the Double Ball Bar (DBB) method. Although this method effectively identifies geometric errors, it is more suited to controlled testing scenarios, such as the Circular Interpolation Test, than to dynamic field applications. Furthering this exploration, Pérez et al. (2019) applied the Monte Carlo method to analyze the uncertainty in laser tracker measurements. While laser trackers efficiently capture 3D coordinates and volumetric errors, their uncertainty—reaching up to 30 microns—restricts their use in high-precision applications. Adding to these studies, Jia et al. (2022) developed a mathematical model describing geometric errors in three-linear-axis machine tools. By employing optical methods, their model achieved submicron precision but faced practical challenges in optical path alignment, hindering industrial deployment. Kritikos et al. (2020) conducted an uncertainty analysis on measurements taken with a ZEISS CenterMax CMM, examining factors such as parallelism, angularity, roundness, diameter, and distance. Their findings revealed that interaction effects between stylus size, step interval, and measurement speed were significant at a 95% confidence level. This research underscores the critical role of accuracy and precision in advancing industrial digital transformation.

Schwenke et al. (2008) and Osawa (2009) emphasized the potential of combining laser interferometry with coordinate measuring machines (CMMs). Their research highlighted the importance of using two-dimensional standards, such as ball plates and hole plates, to reduce geometric errors and improve calibration precision. Two-dimensional standards, including the hole plate (Lee, 2001; Sladek, 2016; Takatsuji, 2014), manufactured from NEXCERA material by Krosaki in Japan, are used to evaluate the geometric precision of CMMs. These standards can assess 21 types of geometric deviations across three linear axes. The evaluation parameters may include straightness (pitch (P), roll (R), yaw (YA)), orthogonality (α, β, γ), and linear positioning (L), as shown in Fig. 1. The NEXCERA material is renowned for its exceptional thermal resistance and high strength, ensuring stable and reliable measurement results under changing environmental conditions. This makes it particularly suitable for demanding industrial and scientific applications. In summary, advancements in geometric error measurement and calibration methodologies have significantly enhanced industrial precision and reliability. Two-dimensional standards, such as hole plates made from NEXCERA material, have proven to be effective solutions for evaluating CMM geometric deviations, offering outstanding thermal stability and durability. These characteristics make the hole plate a reliable tool for assessing critical parameters such as straightness, orthogonality, and linear positioning, even under varying environmental conditions. this NEXCERA-based hole plate has been officially recognized as an artifact for comparison by the National Metrology Institute of Japan (NMIJ, 2024). However, users still seek additional experimental data on the dimensional stability of the hole plate to further enhance confidence in its long-term reliability and precision, especially for industrial applications.

This study evaluated and compared three methods for measuring squareness errors in three-axis machine tools: the swing round method (SRM), the reversal techniques method (RM), and external calibration. Both RM and SRM are classified as metrology-grade methods, ensuring compliance with measurement traceability requirements. Furthermore, the calibration process guarantees that measurement values can be reliably traced back to national metrology standards. The objective was to examine the differences among these approaches and identify which measurement method, in conjunction with the holeplate, offers sufficient stability. Furthermore, this study seeks to offer valuable insights for industrial metrology applications, particularly in integrating measurement probes with machine tools that require a precision of up to 20 μm (a fundamental requirement specified in ISO 10791-4 [ISO, 1998]). By addressing these aspects, the findings aim to enhance user confidence in practical implementation and support the broader adoption of reliable measurement techniques.

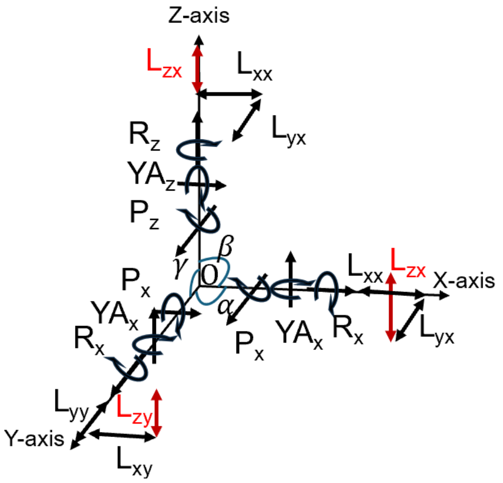

Fig. 1. Schematic diagram of geometric errors in a 3-axis machine

PROCEDURE FOR THE EXPERIMENTAL SETUP OF THE HOLEPLATE

Description of the holeplate in the experiment

The holeplate itself has measurable feature dimensions arranged in the x and y directions, hence it is referred to as a two-dimensional reference standard. By providing the standard length between measurable features in two directions as a traceable reference dimension, it allows for further geometric error analysis of the CMM or machine tool by comparing the length between measured features and the standard. This is the key feature of the holeplate. The holeplate used in this article was made by KROSAKI HARIMA CORPORATION and is made from Zero Expansion Ceramic (NEXCERA). NEXCERA has a near-zero thermal expansion coefficient, with $\alpha = (0.00 \pm 0.05) \times$ 10-6 K^{-1} at 20 °C. The holeplate has overall dimensions of 630 mm × 630 mm × 50 mm, with a measuring area of 550 mm × 550 mm, as illustrated in Fig. 2. It contains 28 holes, each with a diameter of 20 mm, arranged with a 50 mm pitch between hole centers. The holeplate is equipped with a coupling fixture that enables secure horizontal mounting, supported by three elements to ensure stability when fixed onto the CMM table.

Additionally, the holeplate can be mounted on various reference planes using the fixture, facilitating geometric error measurements in three-dimensional space. When positioned horizontally, it enables measurements along the X and Y axes. When oriented vertically, it allows for measurements along the X and Z axes as well as the Y and Z axes, providing comprehensive evaluation capabilities. The holeplate is chosen as a geometric error measurement tool not only for its versatility in positioning accuracy measurement, which establishes it as an essential tool for multi-axis precision geometric calibration, but also for its demonstrated effectiveness in monitoring and compensating for machine tool errors, positioning it as a promising solution for future applications. This capability ensures exceptional precision in industrial processes. With adequate stability, the holeplate could be seamlessly integrated into measurement systems, enabling real-time adjustments and significantly improving the reliability and consistency of manufacturing operations.

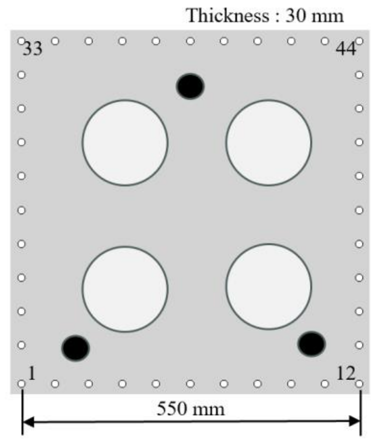

Fig. 2. Schematic diagram of the holeplate used in the experiment

DESCRIPTION OF THE CMM IN THE EXPERIMENT

The coordinate measuring machine (CMM) used in this experiment is the Leitz PMM-C Ultra, a highly accurate three-axis CMM located at the National Measurement Laboratory in Taiwan. This state-of-the-art CMM is renowned for its exceptional precision and is widely used in industries requiring high-accuracy measurements. The Leitz PMM-C Ultra features a gantry structure with a measurement range of 1400 mm along the X-axis, 700 mm along the Y-axis, and 600 mm along the Z-axis. The maximum permissible error (MPE) claimed for this model is defined as (0.4 + L / 850) μm, where L represents the measurement travel distance in meters. This emphasizes the precision of the measurement standard and ensures the reliability of the experiments conducted to evaluate the stability of the holeplate.

To validate the proposed measurement methods, the experiment was conducted in a temperature-controlled laboratory where the environment was maintained at a stable (20 ± 0.5)°C. This controlled environment was critical for minimizing measurement uncertainties caused by thermal expansion. A data logger was used to continuously monitor and record temperature and humidity, ensuring that environmental conditions remained stable throughout the experiment. This approach further underscores the commitment to achieving the highest level of precision and reliability in measurements, utilizing a top-tier, industry-standard measurement system.

MEASUREMENT TECHNIQUES

This experiment will use a holeplate in conjunction with two measurement methods to determine the X-Y squareness error among the geometric errors of the CMM, as shown in Fig. 3. A 5 mm diameter probe is used to perform the measurements. While this probe size is well-suited for the holes on the holeplate, larger diameter probes can also be employed to minimize the influence of form errors. The following sections provide a detailed introduction to the measurement procedures for these two methods.

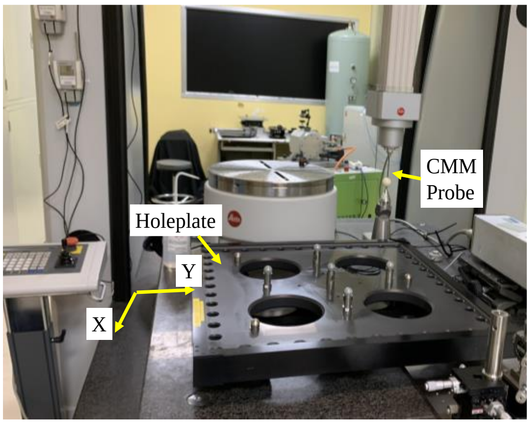

Fig. 3. Schematic diagram of the holeplate positioned on the X-Y plane of the CMM

- **Measurement Procedures of Reversal Technique Method (RM) in the Experiment**

RM is essential for improving the accuracy and reliability of measurements, especially when measuring squareness error, which refers to the deviation from a perfect 90-degree angle during movements along the X and Y axes. These deviations are often influenced by various sources of error, including mechanical misalignments, thermal effects, and inherent inaccuracies in both the CMM and the reference standard. When these errors combine, they can lead to significant discrepancies in measurement results.

To reduce the inherent inaccuracies of the CMM (Coordinate Measuring Machine) and the reference standard, the RM is employed. This technique involves taking measurements along one axis, and then repeating the measurements after rotating either the reference standard or the measurement axis by 180 degrees. By performing these two measurements in opposite directions, the errors that are symmetrical in nature—such as those caused by mechanical misalignments or certain systematic errors—are effectively canceled out. This results in a more accurate assessment of the CMM's inherent performance, as the external artifacts' influence on the measurement is minimized.

In this experiment, the RM mathematically separates errors that may be introduced by the machine or the reference standard, effectively minimizing the influence of artifacts on the measurement results. This ensures that the measurements closely reflect the true accuracy of the CMM, making it particularly suitable for high-precision applications. In such cases, even the smallest deviations can lead to significant discrepancies in the final product. By applying this technique, manufacturers can achieve more reliable and accurate measurements, which are critical for maintaining precision and quality in industries such as aerospace, automotive, and medical device manufacturing.

The measurement process is described below using mathematical formulas, which can be cross-referenced with Fig. 4.

$$\rho=\theta-\delta \tag{1}$$

θ : Measuring value

δ : Deviation come from the machine geometric errors

After using reverse method, the squareness (ρ') can be written as the following

$$\rho'=-\theta-\delta \tag{2}$$

Combined the equation (1) and (2), the squareness of holeplate will be obtained. Moreover, deviation come from the machine geometric errors will be

$$\alpha=(\rho+\rho')/(-2) \tag{3}$$

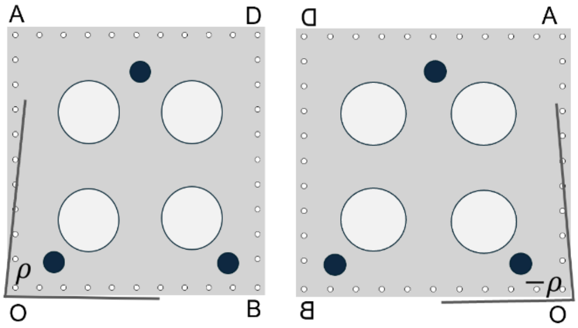

Fig. 4. Measurement process utilizing the RM

- **Measurement Procedures of Swing Round Method (SRM)**

The SRM, as described in the Osawa publication in 2019, is a precise measurement technique that operates within the Hole Plate Coordinate System (HPCSY). Designed to enhance the accuracy of CMM, this method follows a systematic series of steps to minimize measurement uncertainties and ensure reliable results. It is particularly effective for evaluating the alignment and geometric properties of a hole plate.

(1) Establishing the Coordinate System

The process begins with the determination of a stable reference point, or origin, which is a critical prerequisite for all measurements. This involves measuring points on the inner cylindrical surface of a reference hole, typically Hole 1, projecting these points onto the XY plane, and calculating the center using a least-squares fitting method. This origin serves as the foundation for the coordinate system, ensuring consistency and accuracy.

To further define the coordinate system, the X-axis is established by measuring points on the inner cylindrical surface of Hole 12. These points are similarly projected onto the XY plane, and their least-squares fitted circle's center is used as the X-axis reference point. These steps guarantee a robust and reliable coordinate system for subsequent measurements.

(2) Measurement Process in Four Positions

With the coordinate system established, the hole plate is placed horizontally on the machine's XY plane, and measurements are conducted in four distinct positions [Osawa (2009)]:

1. Position D0 (Basic Position):
The hole plate is measured in its initial orientation, which serves as the baseline for comparison.
2. Position DZ (Rotate 180° around the Z-axis):
The hole plate is rotated 180° around the vertical (Z) axis. This step is crucial for detecting alignment errors introduced by rotation around the vertical axis.
3. Position DY (Rotate 180° around the Y-axis):
The plate is rotated 180° around the Y-axis to identify alignment deviations or mechanical distortions in this direction.
4. Position DX (Rotate 180° around the X-axis):
The final position involves rotating the plate 180° around the X-axis, allowing for the evaluation of deviations along this axis.

For each position, the alignment of the plate is assessed by determining the XY coordinates of the centers of specific holes relative to the object coordinate system, located 15 mm below the XY plane. The high-resolution measurements, often with a precision of up to 10 nm, allow for the detection of geometric deviations caused by rotations along the X, Y, and Z axes. This systematic approach ensures comprehensive data collection and provides valuable insights into the CMM's geometric performance.

Finally, the position of each hole is calculated by averaging the coordinates obtained from all four measurement positions, as shown in Fig. 5, using the following formula [Osawa (2009)]:

$$(x,y) = \left(\frac{x_{D0}+x_{Dz}+x_{Dy}+x_{Dx}}{4}, \frac{y_{D0}+y_{Dz}+y_{Dy}+y_{Dx}}{4}\right) \tag{4}$$

x_{D0}, y_{D0}: The X and Y coordinates of the hole in the basic position (D0).
x_{Dz}, y_{Dz}: The X and Y coordinates of the hole after a 180° rotation around the Z-axis (DZ position).
x_{Dy}, y_{Dy}: The X and Y coordinates of the hole after a 180° rotation around the Y-axis (DY position).
$x_{Dx,}y_{Dx,}$: The X and Y coordinates of the hole after a 180° rotation around the X-axis (DX position).

The SRM not only minimizes system errors but also validates the suitability of CMMs for high-precision applications. It is particularly relevant in industries such as aerospace, automotive, and advanced manufacturing, where accuracy is critical. The use of the hole plate as a stable and reproducible reference further enhances the system's reliability, enabling it to serve as a transfer standard for calibrating and verifying precision measurement instruments.

By integrating these structured steps and leveraging high-resolution measurements, the SRM provides a robust mechanism for achieving precise and reliable measurement outcomes, making it a cornerstone of modern metrology.

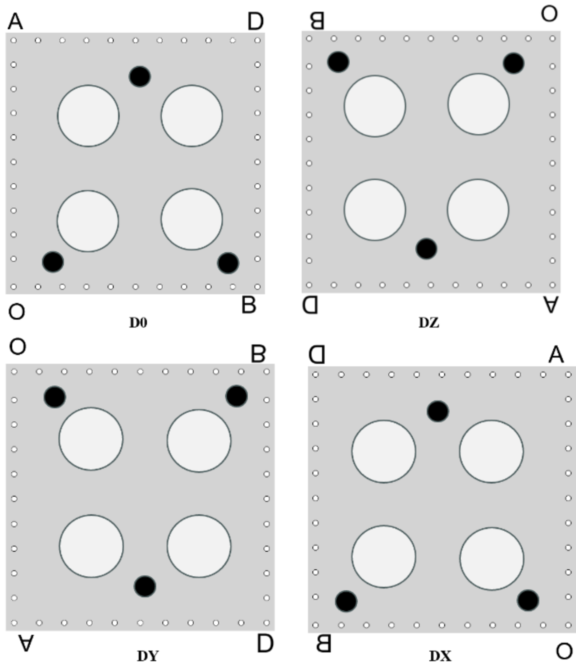

Fig. 5. The four plate positions used for the SRM

EXPERIMENTAL RESULTS AND DISCUSSION

Based on the measurement data from Tables 1 to 3 and further analysis at different positions using graphical representations in Fig. 6 and Fig. 7, the experimental results indicate that both the Swing Round Method (SRM) and the Reversal Method (RM) exhibit high precision, with measurement differences consistently within 2 μm.

However, when the measurement data is converted to squareness error, the RM's squareness error is approximately 2.6 arcseconds, slightly higher than SRM's 1.8 arcseconds, yet still within the 1 arcsecond permissible range. These findings suggest that RM may be more susceptible to systematic errors and external factors, such as alignment inaccuracies during the reversal process or environmental variations. Future research could explore the integration of compensation models to mitigate these issues and further enhance RM's measurement precision, particularly considering that RM requires fewer measurement steps compared to SRM.

The holeplate used in this experiment was sent to NMIJ for calibration upon purchase, where the coordinates of each hole were measured and recorded. Further comparison with the manufacturer's report (certificate no. 193071, 2019), as shown in Fig. 8, validates the reliability of the RM, demonstrating that the squareness error of the analyzed holeplate is negligible. This consistency also confirms the structural stability of the holeplate and its suitability as a geometric reference standard, providing users with greater confidence in its use. This is particularly beneficial in light of the rapid development of Industry 4.0, where the demand for on-machine, in-line, and in-process measurements is significantly increasing. Tools can be quickly replaced and converted into 3D measurement probes to evaluate the holeplate as a two-dimensional reference standard after measurement. Measurement results can be transmitted instantly for applications such as health monitoring, real-time compensation, or other operational tasks.

The experimental results of SRM, RM, and external calibration methods highlight the differences among these approaches, allowing the applicable precision ranges of different machines to be clearly identified. This provides an important reference for selecting an efficient measurement method.

Table 1. Measurement results using the SRM

	First meas. Y=0 mm	First meas. Y=550 mm	Second meas. Y=0 mm	Second meas. Y=550 mm	Avg. Y=0 mm	Avg. Y=550 mm
X= 0 mm	0.0	0.0	0.0	0.0	0.0	0.0
X= 50 mm	0.4	0.5	0.7	0.7	0.6	0.6
X= 100 mm	0.9	1.0	1.7	1.8	1.3	1.4
X= 150 mm	1.2	1.4	2.4	2.5	1.8	2.0
X= 200 mm	1.7	2.0	3.0	3.1	2.4	2.6
X= 250 mm	2.3	2.6	3.5	3.7	2.9	3.1
X= 300 mm	2.8	3.1	4.0	4.2	3.4	3.7
X= 350 mm	3.2	3.7	4.4	4.6	3.8	4.1
X= 400 mm	3.6	4.1	4.4	4.6	4.0	4.3
X= 450 mm	4.1	4.6	4.5	4.7	4.3	4.6
X= 500 mm	4.6	5.1	4.6	4.7	4.6	4.9
X= 550 mm	4.9	5.5	4.7	4.9	4.8	5.2

Table 2. Measurement results using the RM

	First meas. Y=0 mm	First meas. Y=550 mm	Second meas. Y= 0 mm	Second meas. Y=550 mm	Avg. Y=0 mm	Avg. Y=550 mm
X= 0 mm	0.0	0.0	0.0	0.0	0.0	0.0
X= 50 mm	0.7	0.6	0.9	1.0	0.8	0.8
X= 100 mm	1.7	1.7	2.3	1.8	2.0	1.8
X= 150 mm	2.8	2.7	3.0	3.0	2.9	2.9
X= 200 mm	3.7	3.6	3.3	4.0	3.5	3.8
X= 250 mm	4.5	4.4	4.0	4.8	4.3	4.6
X= 300 mm	5.2	5.2	4.6	5.6	4.9	5.4
X= 350 mm	5.7	5.9	5.2	6.3	5.5	6.1
X= 400 mm	6.1	6.5	5.8	6.9	5.9	6.7
X= 450 mm	5.7	6.6	6.0	7.1	5.8	6.8
X= 500 mm	6.8	6.8	6.0	7.2	6.4	7.0
X= 550 mm	7.0	7.1	7.5	7.5	7.2	7.3
					Unit ：µm	

Table 3. Comparisons of squareness of holeplate by manufacturer's report

	First meas. Y=0 mm	First meas. Y=550 mm	Average Y=550 mm
X= 0 mm	0	0	0.0
X= 50 mm	0.3	0.2	0.8
X= 100 mm	0.6	0.6	1.8
X= 150 mm	1.9	1.8	2.9
X= 200 mm	2.1	2.0	3.8
X= 250 mm	6.0	5.9	4.6
X= 300 mm	-3.8	-3.8	5.4
X= 350 mm	-2.3	-2.2	6.1
X= 400 mm	-1.4	-1.2	6.7
X= 450 mm	-0.3	0.2	6.8
X= 500 mm	3.8	3.8	7.0
X= 550 mm	5.5	5.5	7.3
			Unit ：µm

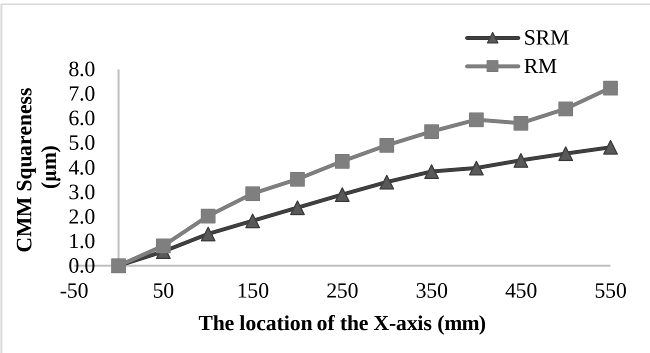

Fig. 6. Comparisons of squareness of SRM and RM in Y=0 mm

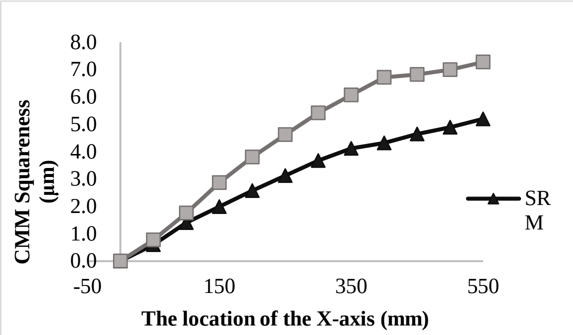

Fig. 7. Comparisons of squareness of SRM and RM in Y=550 mm

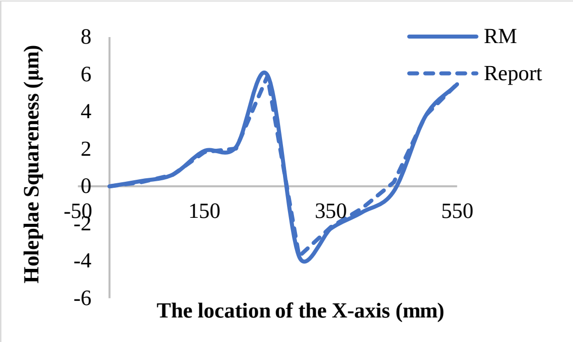

Fig. 8. Comparisons of squareness of holeplate by manufacturer's report

CONCLUSIONS

This study evaluated and compared three methods for measuring squareness errors in three-axis machine tools: the Swing Round Method (SRM), the Reversal Method (RM), and External Calibration. Experimental results indicate that all three methods exhibit high measurement precision, with measurement differences consistently maintained within 1 arcsecond.

Each method offers distinct advantages, making them suitable for different accuracy requirements, cost considerations, and operational flexibility. While SRM and external calibration provide higher measurement accuracy, they involve more complex procedures and relatively higher costs. In contrast, RM offers greater operational flexibility but may introduce larger uncertainties. The selection of an appropriate method depends on the machine's precision requirements and overall measurement costs.

Furthermore, this study validated the structural stability and reliability of the holeplate, further enhancing its practical value at this level of precision. The holeplate has been proven to serve as a stable geometric reference standard, playing a crucial role in industrial metrology by ensuring measurement consistency and repeatability under varying conditions. This also facilitates its adoption as a standardized measurement artifact for future applications. This further establishes the holeplate as an ideal reference standard for modern and future manufacturing processes, particularly for machine tools requiring a precision level of up to 20 μm, such as on-machine measurement applications.

Future research could explore the integration of these measurement methods into automated systems to further improve efficiency and applicability in Industry 4.0 environments. Additionally, the development of hybrid measurement techniques could unlock new possibilities for achieving sub-micron precision. These advancements would meet the evolving demands of high-precision industries, including aerospace and semiconductor manufacturing.

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DECLARATIONS

Conflict of interest：The authors declare no conflict of interests.

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NOMENCLATURE

θ : measuring value
δ : Deviation come from the machine geometric errors
x_{D0}, y_{D0}: The X and Y coordinates of the hole in the basic position (D0).
x_{Dz}, y_{Dz}: The X and Y coordinates of the hole after a 180° rotation around the Z-axis (DZ position).
x_{Dy}, y_{Dy}: The X and Y coordinates of the hole after a 180° rotation around the Y-axis (DY position).
$x_{Dx,}y_{Dx,}$: The X and Y coordinates of the hole after a 180° rotation around the X-axis (DX position).
P ： Pitch
YA ：Yaw
R ： Roll
L ： Positioning/ Straightness error
α, β, γ：Squareness between two axes in a three-axis coordinate system

計量級的垂直度誤差量測方法比較

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摘 要

本研究主要比較兩種適用於三軸機床垂直度誤差量測的計量級方法：輪轉方法 (SRM) 和反轉法 (RM)。實驗採用具有標準尺寸傳遞功能孔位的 holeplate 作為幾何誤差分析基準來進行實驗，以對兩種方法進行比較。實驗結果顯示，這兩種方法的量測差異穩定可在 1 角秒以內，足以滿足 20 μm 精度需求的機床應用，文中同時說明了外部校準與自我校準反轉法對於 holeplate 本身垂直度分析結果的一致性，因此足以確認實驗所選的 holeplate 是足夠穩定性作為待測物基準，另外實驗結果中也可發現外部校準和輪轉方法雖能提供高精確度，但成本較高或程序複雜，而反轉法提供了較大的靈活性，雖然結果可能會引入較大的量測誤差。未來研究可進一步探索這些方法在超精密加工領域的應用，並開發混合量測技術，以降低不確定性並提升精度。