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Identification of geometric errors of rotary axes on five-axis machine tools by tactile on-machine measurement

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Abstract

Identification of geometric errors in machine tools is widely deployed to improve machining accuracy. While double-ball bar, R-test, and interferometry-based error calibration techniques are widely used, on-machine measurement (OMM) is increasingly available on machine tools and can be utilized as an alternative technique for calibrating geometric errors. This work proposes a method to calibrate geometric errors of rotary axes on five-axis machine tools using tactile on-machine measurement. The positions of three precision spheres mounted on the rotary table at different heights are measured by a tactile on-machine measurement system while the rotary axis is positioned at various rotational angles. Geometric errors of the rotary axis are then identified based on the measured sphere positions. A validation experiment is conducted to demonstrate the identification accuracy. After correcting for the identified errors, roundness of the circular trajectory of a single sphere mounted on the rotary table is improved by over 50%. Furthermore, the contribution of OMM probing repeatability on the error identification uncertainty is analysed. The proposed geometric error identification method is cost-effective and suitable for periodic verification of geometric errors as outlined in ISO 230-2, enabling continuous monitoring and restoration of machine tool accuracy during manufacturing operations.

Keywords: five-axis machine tools, rotary axes, geometric errors, error calibration, on-machine measurement

1. Introduction

Five-axis machine tools are vital equipment for the production of crucial aerospace components like blades and impellers [1-2]. The high precision required for the manufacture of these parts makes it imperative to maintain the accuracy of the machine tools [3]. The accuracy of machine tools tends to decrease over time due to factors such as component wear. As a result, conducting regular inspections is crucial in ensuring the maintenance of machine tool accuracy. Performing 'periodic verification' is a vital practice in the maintenance of machine tool accuracy, as emphasized by ISO 230-2. Similarly, ISO 10360-1 stresses the importance of carrying out 'interim checks' to maintain the precision of high-precision measuring tools [4]. As periodic verification necessitates more frequent testing compared to acceptance testing, testing efficiency plays a crucial role in achieving production efficiency. Geometric errors on rotary axes are commonly indirectly identified using measurement instruments, including double-ball bar, R-test, and laser interferometer, which require highly skilled operators and expensive equipment. Recently, there has been an increasing focus on applying on-machine measurement technology [5-6] to identify geometric errors. This approach allows for automated periodic accuracy checks of the machine tools. Despite its potential, this method is yet to be commercialized, with no international standards established for its use. This paper proposes a geometric errors identification method of rotary axes on a five-axis machine tool using on-machine measurement. Section 2 describes the method of geometric errors identification. Section 3 describes the geometric error identification experiment and verification. Section 4 concludes the main findings of this work.

2. Method of identification

2.1. definition of geometric errors

The method of identifying the geometric errors in the rotary B- and C- axes in five-axis machine tools is presented. Each rotary axis has six geometric errors that include three linear errors and three angular errors, as shown in Figure 1. During machine operation, the actual position of the workpiece deviates from the nominal position due to these geometric errors, resulting in machining errors in the workpiece. These geometric errors are defined with respect to the machine reference coordinate system, and therefore, the geometric errors of each of the two rotary axes can be identified independently, thus avoiding the coupling effect of the geometric errors on both rotary axes.

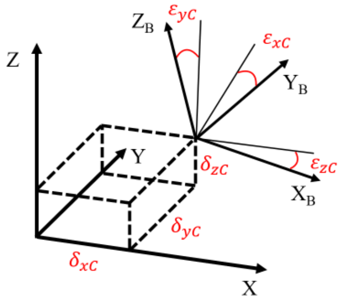

Figure 1. Illustration of geometric errors of the rotary axis

2.2. Geometric errors identification

Geometric errors identification of the C-axis is taken as an example. Three standard spheres are mounted on the rotary worktable at various heights, each positioned at a different radial distance from the rotary axis. The positions of the spheres are measured by a tactile OMM probe as the C-axis is sequentially rotated by an incremental angle. The geometric errors of the rotary axis can be identified by calculating the deviation between the measured and nominal coordinates:

$$\begin{bmatrix} 1 & 0 & 0 & 0 & {}^{M}P_{nZ} & -{}^{M}P_{nY} \\ 0 & 1 & 0 & -{}^{M}P_{nZ} & 0 & {}^{M}P_{nX} \\ 0 & 0 & 1 & {}^{M}P_{nY} & -{}^{M}P_{nX} & 0 \end{bmatrix} \begin{bmatrix} \delta_{xC} \\ \delta_{yC} \\ \delta_{zC} \\ \varepsilon_{xC} \\ \varepsilon_{yC} \\ \varepsilon_{zC} \end{bmatrix} = \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix}$$

where ${}^{M}_{A}T \cdot {}^{A}_{C}T \cdot {}^{C}P = {}^{M}P_{n}$, ${}^{M}_{A}T$ and ${}^{A}_{C}T$ are transformations between coordinate systems. ${}^{C}P$ represents the coordinate of the sphere when the C-axis is at zero position, while ${}^{M}P_{n}$ represents the nominal coordinate of the sphere in the machine reference coordinate system. $[\Delta x \quad \Delta y \quad \Delta z]^{T}$ is the deviation between the measured and nominal sphere centre coordinates.

3. Experiments and verification

3.1. Experiment of geometric error identification

Figure 2 illustrates three standard spheres placed on the rotary table, each one manufactured with high precision (0.2 µm roundness) to ensure minimal sphericity error. The position of the spheres are measured at 30° incremental rotational angles of the C-axis.

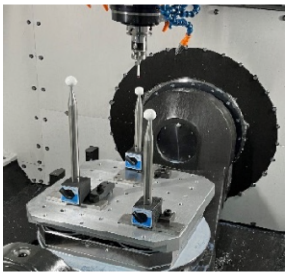

Figure 2. Experimental setup of geometric error identification

The geometric error of rotary axis at any position can be solved given the measured coordinates of the three sphere centres, as outlined in section 2.2. The identified geometric errors are shown in Figures 3 and 4.

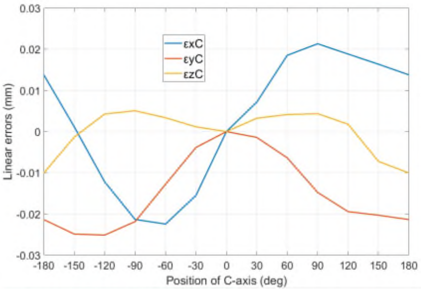

Figure 3. Linear errors identification results of the C-axis

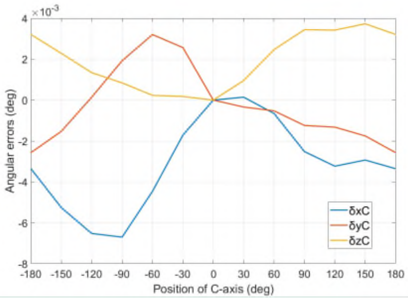

Figure 4. Angular errors identification results of the C-axis

3.2. verification

To validate the identified results, a standard sphere is installed at a new position on the rotary table, and the centre position of the sphere is measured as the C-axis completes a full rotation at an incremental angle of 30°. Roundness of the Gaussian associated circle fitted using the measured sphere centre positions are obtained. The sphere centre coordinates are corrected for the identified geometric errors according to the established error model. After correction, the roundness of the sphere circular trajectory is reduced from 7.2 µm to 3.5 µm, achieving an improvement of over 50% and demonstrating the effectiveness of the proposed identification method.

3.3. uncertainty evaluation

The Monte Carlo method, combined with the error ellipsoid, is employed to evaluate the contribution of OMM probing repeatability on the geometric error identification uncertainty. The single-point probing uncertainty in each direction is obtained by repeatedly probing the workpiece 50 times. The error ellipsoid, as shown in Figure 5, precisely depicts the input probability distribution [7]. The uncertainty in identifying the geometric errors is obtained by a Monte Carlo method that adaptively adjusts the number of simulations to reach convergence [7], which is found to be 2000. The identification uncertainties of the linear errors δ_{xC}, δ_{yC} and δ_{zC} are calculated to be 1.7 µm, 2.1 µm and 2.3 µm, respectively, while the identification uncertainties of the angular errors ε_{xC}, ε_{yC} and ε_{zC} are calculated to be 0.00045deg, 0.00036deg and 0.00034deg, respectively.

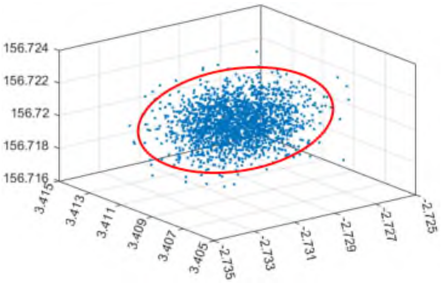

Figure 5. Error ellipsoid of single point probing repeatability

4. Conclusions

This work investigates the calibration of geometric errors of rotary axes on five-axis machine tools by tactile on-machine measurement. Method of identification is established. Experiments are performed to identify the geometric errors using three standard spheres by on-machine measurement. Six geometric errors are identified by the proposed method. The results of identification indicate that the correction effectiveness in on-machine measurement surpasses 50%, validating the identification method. Additionally, the adaptive Monte Carlo method based on the error ellipsoid is utilized to evaluate the identification uncertainty, thereby illustrating the identification outcome's reliability. This approach allows for automated periodic accuracy checks of the machine tools, which enables consistency in machining quality. Future research for improving correction performance will concentrate on identifying position-independent geometric errors caused during machine tool assembly, alongside simultaneous identification of position-dependent and position-independent geometric errors.

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