euspen's 25th International Conference & Exhibition, Zaragoza, ES, June 2025
www.euspen.eu

Identification algorithm for position-independent geometric errors in table-tilting 5-axis machine tools

Gyungho Khim[1], Quoc-Khanh Nguyen[1], Jeong Seok Oh[1], and Chang-Kyu Song[1]

[1]*Department of Ultra Precision Machines & Systems, Korea Institute of Machinery and Materials*

gyungho@kimm.re.kr

Abstract
The accuracy of 5-axis machine tools significantly affects the machining quality of complex and delicate parts used in industries such as aerospace and medicine. Geometric errors in 5-axis machine tools ultimately appear as volumetric errors caused by deviations between the tool and the workpiece, making it essential to measure and compensate for these errors. Position-independent geometric errors are one of the main factors affecting volumetric errors and are defined by 11 components: 3 squareness errors between linear axes, 3 squareness errors and 4 offset errors related to the rotary axes. These errors are independent of axis position and are primarily determined during machine assembly. To measure these errors, a method using a touch trigger probe and a datum ball was developed. The datum ball is placed on the rotary table, and its center points are measured by the touch trigger probe as the rotary table is rotated to different positions, enabling for the identification of the 11 geometric errors. This paper introduces a new algorithm for identifying all 11 geometric errors. This method, the so-called "three-rotation method," sequentially calculates the geometric errors using three different measurement patterns and provides an explicit solution. The effectiveness of this method was demonstrated through numerical simulations.

Keywords: 5-axis machine tools, Geometric errors, Touch trigger probe, Error identification, thee-rotation method

1. Introduction

The geometric errors of 5-axis machine tools greatly influence their overall accuracy, therefore, these errors must be measured and compensated for to improve machining quality. The geometric errors are classified into component errors (position-dependent errors) and location errors (position-independent errors). Component errors are the 6-DoF motion errors of linear or rotary axes, which depend on their positions. Conversely, location errors are defined as the deviations from nominal position and orientation in the machine coordinate system[1,2]. These errors, such as squareness and offset errors, are independent of axis position and are primarily determined during the assembly process. In this study, we focus on these location errors as a crucial factor in improving the accuracy.

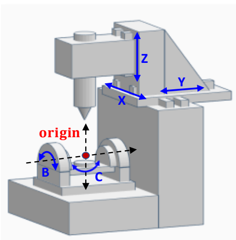
Accurately measuring location errors is challenging because it requires simultaneous control of the machine's multiple axes during measurement process. In addition, these errors cannot be measured all at once but instead requires separate measurements using specialized equipment. A variety of methods have been developed to measure the location errors including the double ball bar system[3], the R-test[4], machining tests on workpieces[5], and the touch trigger probe[6]. Among these, the touch trigger probe is a standard feature in most machine tools, making it highly practical and widely applicable. However, most of the existing studies have focused solely on the location errors related to the rotary axes of 5-axis machine tools. A study on measuring all 11 position-independent geometric errors simultaneously has been granted as a patent[7]. This method requires multiple measurement patterns to identify the errors and involves an approximation process during the calculation, making the computation somewhat complex.

In this paper, we propose a new method for simultaneously measuring and identifying all 11 position-independent geometric errors in table-tilting 5-axis machine tools using a touch probe and a datum ball with a simpler measurement pattern and calculation method. The proposed method, called the "three-rotation method," sequentially calculates the geometric errors through three distinct measurement patterns and provides an explicit solution. This paper introduces this algorithm and verifies its effectiveness through numerical simulations.

2. Modelling

2.1. Definition of geometric errors

Figure 1 shows a table-tilting 5-axis machine tool consisting of three linear axes(X, Y, Z) and two rotary axes(B, C). The reference coordinate system is assumed to be located at the intersection of B- and C-axes.



Symbol	Description
α_{YZ}	Squareness error between Y- and Z-axis
β_{XZ}	Squareness error between X- and Z-axis
γ_{XY}	Squareness error between X- and Y-axis
α_{ZB}	Squareness error between Z- and B-axis
γ_{XB}	Squareness error between X- and B-axis
δ_{XB}	Offset error of B-axis in X-direction
δ_{ZB}	Offset error of B-axis in Z-direction
α_{YC}	Squareness error between Y- and C-axis
β_{XC}	Squareness error between X- and C-axis
δ_{XC}	Offset error of C-axis in X-direction
δ_{YC}	Offset error of C-axis in Y-direction

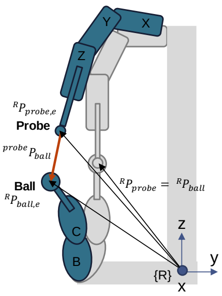
Figure 1. 11 geometric errors of 5-axis machine tools

There are a total of 11 geometric errors in this type of machine tools. Three squareness errors (α_{YZ}, β_{XZ}, and γ_{XY}) are defined among the linear axes. For the B-axis, two squareness errors (α_{ZB} and γ_{XB}) and two offset errors (δ_{XB} and δ_{ZB}) are defined. Similarly, for the C-axis, and two sqaureness errors (α_{YC} and β_{XC}) and two offset errors (δ_{XC} and δ_{YC}) are defined. The orientations of these errors are determined according to the right-hand rule in the reference coordinate system.

2.2. Identification algorithm

The locations of datum ball and touch trigger probe are described using rigid body kinematics and the homogeneous transformation matrix (HTM) with respect to the reference coordinate system, as shown in Figure 2. ${}^{R}P_{probe}$ and ${}^{R}P_{ball}$ are the locations of touch probe and ball artifact with respect to the reference coordinate system, respectively.

Ideally, the locations of the touch trigger probe perfectly match those of the ball artifact, however, inconsistencies arise between them due to geometric errors. As a result, the error vector (${}^{probe}P_{ball}$) is defined as a function of geometric errors. The actual locations of the ball artifact can be represented as a combination of the ideal locations and the error vectors associated with the 11 geometric errors. By measuring the center positions of the ball artifact with a touch trigger probe at multiple locations on the rotary axes and analyzing the measured data, all 11 geometric errors can be determined.



$$ {}^{R}P_{ball,e} = {}^{R}T_{B,e}\,{}^{B}T_{C,e}\,{}^{C}P_{ball} $$
$$ {}^{R}P_{probe,e} = {}^{R}T_{X,e}\,{}^{X}T_{Y,e}\,{}^{Y}T_{Z,e}\,{}^{Z}P_{probe} $$
$$ {}^{probe}P_{ball,e} = {}^{R}P_{ball,e} - {}^{R}P_{probe,e} $$
$$ \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}_{actual} = \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}_{ideal} + {}^{probe}P_{ball,e} $$

Figure 2. Identification principle

The measurement pattern and identification algorithm are critical for both measurement efficiency and accuracy. This paper presents a new algorithm for identifying all 11 geometric errors. This method, referred to as the "three-rotation method," calculates the geometric errors using data measured during the rotation of the C-axis at three different angles of the B-axis, as shown in Figure 3. The 11 geometric errors are sequentially determined using explicit equations, as shown in Equations (1)~(3). Some geometric errors are calculated using other geometric errors that have already been determined. However, due to length limitations in this paper, only the equations for the three squareness errors between linear axes are presented. R, H, and δ_{YW} represent the installation radius, height, and installation error in the y-direction of the datum ball, respectively. n denotes the number of measurements per rotation. O_z is the z-direction offset distance of the C-axis relative to the B-axis. x, y, and z represent the measured coordinates of the datum ball's center point.

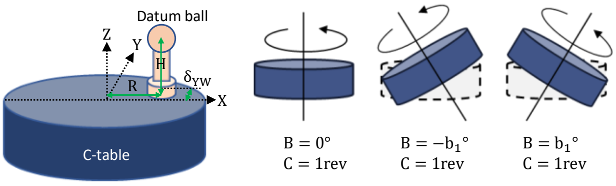


Figure 3. Installation of the datum ball and measurement patterns for the three-rotation method

$$ \alpha_{YZ} = \alpha_{ZB} - \frac{1}{nR\sin b_1}\left(\sum_{i=1}^{n} y(b_1, C_i)\cos C_i - \sum_{i=1}^{n} y(-b_1, C_i)\cos C_i\right) \quad (1) $$

$$ \beta_{XZ} = \frac{1}{nR\sin b_1}\left(\sum_{i=1}^{n} x(b_1, C_i)\cos C_i - \sum_{i=1}^{n} x(-b_1, C_i)\cos C_i\right) + \beta_{XC} \quad (2) $$

$$ \gamma_{XY} = \frac{2}{nR}\left(\sum_{i=1}^{n} x(0, C_i)\sin C_i + \sum_{i=1}^{n} y(0, C_i)\cos C_i\right) \quad (3) $$

3. Identification results

Table 1 shows the verification results of the proposed algorithm through numerical analysis. Geometric errors were initially assumed, and the coordinates of the datum ball's center point and the values that would be measured by the touch probe, assuming these errors, were calculated. These values were then treated as simulated measurement data to recalculate the geometric errors using the proposed algorithms. The algorithms were evaluated by comparing the initially assumed geometric errors with those recalculated by the algorithms. Such simulations were performed 1,000 times for arbitrary geometric errors, and the results confirmed that the proposed algorithm successfully calculated the geometric errors without any issues.

Table 1 Verification of the proposed algorithm

(a) Simulation for a specific geometric errors

	R	δ_{YW}	H	α_{YZ}	β_{XZ}	γ_{XY}	α_{ZB}	γ_{XB}	δ_{XB}	δ_{ZB}	α_{YC}	β_{XC}	δ_{XC}	δ_{YC}
	(mm)	(mm)	(mm)	(μrad)	(μrad)	(μrad)	(μrad)	(μrad)	(μm)	(μm)	(μrad)	(μrad)	(μm)	(μm)
Assumed	200.000	300.000	0.100	-34.000	29.000	17.000	-17.000	75.000	-12.000	19.000	-87.000	42.000	10.000	-15.000
Estimated	200.000	300.000	0.100	-33.982	29.017	17.004	-16.986	75.003	-11.995	18.998	-86.994	42.052	9.984	-14.999
Difference	0.000	0.000	0.000	-0.018	-0.017	-0.004	-0.014	-0.003	-0.005	0.002	-0.006	-0.052	0.016	-0.001

(b) 1,000 simulations for arbitrary geometric errors (STD: Standard Deviation)

	R	δ_{YW}	H	α_{YZ}	β_{XZ}	γ_{XY}	α_{ZB}	γ_{XB}	δ_{XB}	δ_{ZB}	α_{YC}	β_{XC}	δ_{XC}	δ_{YC}
	(mm)	(mm)	(mm)	(μrad)	(μrad)	(μrad)	(μrad)	(μrad)	(μm)	(μm)	(μrad)	(μrad)	(μm)	(μm)
MEAN	0.000	0.000	0.000	-0.001	-0.002	0.000	-0.001	0.000	-0.001	0.000	0.001	0.001	0.000	0.000
STD	0.006	0.000	0.000	0.015	0.043	0.005	0.014	0.004	0.017	0.002	0.033	0.041	0.012	0.010

4. Summary

In this paper, we present a new method for identifying all 11 position-independent geometric errors in table-tilting 5-axis machine tools using a touch trigger probe and a datum ball. The proposed three-rotation method provides an explicit solution for these 11 geometric errors through three measurement patterns, and its effectiveness has been verified through numerical simulations.

Future work includes implementing the proposed algorithm on an actual 5-axis machine tool and verifying its performance through experiments, which are currently in progress.

Acknowledgement

This work was supported by research program 20021902 funded by the Ministry of Trade, Industry & Energy (MOTIE, Korea).

References

[1] Schwenke H, Knapp W, Haitjema H, Weckenmann A, Schmitt R and Delbressine F 2008 *CIRP Annals-Manuf Technol* **57** 660-75
[2] ISO 230-1, Test Code for Machine Tools-Part1 2012 ISO
[3] Lee K and Yang S 2016 *Int J Adv Manuf Technol* **84** 981-88
[4] Hong C, Ibaraki S and Oyama C 2012 *Int J Machine Tools Manuf* **59** 24-33
[5] Ibaraki S, Sawada M, Matsubara A and Matsushita T 2010 *Pres Eng* **34** 387-98
[6] Ibaraki S, Iritani T and Matsushita T 2012 *Int J Machine Tools Manuf* **58** 44-53
[7] Okuma Corporation 2013 Method and program for identifying mechanical errors *US Patent* US8494800