International Journal of Precision Engineering and Manufacturing (2020) 21:2391–2398
https://doi.org/10.1007/s12541-020-00437-2

Online ISSN 2005-4602
Print ISSN 2234-7593

REGULAR PAPER

Sequential Measurement of Position-independent Geometric Errors in the Rotary and Spindle Axes of a Hybrid Parallel Kinematic Machine

Seung-Han Yang[1] · Dong-Mok Lee[2] · Hoon-Hee Lee[3] · Kwang-Il Lee[4]

Received: 16 March 2020 / Revised: 9 October 2020 / Accepted: 26 October 2020 / Published online: 9 November 2020

Abstract

We propose a technique to measure position-independent geometric errors (PIGEs) in the rotary and spindle axes of a hybrid parallel kinematic machine (PKM). The PKM investigated here includes one more rotary axis than an Exechon PKM, which is used to improve the productivity of hybrid processes, such as machining and direct-energy-deposition three-dimensional metal printing. Errors in the measured position and orientation of the rotary axis, and the orientation of the spindle axis produce volumetric errors in the processed workpiece. If accuracy is to be improved, the deviation of each axis must be measured and compensated. In our approach, errors are measured using three methodologies that require only control of the rotary axis: in the first, no offset is applied to account for positional deviation of the rotary axis; in the second, an offset is used to correct the orientation of the rotary axis; and in the third, a tool offset is used to correct the orientation of the spindle axis. We developed an algorithm that uses the three measured datasets to identify PIGEs. The proposed method was applied to a hybrid PKM and the PIGEs were measured and compensated. This technique uses simple measurement paths and sequential measurements to correct rotary and spindle axis errors, and could therefore be widely used in industry.

Keywords Position-independent geometric error · Sequential measurement · Rotary axis · Spindle axis · Parallel kinematic machine · Double ball-bar

✉ Kwang-Il Lee
kilee@kiu.kr

Seung-Han Yang
syang@knu.ac.kr

Dong-Mok Lee
dmlee@maxrotec.com

Hoon-Hee Lee
hhlee84@kitech.re.kr

[1] School of Mechanical Engineering, Kyungpook National University, 80, Daehak-ro, Buk-gu, Daegu, Republic of Korea

[2] R&D Center, Maxrotec Co, 40, Seongseo-ro 71-gil, Dalseo-gu, Daegu, Republic of Korea

[3] Transport Machine Components R&D Group, Korea Institute of Industrial Technology, 25, Yeonkkot-ro 165beon-gil, Jeongchon-myeon, Jinju-si, Gyeongnam 52845, Republic of Korea

[4] School of Mechanical and Automotive Engineering, Kyungil University, 50, Gamasil-gil, Hayang-eup, Gyeongsan-si, Gyeongbuk 38428, Republic of Korea

Abbreviations

c	Rotary axis angle of rotation $\boldsymbol{C}$, *rad*.
k	Coverage factor, $k=2$.
m	Double ball-bar measurement sample number.
o_{H}	Height offset, *mm*.
o_{T}	Tool offset, *mm*.
o_{xc}, o_{yc}	Offset errors in the $\boldsymbol{x}$, $\boldsymbol{y}$-direction of a rotary axis $\boldsymbol{C}$, μm.
s_{xc}, s_{yc}	Squareness errors around the $\boldsymbol{x}$, $\boldsymbol{y}$-direction of a rotary axis $\boldsymbol{C}$, μrad.
s_{xs}, s_{ys}	Squareness errors around the $\boldsymbol{x}$, $\boldsymbol{y}$-direction of a rotary axis $\boldsymbol{S}$, μrad.
R	Nominal length of the double ball-bar, *mm*.
ΔR_{ij}	j-Th radial deviation at i-th measurement, ($i=1$, 2, 3; $j=1$, …, m), μm.
(e_{xi}, e_{yi})	Eccentricity of the radial deviation ΔR_{ij} ($i=1$, 2, 3; $j=1$, …, m), μm.
$\{\boldsymbol{i}\}$	$\boldsymbol{i}$-Axis coordinate system $\{\boldsymbol{i}=\boldsymbol{C}, \boldsymbol{S}\}$.
$\{\boldsymbol{R}\}$	Reference coordinate system

1 Introduction

Parallel kinematic machines (PKMs) are widely used in industry, as their closed kinematic loops provide high structural rigidity and stiffness [1]. The Exechon PKM (Exechon Enterprises, LLC) is a commercially available PKM used to control the position and orientation of an end-effector [2]. Recently, a hybrid PKM (DABO MDP-1000; Maxrotec Co., Ltd) was developed for hybrid processes, including machining and direct-energy-deposition (DED) three-dimensional (3-D) metal printing [3]. The hybrid PKM combines a rotary axis with the Exechon PKM, which is used to increase productivity by controlling the workpiece orientation. The volumetric accuracy and kinematic errors of the Exechon PKM can be determined through calibration processes supported by Exechon Enterprises LLC [4]. However, calibration of the additional rotary axis is not supported, which can result in volumetric errors when the hybrid PKM is used. The position and orientation of the rotary and spindle axes deviate from the design during assembly. The positional and orientation errors are defined as offset and squareness errors, respectively, and are collectively described as position-independent geometric errors (PIGEs) [5] (also called location errors [6] and location and orientation errors [7]). It is essential that the PIGEs are directly or indirectly measured and compensated to keep volumetric errors within tolerance [8, 9].

Several techniques can be used to measure the PIGEs of a rotary axis, such as a double ball-bar (DBB), the *R* test, a touch-trigger probe, multilateration, and machining tests. A DBB can be used with three measuring paths in the radial, axial, and tangential directions requiring simultaneous three-axis control [10]. The test conditions for the measurements are specified in ISO 10,791–6 [11]. PIGE identification with a cylindrical coordinate system is superior to PIGE identification with a Cartesian coordinate system, in terms of the number of measurements [12]. Control of the linear axis is avoided by the use of simple DBB measuring paths that require only control of the rotary axis [13]. Similar to the DBB method, the R-test was developed to identify the PIGEs of a rotary axis, by using a 3-D sensor to measure the position of a ball [14]. The error motions of controlled linear axes during the R-test also affect PIGE identification, so it is recommended that these be measured and compensated for [15]. Thermal errors can also affect PIGE identification [16], so it is necessary to identify PIGEs rapidly. A touch-trigger probe is used to measure ball positions for PIGE identification of four-axis machine tools [17], five-axis machine tools with a tilting-rotary table [18], and five-axis machine tools with a universal head [19]. A touch-trigger probe can also be used to identify PIGEs by precisely measuring a test piece of five-axis machine tools with a tilting-rotary table [20] and tilting head [21], so that PIGEs can be identified without the need for additional measurement devices. In multilateration, a laser tracker is used to measure the coordinates of several target points using the same principle as a global positioning system [22]. It is also used to identify PIGEs by machining a test-piece on a machine tool and measuring the features of the machined test piece with a coordinate measuring machine (CMM), for five-axis machine tools with a tilting-rotary table [23] and tilting head [24].

Typically, the PIGEs of a spindle axis are measured using a test mandrel [25], or a DBB is used to conduct two circular tests with different tool lengths for three-axis machine tools [26].

Recently, a DBB method was proposed to identify the PIGEs of linear axes, rotary axes, and a spindle axis by selective analysis of the data in Cartesian and cylindrical coordinate systems [27]. However, PIGE identification is affected by error motions arising due to the control of the linear axes during measurements.

In summary, rotary and spindle axis PIGEs can be measured using existing techniques, with three-axis controls in generally being required; however, these methods are typically expensive, complicated, and time-consuming. In addition, no studies concerned only with PIGE identification of rotary and spindle axes have been published. Therefore, we propose a technique that can be used to simultaneously identify the PIGEs of rotary and spindle axes, using a DBB and fixtures to conduct simple measurements not affected by the error motion of linear axes. In Sect. 2, a hybrid PKM is introduced and the PIGEs of rotary and spindle axes are summarized. Measurement paths are proposed, and an algorithm is developed that can identify the PIGEs from sequentially measured data. In Sect. 3, the proposed technique is used to measure and compensate the PIGEs of a hybrid PKM, and the measurement uncertainty is analyzed. The main advantages of our proposed method are summarized in Sect. 4.

2 A Hybrid PKM and PIGE Measurements

2.1 A Hybrid PKM and the PIGEs of Rotary and Spindle Axes

A hybrid PKM comprises three parallel linear axes, $\boldsymbol{L_1}$, $\boldsymbol{L_2}$, $\boldsymbol{L_3}$, two serial wrist axes, $\boldsymbol{W}_1$, $\boldsymbol{W}_2$, for tool position and orientation, and a rotary axis, $\boldsymbol{C}$, for workpiece orientation

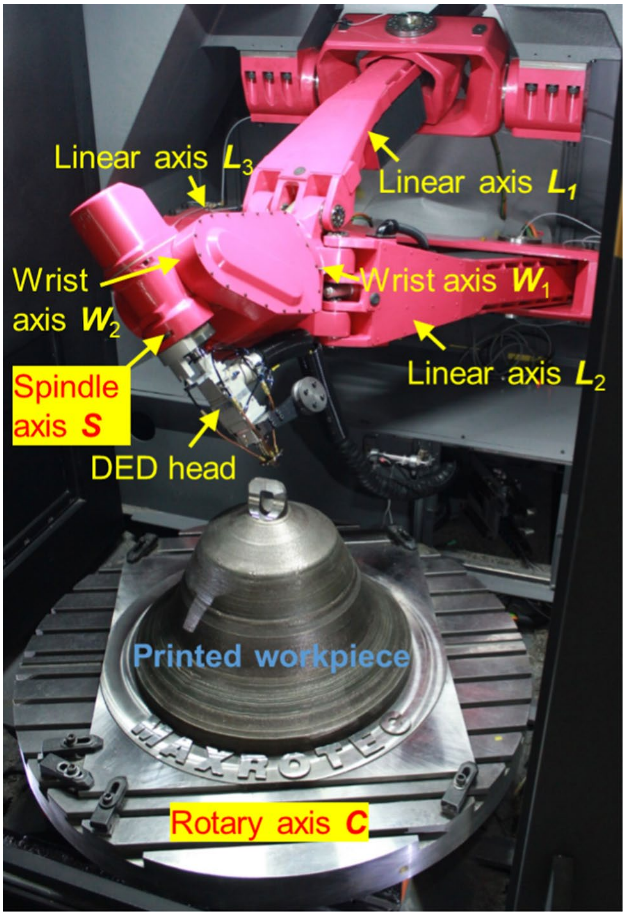

Fig. 1 The structure of a hybrid parallel kinematic machine (PKM)

Table 1 The hybrid PKM specification

Parameter	Unit	Value
Stroke of linear axes $\boldsymbol{L_1}$, $\boldsymbol{L_2}$, $\boldsymbol{L_3}$	mm	700
Stroke of rotary axes $\boldsymbol{W_1}$, $\boldsymbol{W_2}$	degree	540, 180
Stroke of a rotary axis $\boldsymbol{C}$	degree	360 (continuous)
Resolution of linear axes $\boldsymbol{L_1}$, $\boldsymbol{L_2}$, $\boldsymbol{L_3}$	µm	1.0
Resolution of wrist axes $\boldsymbol{W_1}$, $\boldsymbol{W_2}$	degree	0.001
Resolution of a rotary axis $\boldsymbol{C}$	degree	0.001
Controller	–	Siemens 840D sl

control, as shown in Fig. 1. The machine specification is summarized in Table 1 [28]. In this study, we assume that the three linear and two wrist axes were fully calibrated according to the processes recommended by Exechon Enterprises, LLC, such that the volumetric errors due to these axes are negligible. Here, the hybrid PKM errors are caused primarily by the position and orientation deviation of $\boldsymbol{C}$ and the spindle axis, $\boldsymbol{S}$. The PIGE deviation is illustrated in Fig. 2. Specifically, $\boldsymbol{C}$ is offset from its nominal position by o_{xc}, o_{yc}, and deviates from its nominal orientation by s_{xc}, s_{yc} in/around the $\boldsymbol{x}$, $\boldsymbol{y}$-direction, respectively. $\boldsymbol{S}$ deviates from its nominal orientation by s_{xs}, s_{ys} around the $\boldsymbol{x}$-, $\boldsymbol{y}$-direction, respectively.

2.2 DBB Measuring Paths and Measurement of the PIGEs

The PIGEs were measured using a DBB and three movement paths, as shown in Fig. 3a, b, c. Figure 3a shows how the offset errors o_{xc} and o_{yc} were measured using a DBB installed between the tool nose and a center mount on the workpiece table. $\boldsymbol{C}$ was unilaterally controlled according to the rotation angle, c, as $R+\Delta R_{1\text{j}}$ was recorded. As shown in Fig. 3b, the squareness errors s_{xc} and s_{yc} were measured by installing the DBB in the z-direction with a height offset o_{H}, and $R+\Delta R_{2\text{j}}$ was recorded as $\boldsymbol{C}$ was controlled. The squareness errors s_{xs} and s_{ys} were measured by installing the DBB at the same height shown in Fig. 3a with a tool offset o_{T}, as shown in Fig. 3c.

In general, PIGEs are calculated from DBB measurement data ($R+\Delta R_{\text{ij}}$) by calculating the eccentricities, e_{xi} and e_{yi} [10, 29]. It is trivial to determine o_{xc} and o_{yc} from $R+\Delta R_{1\text{j}}$, however it is more difficult to determine s_{xc} and s_{yc}, and s_{xs} and s_{ys} as they are components of $R+\Delta R_{2\text{j}}$ and $R+\Delta R_{3\text{j}}$, respectively, which are compounded with o_{xc} and o_{yc}. Therefore, the offset errors are measured and compensated by the first measurement, and the second and third measurements are then made sequentially so that the magnitudes of the squareness errors can be calculated. In this paper, this process is referred to as sequential measurement. The PIGEs are calculated from the eccentricities as described by Eq. (1), in which the columns are fully decoupled due to the sequential measurement.

$$\begin{bmatrix} o_{xc} \\ o_{yc} \\ s_{xc} \\ s_{yc} \\ s_{xs} \\ s_{ys} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1/o_H & 0 & 0 \\ 0 & 0 & 1/o_H & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1/o_T \\ 0 & 0 & 0 & 0 & 1/o_T & 0 \end{bmatrix} \begin{bmatrix} e_{x1} \\ e_{y1} \\ e_{x2} \\ e_{y2} \\ e_{x3} \\ e_{y3} \end{bmatrix} \tag{1}$$

3 Experimental Study of the Proposed Method

The proposed method was applied to a hybrid PKM [3] so that the PIGEs of $\boldsymbol{C}$ and $\boldsymbol{S}$ could be measured and compensated, as shown in Fig. 4. A 100-mm-long QC20-W ball bar (Renishaw plc) was used, and a large height and tool offset (320 and 325 mm, respectively) were employed to reduce the

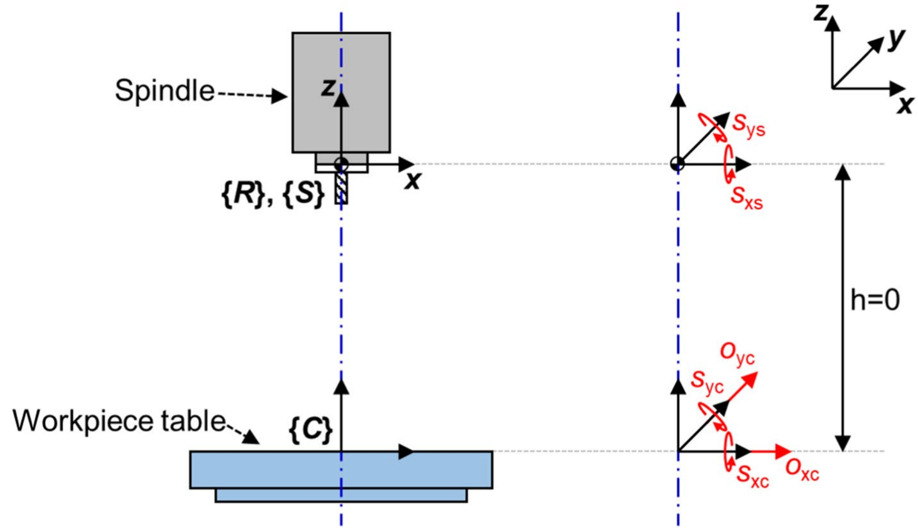

Fig. 2 The position-independent geometric errors (PIGEs) of the rotary axis, ***C***, and spindle axis, ***S***

PIGE measurement uncertainty. The large offsets o_H and o_T can be used to identify squareness errors, and the offsets can be increased with additional fixtures.

As shown in Fig. 5, large $R+\Delta R_{ij}$ peak-to-valley (PV) values of 29.5, 50.9, and 79.7 µm were measured when i was equal to 1, 2, and 3, respectively. This was primarily due to the eccentricities caused by the PIGEs of ***C*** and ***S***. The eccentricities of $R+\Delta R_{ij}$ were calculated using Eq. (1), as summarized in Table 2.

The measurements were repeated after compensation of the PIGEs shown in Table 2, and corrected $R+\Delta R_{ij}$ PV values of 2.4, 8.8, 5.4 µm were recorded when i was equal to 1, 2, and 3, respectively. These values represent an improvement of 92, 83, and 93%, respectively, which demonstrates the validity of the method proposed here. The contributors to the PIGE measurement uncertainty are summarized in Table 3, when the coverage factor $k=2$. It was assumed that the repeatability of ***C*** and the PKM was ± 1 µm, which is of the same order as the resolution of the linear axes $\boldsymbol{L}_1$, $\boldsymbol{L}_2$, $\boldsymbol{L}_3$, and that the repeatability followed a rectangular distribution [30].

Theoretically, the measurement uncertainties of the squareness errors are identical if o_H and o_T are equal. As shown in Fig. 6, the squareness error measurement uncertainties were calculated as a function of the offset. The measurement uncertainty and offset were found to have an inverse relationship; however, the uncertainty did not decrease significantly when the offset was over 300 mm. Therefore, height and tool offsets of 320 and 325 mm, respectively, were used throughout this study.

4 Conclusion

Here, we proposed a simple and effective method to improve the volumetric accuracy of a hybrid PKM, in which the PIGEs of the rotary and spindle axes were measured. For simplicity, only a double ball-bar was used to conduct the measurements; three motion paths were followed, which only required movement of the rotary axis. Additionally, sequential measurements and an analytical method were used to determine the PIGEs using the three measured datasets, and their eccentricities. The proposed method was tested with a hybrid PKM, and validated by measurement and compensation of the PIGEs; in this manner. the PV and double ball-bar errors were improved significantly.

It should be noted that the proposed method is not restricted to double ball-bar measurements; it could also be utilized for precise measurement of the position of a ball in a reference coordinate system, via the touch-trigger probe and R-test techniques, for example.

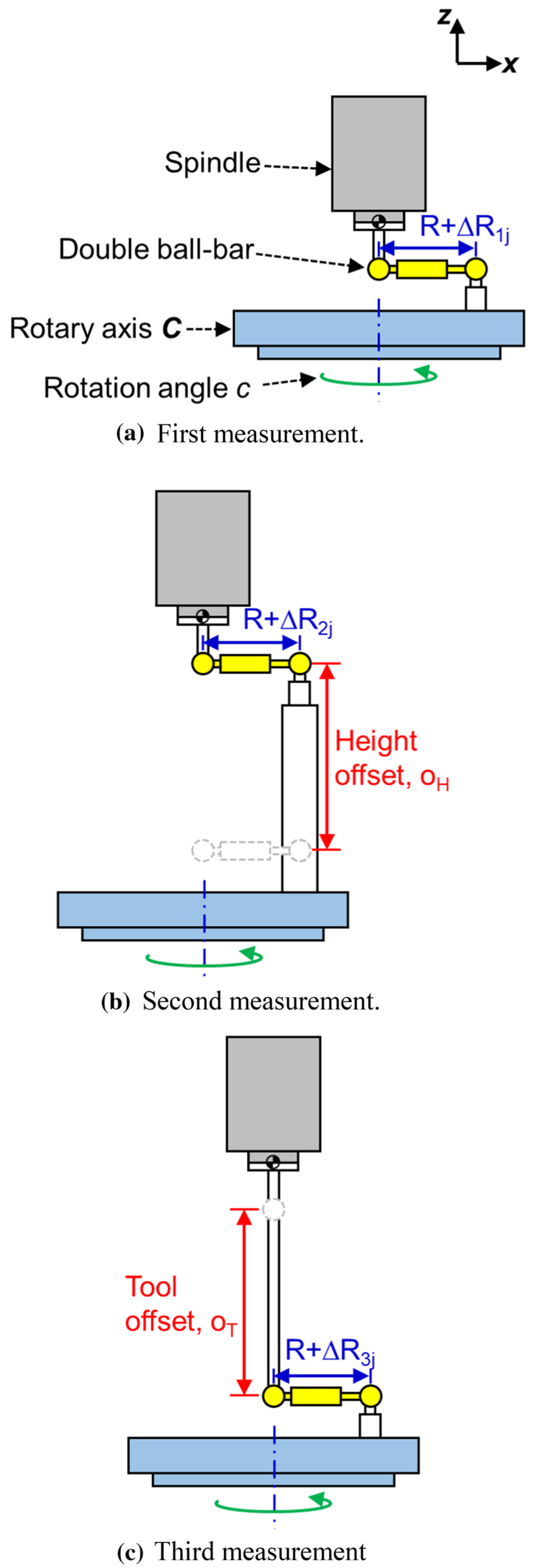

Fig. 3 The PIGE paths measured using a double ball-bar (DBB)

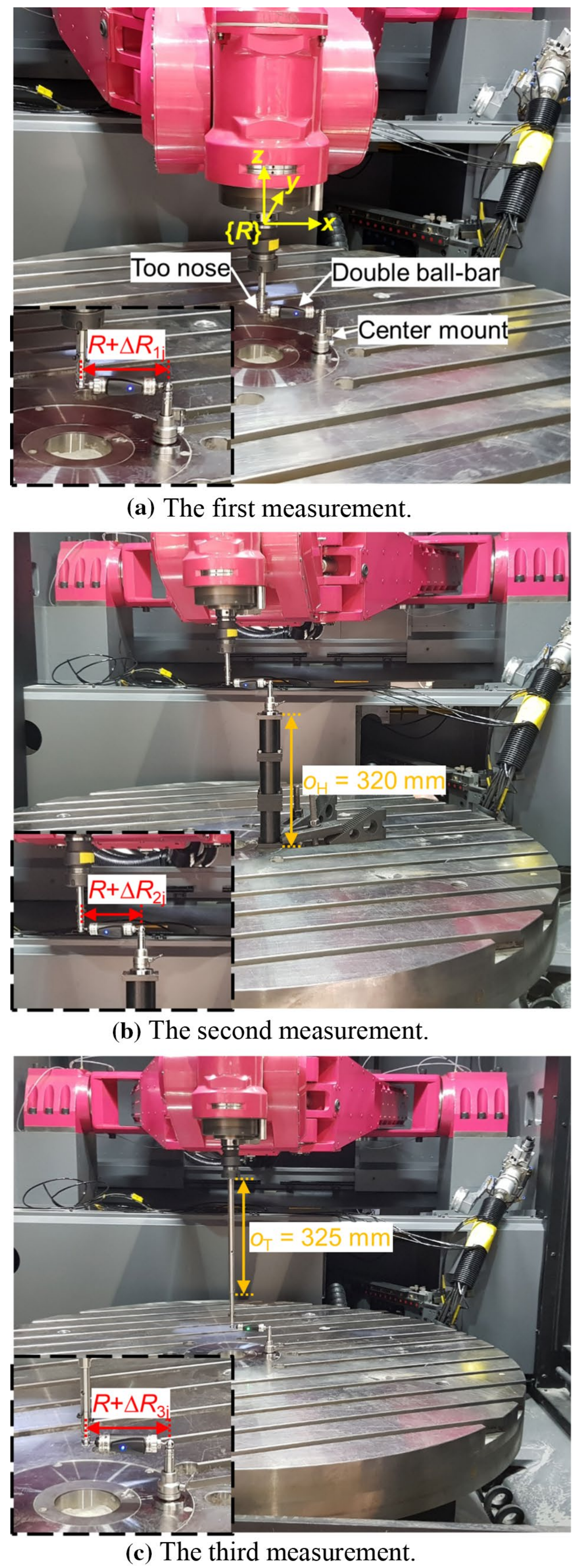

Fig. 4 The PIGE measurement and compensation measurement process

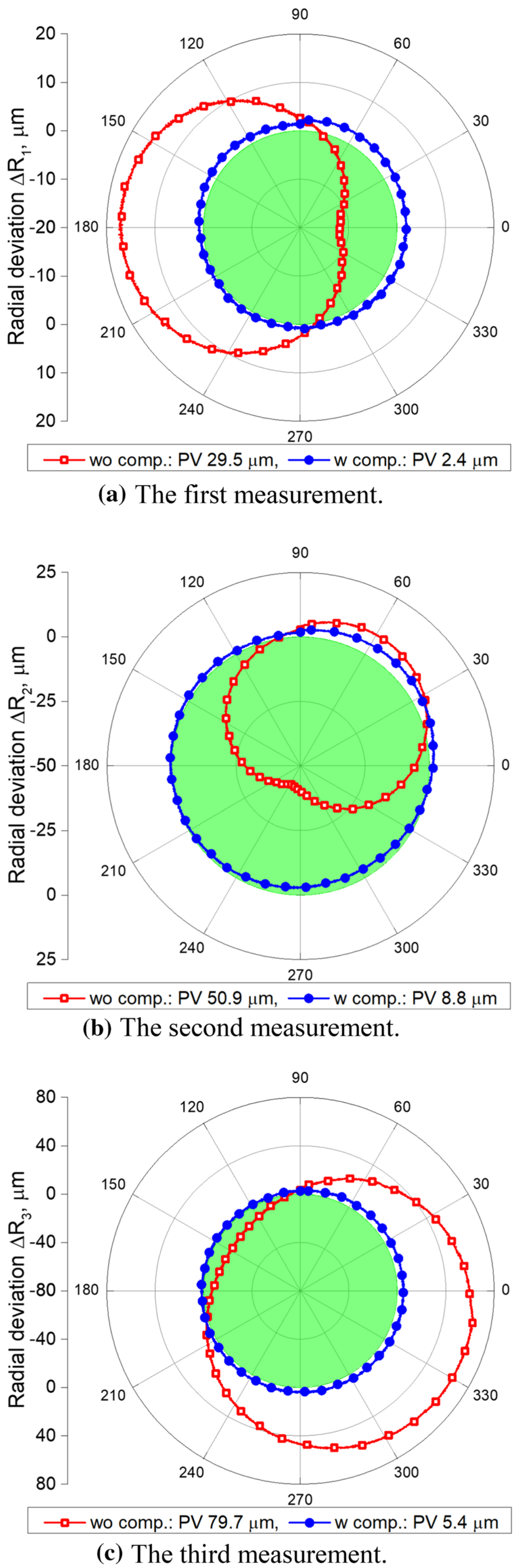

Fig. 5 The radial deviation ΔR_{ij} with and without compensation

Table 2 The PIGEs identified with and without compensation

Parameter	Unit	Value		Measurement uncertainty ($k=2$)
		Without compensation	With compensation	
o_{xc}	µm	– 14.4	0.5	1.6
o_{yc}	µm	0.3	0.6	1.6
s_{xc}	µrad	– 69.4	– 9.3	7.2
s_{yc}	µrad	36.0	1.8	7.2
s_{xs}	µrad	– 102.8	1.4	7.1
s_{ys}	µrad	– 64.9	5.7	7.1

Table 3 Contributors to PIGE measurement uncertainty ($k=2$)

Contributor	Unit	Value
DBB accuracy	µm	0.46
Assumed repeatability of ***C*** in the radial direction	µm	1.15
Assumed repeatability of the hybrid PKM in the radial direction	µm	1.15

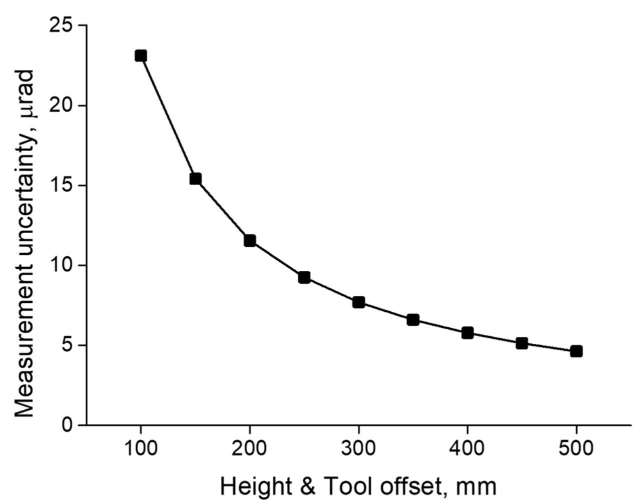

Fig. 6 The squareness error measurement uncertainty as a function of the offset

Acknowledgements This work was supported by the National Research Foundation of Korea(NRF) funded by the Ministry of Education (2020R1C1C100330011), and by the Korea Evaluation Institute of Industrial Technology(KEIT) funded by the Ministry of Trade, Industry and Energy (10053878).

References

1. Weck, M., & Staimer, D. (2002). Parallel kinematic machine tools – current state and future potentials. *CIRP Annals, 51*(2), 671–683.
2. Bi, Z. M., & Jin, Y. (2011). Kinematic modeling of Exechon parallel kinematic machine. *Robotics and Computer-Integrated Manufacturing, 27*(1), 186–193.
3. https://www.maxrotec.com/ at 2019.10.04
4. https://www.exechon.com/ at 2019.10.04
5. Lee, K. I., & Yang, S. H. (2013a). Measurement and verification of position–independent geometric errors of a five–axis machine tool using a double ball–bar. *International Journal of Machine Tools and Manufacture, 70,* 45–52.
6. ISO 230–7, Test Code for Machine Tools – Part 7 (2006) Geometric accuracy of axes of rotation, In: ISO
7. ISO 230–1, Test Code for Machine Tools – Part 1 (2012) Geometric accuracy of machines operating under no–load or quasi–static conditions, In: ISO
8. Schwenke, H., Knapp, W., Haitjema, H., Weckenmann, A., Schmitt, R., & Delbressine, F. (2008). Geometric error measurement and compensation of machines – an update. *CIRP annals, 57*(2), 660–675.
9. Ibaraki, S., & Knapp, W. (2012). Indirect measurement of volumetric accuracy for three–axis and five–axis machine tools: A review. *International Journal of Automation Technology, 6*(2), 110–124.
10. Tsutsumi, M., & Saito, A. (2003). Identification and compensation of systematic deviations particular to 5-axis machining centers. *International Journal of Machine Tools and Manufacture, 43*(8), 771–780.
11. ISO 10791–6, Test Conditions for Machining Centres – Part 6 (2014) Accuracy of speeds and interpolations, In: ISO
12. Tsutsumi, M., Tone, S., Kato, N., & Sato, R. (2013). Enhancement of geometric accuracy of five–axis machining centers based on identification and compensation of geometric deviations. *International Journal of Machine Tools and Manufacture, 68,* 11–20.
13. Lee, K. I., & Yang, S. H. (2013b). Robust measurement method and uncertainty analysis for position-independent geometric errors of a rotary axis using a double ball–bar. *International Journal of Precision Engineering and Manufacturing, 14*(2), 231–239.
14. Weikert, S. (2004). R–test, a new device for accuracy measurements on five axis machine tools. *CIRP Annals, 53*(1), 429–432.
15. Kenno, T., Sato, R., Shirase, K., Natsume, S., & Spaan, H. A. M. (2020). Influence of linear–axis error motions on simultaneous three–axis controlled motion accuracy defined in ISO 10791–6. *Precision Engineering, 61,* 110–119.
16. Ibaraki, S., Inui, H., Hong, C., Nishikawa, S., & Shimoike, M. (2019). On–machine identification of rotary axis location errors under thermal influence by spindle rotation. *Precision Engineering, 55,* 42–47.
17. Jeong, J. H., Khim, G. H., Oh, J. S., & Chung, S. C. (2019). Measurement of location errors in a horizontal 4–axis machine tool using a touch trigger probe. *Journal of the Korean Society for Precision Engineering, 36*(8), 745–752.
18. Matsushita, T., (2011). Method and program for identifying errors. US Patent Application Publication US2011/0040523A1
19. Lee, K. I., Lee, J. C., & Yang, S. H. (2018). Optimal on–machine measurement of position–independent geometric errors for rotary axes in five–axis machines with a universal head. *International Journal of Precision Engineering and Manufacturing, 19*(4), 545–551.
20. Ibaraki, S., Iritani, T., & Matsushita, T. (2012). Calibration of location errors of rotary axes on five–axis machine tools by on–the–machine measurement using a touch–trigger probe. *International Journal of Machine Tools and Manufacture, 58,* 44–53.
21. Jiang, Z., Bao, S., Zhou, X., Tang, X., & Zheng, S. (2015). Identification of location errors by a touch-trigger probe on five–axis machine tools with a tilting head. *International Journal of Advanced Manufacturing Technology, 81*(1–4), 149–158.
22. Schwenke, H., Schmitt, R., Jatzkowski, P., & Warmann, C. (2009). On–the–fly calibration of linear and rotary axes of machine tools and CMMs using a tracking interferometer. *CIRP Annals, 58*(1), 477–480.
23. Ibaraki, S., Sawada, M., Matsubara, A., & Matsushita, T. (2010). Machining tests to identify kinematic errors on five–axis machine tools. *Precision Engineering, 34*(3), 387–398.
24. Yang, H., Huang, X., Ding, S., Yu, C., & Yang, Y. (2018). Identification and compensation of 11 position–independent geometric errors on five–axis machine tools with a tilting head. *International Journal of Advanced Manufacturing Technology, 94*(1–4), 533–544.
25. ISO 10791–2, Test Conditions for Machining Centres – Part 2 (2001) Geometric tests for machines with vertical spindle or universal heads with vertical primary rotary axis (vertical Z–axis), In: ISO
26. Lee, K. I., Shin, D. H., & Yang, S. H. (2017). Parallelism error measurement for the spindle axis of machine tools by two circular tests with different tool lengths. *International Journal of Advanced Manufacturing Technology, 88*(9–12), 2883–2887.
27. Yao, Y., Nishizawa, K., Kato, N., Tsutsumi, M., & Nakamoto, K. (2020). Identification method of geometric deviations for multi–tasking machine tools considering the squareness of translational axes. *Applied Sciences, 10,* 1811.
28. Lee, H. H., Lee, D. M., & Yang, S. H. (2019). Accuracy improvement of on–machine measurement for the parallel kinematic machine considering constraint motion. *Journal of the Korean Society for Precision Engineering, 36*(5), 463–469.
29. Lee, D. M., Cha, Y. T., & Yang, S. H. (2010). Analysis of eccentricity in the ball bar measurement. *Journal of Mechanical Science and Technology, 24*(1), 271–274.
30. ISO 230–9, Test Code for Machine Tools – Part 9 (2005) Estimation of measurement uncertainty for machine tool tests according to series ISO 230, basic equations, In: ISO

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Seung-Han Yang, Ph.D. Professor in the School of Mechanical Engineering, Kyungpook National University. His research interest is intelligent manufacturing systems and CAD/CAM.

Hoon-Hee Lee, Ph.D. Senior Researcher in the Korea Institute of Industrial Technology. His research interest is machine tool metrology and metal 3D printing.

Dong-Mok Lee, Ph.D. Director, Research & Development Center in Maxrotec Co., Ltd. His research interest is additive manufacturing systems and CAD/CAM.

Kwang-Il Lee, Ph.D. Professor in the School of Mechanical and Automotive Engineering, Kyungil University. His research interest is precision methodologies for machine tools and 3D printers.