Titre: Title:	Comparison of direct and indirect methods for five-axis machine tools geometric error measurement
Auteurs: Authors:	Kanglin Xing, Sofiane Achiche, Sareh Esmaeili, & J. R. René Mayer
Date:	2018
Type:	Communication de conférence / Conference or Workshop Item
Référence: Citation:	Xing, K., Achiche, S., Esmaeili, S., & Mayer, J. R. R. (octobre 2018). Comparison of direct and indirect methods for five-axis machine tools geometric error measurement [Communication écrite]. 6th CIRP Global Web Conference – Envisaging the future manufacturing, design, technologies and systems in innovation era (CIRPe 2018). Publié dans Procedia CIRP, 78. https://doi.org/10.1016/j.procir.2018.08.310

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 78 (2018) 231–236

www.elsevier.com/locate/procedia

6th CIRP Global Web Conference
"Envisaging the future manufacturing, design, technologies and systems in innovation era"

Comparison of Direct and Indirect Methods for Five-axis Machine Tools Geometric Error Measurement

Kanglin Xing*, Sofiane Achiche, Sareh Esmaeili, J.R.R. Mayer

Department of Mechanical Engineering, École Polytechnique (Montréal), P.O. Box 6079, Station Downtown, H3C 3A7 Montréal, QC, Canada

* Corresponding author. Tel.: +1-438-788-8309; fax: +1-5143405867. *E-mail address:* kanglin.xing@polymtl.ca

Abstract

Geometrical error (GE) is a key criterion for machine tools performance evaluation. GE measurement methods can be classified as direct and indirect methods. As an indirect GE measurement method, the scale and master ball artefact (SAMBA) method can estimate the GE of linear and rotary axes by probing series of master balls and a scale bar artefact installed on the machine tool pallet. The purpose of this study is to research the performance of direct and indirect GE measurement methods (i.e. laser interferometer and SAMBA method) in linear positioning error measurement such as EXX and EYY. These errors of the X- and Y-axis are separately measured on a five-axis machine tool with the two methods. The results reveal that the SAMBA method yields similar results as the laser test in error shape and range. However, there are some minor differences which are discussed.

Selection and peer-review under responsibility of the scientific committee of the 6th CIRP Global Web Conference "Envisaging the future manufacturing, design, technologies and systems in innovation era".

Keywords: Five-axis machine tool; geometric error; SAMBA method.

1. Introduction

Five-axis machine tools are one of the most important components in modern manufacturing facilities owing to their ability for machining complex shapes in a single setup. However, their complexity increases the number of error sources which directly affects the quality of machined parts. Factors such as geometric error (GE), thermally induced errors, tool wear and force-induced deformation and control errors contribute to the machining inaccuracy [1]. Among these factors, GE, resulting from the inaccuracies built in at the assembly and from the individual axes of the machine with degeneration, are the largest error sources (once estimated as 70% of the errors in machine tools) [1].

Nomenclature

EXX	Linear positioning error of X axis
EYY	Linear positioning error of Y axis
EXX_S	Linear positioning error estimated by SAMBA
EXX_L	Linear positioning error measured by laser
EYY_S	Linear positioning error estimated by SAMBA
EYY_L	Linear positioning error measured by laser
EXX_{SL}	Converted linear positioning error of SAMBA
EYY_{SL}	Converted linear positioning error of SAMBA
EXX_{LF}	Fitted linear positioning error measured by laser
EYY_{LF}	Fitted linear positioning error measured by laser

Direct measurement and indirect identification are the two approaches to determine GE. The selection of specific GE measurement methods need to consider the machine geometry and the purpose of its evaluation. For the general machine tools,

Selection and peer-review under responsibility of the scientific committee of the 6th CIRP Global Web Conference "Envisaging the future manufacturing, design, technologies and systems in innovation era".
10.1016/j.procir.2018.08.310

one or more specific errors are individually or simultaneously measured when using direct measurement. These methods can be classified in three groups based on their metrological reference: the material-based methods, the laser-based methods and the gravity-based methods [1]. Positioning errors can be measured with calibrated artefacts with limited sampling data or laser interferometer with almost infinite spatial sampling rate [2]. Angular errors are measured by an electronic level meter or interferometry [3], and straightness errors can also be inspected by interferometry. Generally, laser interferometer is a common method for the measurement of the various geometric errors. However, its disadvantage is that it needs skilled operators, a careful setup and a long measurement time [4]. In addition, Structure Integrated Sensors for Fast Calibration of machine tools have also been developed recently [5]. As for indirect methods, multi-axes motion of the machine tool is involved (movement to measure positions at different X, Y, Z positions, simultaneous movement of at least two axes [1]. Indirect measurement methods may use partially or totally uncalibrated artefacts to estimate the geometric errors [6].

For five-axis machine tools, GE can be measured directly by the devices such as the laser interferometer and 6 degrees of freedom laser system. However, the presence of a rotary axis adds difficulty for the indirect GE measurement [7][8]. Some indirect methods of identifying the GE of five-axis machine tool have been proposed in the past decades. 1D, 2D and 3D ball plate has been used to identify a single GE with developed formulas [9-11]. Measurement based on the displacement using the ball bar or the laser tracker has been presented for the indirect evaluation of GE [12]. R-test combines movements of rotary and linear axes for GE estimation [13]. In addition, chase-the-ball measurement firstly assumes that there is no relative movement between the tool side and the workpiece side of the machine in the nominal state. Then the coordinates deviations of the artefacts are recorded in the simultaneous linear and rotational movements. The relative movement caused by the GE can be reflected in these recorded coordinates and be separated using machine error models [14]. The scale and master ball artefact (SAMBA) method has been applied to five-axis GE estimation in recent years [15]. It can estimate different types of GE based on the user's needs. However, its suitability for updating the linear axis positioning compensation tables in the CNC controller has not been studied. Therefore, comparing the SAMBA method and the direct GE measurement method, which is usually used for this purpose, is a relevant question to answer.

This paper presents a testing plan of a five-axis machine tool GE based on the SAMBA method. The linear positioning error of the X- and Y-axis is estimated and adjusted to the same reference coordinate as the laser interferometer measurement results. Repeated experiments using the SAMBA method and laser interferometer method are conducted separately to test and evaluate the performance of the SAMBA method. The structure of this paper is as follows. The scale and master all artefact method is described in detail in Section 2. Section 3 discusses the experimental study and Section 4 describes the transformation of SAMBA results to Laser measurement results. The experimental results are discussed in Section 5, and finally the conclusions are drawn in Section 6.

2. The scale and master ball artefact method

The SAMBA method models the machine tools with the rigid body assumption and homogenous transformation matrices. It uses master balls and a scale bar artefact which are installed on the machine tool pallet and the touch trigger probe which is installed on the spindle. When there are no errors in the machine tool loop structure, there will be no differences between the actual master balls' positions and the measured master ball positions. However, owing to the existence of the GE in each linear and rotary axis, and between them, there will be some differences (Fig. 1(a) and (b)).

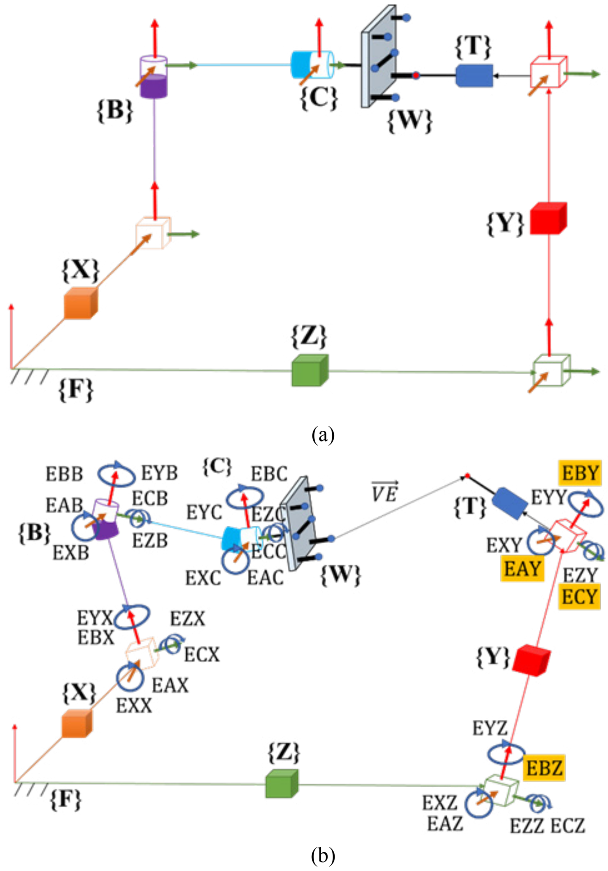

Fig. 1. Nominal (a) and real (b) kinematic models of a five-axis machine tool with WCBXFZYT topology

The measured master ball artefacts coordinates are the inputs of the SAMBA mathematical model. The Jacobian J is generated from the SAMBA model describing the sensitivity of the observed volumetric deviations to the machine error parameters (Eq. 1). V is a column matrix representing the volumetric errors of each master ball probing position. P is a column matrix representing the machine errors (Table 1, 26 errors, some errors such as EAY, EBY and ECY errors are not distinguishable from EXY, EYY and EZY) which are expressed with third degree polynomials with a total of 84 coefficients. For details of the SAMBA modelling, please refer to [15-17]. The linear positioning errors of the X- and Y-axis are modeled by Eq. 2 and Eq. 3. Where x and y is the position value in SABMA coordinates.

$$V = JP \tag{1}$$

$$EXX_S(x) = EXX1 \cdot x + EXX2 \cdot x^2 + EXX3 \cdot x^3 \quad (2)$$

$$EYY_S(y) = EYY0 + EYY1 \cdot y + EYY2 \cdot y^2 + EYY3 \cdot y^3 \quad (3)$$

Based on the topology of the laboratory machine tool (Mitsui Seiki HU40-T) and the calculation requirements of the geometric error coefficients in the SAMBA modelling, 109 probing positions and 29 indexation pairs of the B- and C-axes are including in the SAMBA measurement plan.

Table 1. Geometric errors estimated from SAMBA method on HU40-T five-axis machine tool. The EAY, EBY and ECY errors are not distinguishable from EXY, EYY and EZY because a single tool length was used.

Axis	Error items					
X axis	EXX	EYX	EZX	EAX	EBX	ECX
Y axis	EXY	EYY	EZY	-	-	-
Z axis	EXZ	EYZ	EZZ	EAZ	-	ECZ
B axis	EXB	EYB	EZB	EAB	EBB	ECB
C axis	EXC	EYC	EZC	EAC	EBC	ECC

3. Experiment setups

Fig. 2 (a) shows the experimental setup for the SAMBA measurements. The machine touch probe, which is installed in the spindle, triggers readings of the individual axis positions when touching an artefact's surface. These readings are then recorded. This allows measuring the positions of the four master ball artefacts and one scale bar installed on the machine tool pallet using the three linear axes of the machine. All 109 probing results are acquired in one test, lasting 194 minutes. During the test the ambient temperature of the machine tool is controlled around 21°C (+/-1°C), and the SAMBA measurement is repeated three times. The probing results processed with the SAMBA mathematical model are used to estimate the linear position errors of the X-axis and Y-axis.

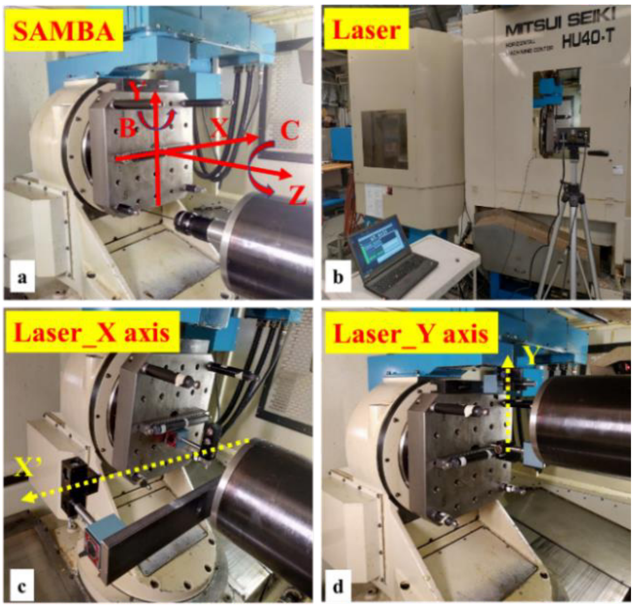

Fig. 2. SAMBA (a) and laser measurement (b, c, d) of the X- and Y-axis linear positioning error of HU40-T five-axis machine tool

After the SAMBA measurement, a Renishaw XL-60 laser interferometer is used to measure the linear position error of the X-axis and Y-axis (Fig. 2 (b, c, d)). Similarly, the ambient temperature of the machine tool is controlled around 21 °C, and the tests are repeated for three times. The moving corner cube retroreflector is installed on the pallet while the interferometer is installed on a fixture attached on the spindle. The pallet moves in X with the X-axis but for the Y-axis it is the spindle which moves in Y. The measurement points for each axis were programmed at 5 mm intervals, including the zero point, to cover the whole axis motion range. The measurement range of the X-axis and Y-axis are 610 mm and 560 mm respectively. The tests employed a bidirectional alternate strategy. The number of passes for the X and Y axis was three. The obtained results were subsequently processed according to the standard ISO 230-2:2006 [2] using XCal-View 2.2 software. The key parameters of linear positioning error measurement are shown in Table 2.

Table 2. Key parameters of laser measurement in X and Y axis linear positioning error

Types	Run type	Axis range	Targets	Temperature	Humidity
X axis	Bidirectional	610 mm	123	20.9 °C	44.35 %RH
Y axis	Bidirectional	560 mm	113	21.2 °C	44.35 %RH

4. Result and discussion

4.1. Laser measurement results

The linear positioning error is the mean bi-directional positional deviation of an axis [2], it is calculated by Eq. 4. Where $\overline{EXX(x)}$ is the mean value of the original measured values in the three passes (Example of X axis).

$$Error = Max.\left[\overline{EXX(x)}\right] - Min.\left[\overline{EXX(x)}\right] \quad (4)$$

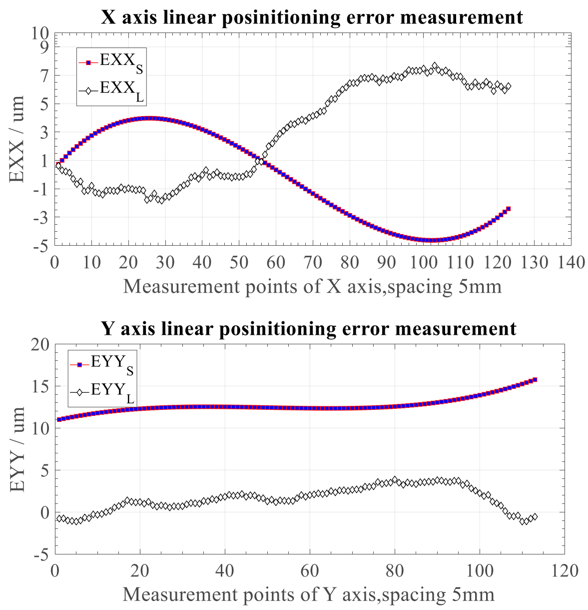

Fig. 3. Initial measurement results of linear positioning error with laser and SAMBA methods

The original measured results are processed with XCal-View 2.2 software, and the final laser measurement results of X axis and Y axis are shown in Fig. 3. The linear positioning error for the X- and Y-axis are 9.8 µm (EXX_L) and 5.1 µm (EYY_L) respectively.

4.2. SAMBA measurement results and their conversion

Three repeated SAMBA tests were carried out on the experimental machine tool. As for the laser test, the average values of EXX and EYY are calculated for the SAMBA results and are shown in Fig. 3. The linear positioning error for the X- and Y-axis estimated by the SAMBA method are 8.7 µm (EXX_S) and 4.8 µm (EYY_S). The error values of the SAMBA and laser methods are similar in magnitude; however, the error shapes do not match. This is caused by the different definitions of the origin and positive directions of the machine, laser and SAMBA model.

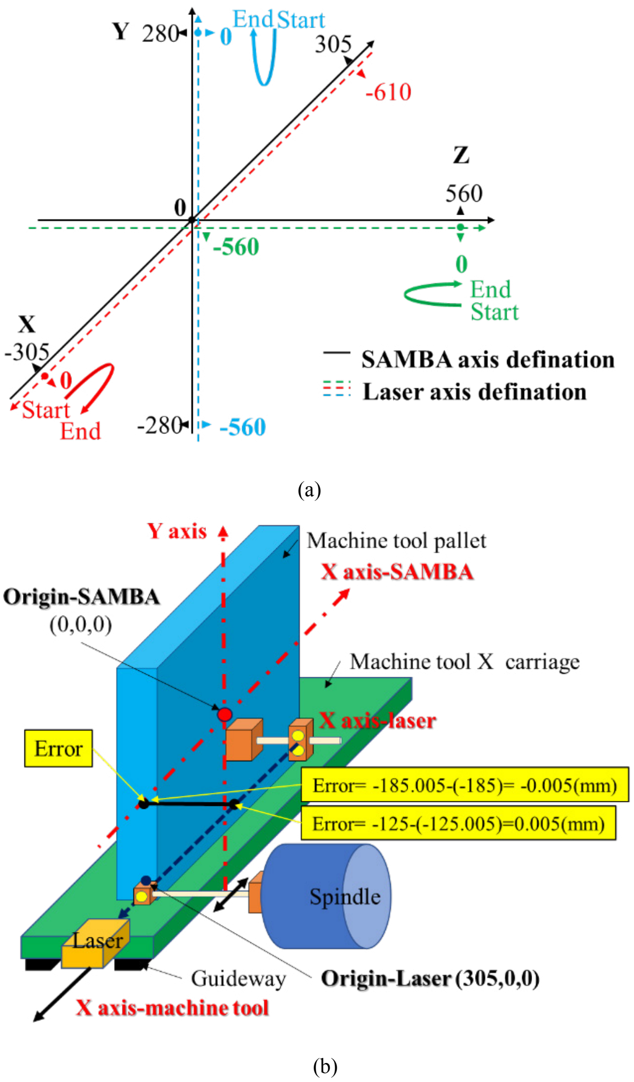

Fig. 4. Explanation of the differences between laser and SAMBA measurements in origin definition (X axis as an example)

Indeed, the SAMBA coordinate is set in the machine tool pallet (Fig. 2 (a)) while the laser coordinate is related to the starting point of the measurement. For example, the origin of laser testing result is (305,0,0). However, it becomes (0,0,0) for the SAMBA method (Fig. 4). In addition, in different coordinate systems, the error of each measurement point calculated from the two methods have different sign towards the same measurement position (Fig. 4). Therefore, the transformation process of SAMBA result to Laser result includes two steps. Firstly, change the sign of the SAMBA result. Secondly, move the origin of SAMBA result to laser result (from (0,0,0) to (305,0,0), this setup). Then, the converted result of SAMBA method to laser method (EXX_{SL} and EYY_{SL}) can be achieved in Eq. 5 and Eq. 6.

$$EXX_{SL}(x) = -1 * [(EXX1 \cdot x + EXX2 \cdot x^2 + EXX3 \cdot x^3) - EXX_S(x = 305)] \quad (5)$$

$$EYY_{SL}(y) = -1 * [(EYY0 + EYY1 \cdot y + EYY2 \cdot y^2 + EYY3 \cdot y^3) - EYY_S(y = 280)] \quad (6)$$

4.3. Results comparison

Fig. 5 shows transferred SAMBA results and laser results. The initial linear positioning error measured by the laser has also been fitted (EXX_{LF}) with the third-degree polynomial coefficients which are the same as SAMBA error modelling. The error fitting is processed with Matlab using (2 and (3 in the laser coordinate. The fitting operation of laser measured results can bring an equal comparison ruler for laser and the SAMBA method. The error range, error value and error differences of the two methods are compared and discussed. In the full range of the X and Y axis, the error ranges of the linear positioning error of X and Y axis measured by Laser are (-2 µm ~ 7.8 µm, EXX_L), (-1.9 µm ~ 7.2 µm, EXX_{LF}) and (-1.2 µm ~ 3.9 µm, EYY_L), (-0.7 µm ~ 3.2 µm, EYY_{LF}) respectively. However, for the SAMBA measurement, they are (-3.2 µm ~ 5.5 µm, EXX_{SL}) and (-4.8 µm ~ 0 µm, EYY_{SL}) respectively. In addition, the linear positioning error of X and Y axis are (9.8 µm, EXX_L, 9.1 µm, EXX_{LF}) and (5.1 µm, EYY_L, 3.9 µm, EYY_{LF}). For the SAMBA results, they are 8.7 µm (EXX_{SL}) and 4.8 µm (EYY_{SL}) respectively. Therefore, the results of the two methods are not only closing in the error range but also closing in error value. The error differences of each measurement position are also discussed in Fig. 6. When using the laser as a reference, this result can reflect the capability of the SAMBA method in linear positioning error estimation in a single measurement position. The maximum differences and their ranges (differences between EXX_{SL} and EXX_{LF} and differences between EYY_{SL} and EYY_{LF}) of the SAMBA and Laser methods in X and Y axis linear positioning error estimation are around 2.2 µm, (0.7 µm ~ 2.2 µm, 1.5 µm) and 4.9 µm, (0 µm ~ 4.9 µm, 4.9 µm) respectively. The difference is relatively big for Y axis linear positioning error.

When considering the effective working space of the machine tool (the machine tool pallet size is 400mm×400mm), the maximum differences and their ranges indicating in the area between two blue lines towards X and Y axis are around 2.1 µm, (1.5 µm ~ 2.1 µm, 0.6 µm) and 4.9 µm, (1 µm ~ 4.9 µm, 3.9 µm) respectively. These differences between the two methods are relatively small.

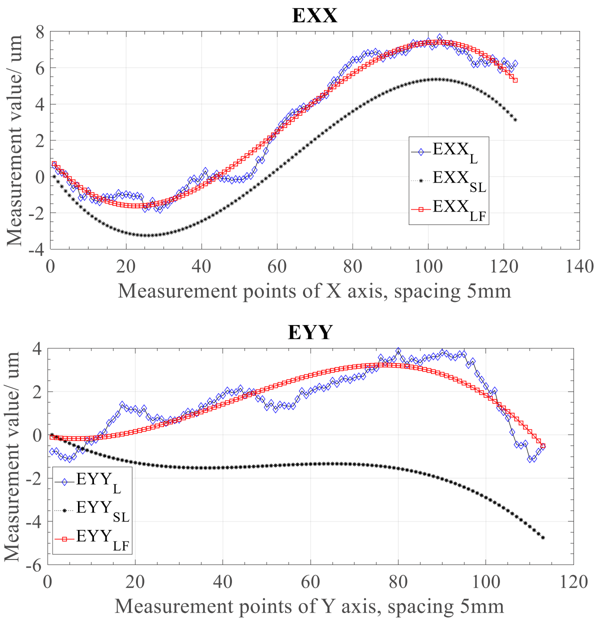

Fig. 5. Results of SAMBA and Laser in X and Y axis linear positioning error measurement

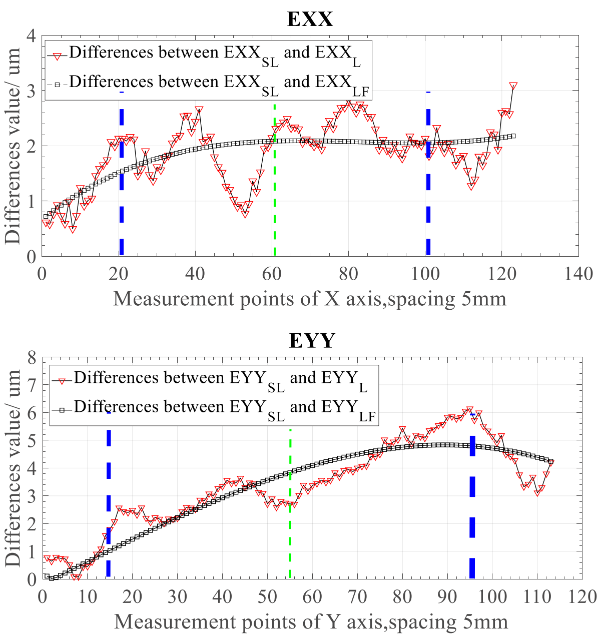

Fig. 6. Differences between SAMBA and Laser methods in X and Y axis linear positioning error measurement

4.4. Discussion

Comparison results reveal that the SAMBA method and Laser method all perform well in the five-axis machine tool linear position error measurement. The maximum differences of the two methods are within 4.9 µm which is small when considering error sources such as laser alignment, abbe errors, the thermal state of machine tool. Fig. 2 reveals the actual measured axis of X and Y axes which are indicated by the red and yellow axis. Take the X axis as an example, the alignment differences between the SAMBA modelled X axis and Laser measured X axis is about 50 mm in the Z direction and 10 mm in the Y direction. This 3D dimensional offset of axes can contribute to the differences between the SAMBA and laser measurement in linear positioning error measurement. The presence of angular error motions due to Abbe effects and the differences in the machine thermal state between the two tests could also contribute to the differences. Therefore, these possible factors need to be further investigated.

5. Conclusions

In this paper, a direct geometric error (GE) measurement method, i.e. laser interferometer, and an indirect GE measurement method, i.e. the SAMBA method, are compared for a five-axis machine tool linear positioning error measurement. After the transformation of the SAMBA testing results, the two sets of measurement results are comparable in error range and shape. The results from the two measurement methods are not only closing in the error range but also closing in error value. The differences range between SAMBA and laser testing in linear positioning error are around 1.5 µm and 4.9 µm in X and Y axis. In the range of machine tool pallet indicating the effective working space for X and Y axis, the differences range can decrease to 0.6 µm and 3.9 µm.

Future works will focus on the SAMBA model optimization of the linear positioning error calculation considering different setup position of actual axis of laser measurement and the testing conditions of machine tool.

Acknowledgements

The authors would like to thank the technicians Guy Gironne and Vincent Mayer for conducting the experimental part of this work. Authors also acknowledge the financial support from Natural Sciences and Engineering Research Council of Canada (NSERC) under the CANRIMT Strategic Research Network Grant NETGP 479639-15 and China Scholarship Council.

References

[1] Ramesh, R., M.A. Mannan, A.N. Poo, Error compensation in machine tools — a review: Part I: geometric, cutting-force induced and fixture-dependent errors. International Journal of Machine Tools and Manufacture, 2000;40:1235-1256.

[2] ISO 230-2:2006, Test code for machine tools, in Part 2: Determination of accuracy and repeatability of positioning numerically controlled axes. 2006: Switzerland.

[3] Xu Zhang, Xiaoqin Zhou, Qiang Liu, Pengzi Xu. The analysis and measurement of motion errors of the linear slide in fast tool servo diamond turning machine. Advances in Mechanical Engineering, 2015;7:1-8.

[4] Okafor, A.C., Y.M. Ertekin, Vertical machining center accuracy characterization using laser interferometer: Part 1. Linear positional errors. Journal of Materials Processing Technology, 2000;105:394-406.

[5] Benjamin Montavon, Philipp Dahlem, Martin Peterek, Markus Ohlenforst and Robert H. Schmitt. Modelling Machine Tools using Structure Integrated Sensors for Fast Calibration. Journal of Manufacturing and Materials Processing, 2018;2:1-14.

[6] G.Belforte, B.Bona, E.Canuto, F.Donati, F.Ferraris, I.Gorini, S.Morei, M.Peisino, S.Sartori, R.Levia. Coordinate Measuring Machines and Machine Tools Selfcalibration and Error Correction. CIRP Annals, 1987;36:359-364.

[7] K.Lau, Q.M., X.Chu,Y.Liu,S.Olson, An Advanced 6-Degree-of-Freedom Laser System for Quick CNC Machine and CMM Error Mapping and Compensation. Automated Precision, 2002.
[8] Hsu, Y.Y. and S.S. Wang, A new compensation method for geometry errors of five-axis machine tools. International Journal of Machine Tools and Manufacture, 2007;47:352-360.
[9] Bringmann, B., A. Küng, and W. Knapp, A Measuring Artefact for true 3D Machine Testing and Calibration. CIRP Annals, 2005; 54:471-474.
[10] G.X. Zhang and Y.F. Zang, A Method for Machine Geometry Calibration Using 1-D Ball Array. CIRP Annals, 1991;40:519-522.
[11] Kunzmann, H., E. Trapet, and F. Wäldele, A Uniform Concept for Calibration, Acceptance Test, and Periodic Inspection of Coordinate Measuring Machines Using Reference Objects. CIRP Annals, 1990;39:561-564.
[12] H. Schwenke, M. Franke, J. Hannaford, H. Kunzmann, Error mapping of CMMs and machine tools by a single tracking interferometer. CIRP Annals, 2005;54:475-478.
[13] Tsutsumi, M. and A. Saito, Identification and compensation of systematic deviations particular to 5-axis machining centers. International Journal of Machine Tools and Manufacture, 2003;43:771-780.
[14] Bringmann, B. and W. Knapp, Model-based 'Chase-the-Ball' Calibration of a 5-Axes Machining Center. CIRP Annals, 2006;55:531-534.
[15] Mayer, J.R.R., Five-axis machine tool calibration by probing a scale enriched reconfigurable uncalibrated master balls artefact. CIRP Annals, 2012;61:515-518.
[16] Erkan, T., J.R.R. Mayer, and Y. Dupont, Volumetric distortion assessment of a five-axis machine by probing a 3D reconfigurable uncalibrated master ball artefact. Precision Engineering, 2011;35:116-125.
[17] Mchichi, N.A.,J.R.R. Mayer, Axis Location Errors and Error Motions Calibration for a Five-axis Machine Tool Using the SAMBA Method. Procedia CIRP, 2014;14:305-310.