euspen's 21st International Conference & Exhibition, Copenhagen, DK, June 2021

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Geometric error measurement of an ultra-precision machine tool using integrated confocal sensor

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Abstract

The geometric error of an ultra-precision machine tool will degrade the form accuracy of machined surfaces. This paper proposes a error measurement method for a three-axis (XZC) ultra-precision machine tool based on an integrated confocal probe (1 kHz sampling rate and 9 nm repeatability). A variance-based global sensitivity analysis method was used to identify major error sources. To avoid potential alignment runout, a Φ30 mm brass bar was SPDT turned (Sa < 5 nm) and used as the artefact for the error measurement. The reveral method and improved multi-probe method were used to measure the straightness errors of linear slides and the radial/axial errors of the aerostatic spindle respectively. The results indicate that the straightness error of linear slide (E_{ZX} E_{YX} E_{XZ} E_{YZ}) and axial/radial errors of the spindle (E_{XC} E_{YC} E_{ZC}) are major geometric error sources. The spindle axis offsets are within 20 nm and radial errors are less than 80 nm under tested spindle speeds (60/120/180/240 RPM).

Keywords: Geometric errors; global sensitivity analysis; on-machine measurement; ultra-precision machining tool

1. Introduction

The achievable machined surface quality significantly rely on the machine tool motion accuracy. How to detect and compensate the geometric error of machine tools has been continuously investigated for past decades [1]. Although ISO has published series of documents to standardize the error calibration process, most recommended methods and metrology instruments are only beneficial for traditional/precision 3-5 axis machine tools. It is widely recogonised that the motion accuracy of ultra-precision machine tools are in the nanometer range, which brings challenges on the calibration of ultra-precision machine tools.

The general routine for ultra-precision machines calibration follows the error modelling, measurement, and compensation. The error modelling, which is mostly developed according to the multibody system (MBS) theory and the homogenous transformation method (HTM), builds the relationship between each error component and the deviation of the end cutting point. It is important to measure major geometric errors predicted by modelling, from which a compensation value can then be generated to modify the NC code for corrective machining. Many research works have focused on directly measuring errors of single linear/rotary axis [2] or evaluating the systematic effect of multiple motion axes by the trial cutting method [3]. However, it remains challenging to measure and decompose each error component and analyse its effects on the machined surface.

In this paper, a geometric error identification and measurement method was developed for the XZC type ultra-precision machine tool using the integrated confocal probe. A variance-based global sensitivity analysis [4] was adapted to identify the major error components of the machine and important geometric errors are measured by the integrated on-machine surface metrology system.

2. Methodology

2.1. Experimental setup

The schematic diagram of a three-axis ultra-precision machine tool and the kinematic chain are illustrated in Fig. 1. The machine has one air bearing spindle and two hydrostatic linear slideways that are actuated by the symmetrical placed linear motors over the 220 mm travel range. A confocal measurement system (1 kHz sampling rate and 9 nm repeatability) is integrated into the ultra-precision machine tool and a controller board is self-developed to control the fast-tool-servo machining and on-machine surface measurement (OMSM) process [5].

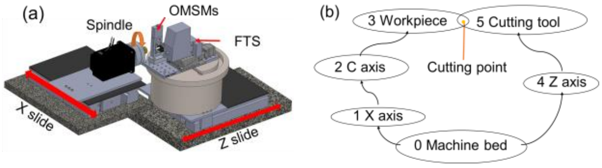

Figure 1. (a) XZC type ultra-precision machine tool and (b) topological structure

2.2. Geometric error sensitivity analysis

According to MBS theory, the identified 21 geometric errors are listed in Table 1 using HTM method. Then the error modelling along X and Z direction can be simplified to Eq. 1 and Eq. 2 if the quadratic term and more are ignored.

Table 1 Geometric errors of three axis ultra-precision machine

Error source	Error components
X axis	E_{XX} E_{YX} E_{ZX} E_{AX} E_{BX} E_{CX}
Z axis	E_{XZ} E_{YZ} E_{ZZ} E_{AZ} E_{BZ} E_{CZ}
C axis	E_{XC} E_{YC} E_{ZC} E_{AC} E_{BC} E_{CC}
Squareness errors	E_{AOC} E_{BOC} E_{BOZ}

$$\begin{aligned} E_X = {} & E_{XC} * \cos C + E_{XX} * \cos C - E_{XZ} * \cos C - E_{YC} * \sin C - \\ & E_{YX} * \sin C + E_{YZ} * \sin C - E_{BOC} * z - E_{BC} * z * \cos C - \\ & E_{BX} * z * \cos C + E_{BZ} * z * \cos C - E_{CC} * x * \sin C - \\ & E_{AC} * z * \sin C - E_{AX} * z * \sin C + E_{AZ} * z * \sin C \end{aligned} \quad \text{Eq. 1}$$

$$E_Z = E_{ZC} + E_{ZX} - E_{ZZ} - E_{BC} * x - E_{BOC} * x * cosC + E_{AOC} * x * sinC \quad \text{Eq. 2}$$

The Sobol method [4] was used to identify the major error components in Eq. 1 and Eq. 2. Based on our previous experiment [6], the error interval was set to [-10, 10] nm, [-50, 50] nm and [-0.1”, 0.1”] for positioning errors, straightness errors and angle errors, respectively. The widely used spiral scanning method, that requires the X slide and the spindle to simultaneously move, is considered, so the sensitivity index is Monte-Carlo simulated at X and C evenly spaced from 0 mm to 40 mm with 5 mm interval and from 45° to 360° with 45° interval, respectively. Fig. 2 shows one typical sensitivity analysis result at X= 10 mm and C= 45°. The results indicated that the straightness errors of linear slide (E_{ZX} E_{YX} E_{XZ} E_{YZ}) and axial/radial errors of the spindle (E_{XC} E_{YC} E_{ZC}) were major error components.

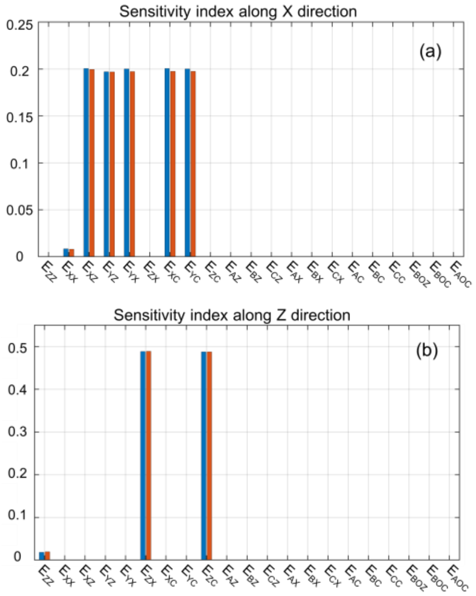

Figure 2. Sensitivity analysis along (a) X and (b) Z direction

2.3. Measuring principle for linear and rotary axis

The reversal method [7] and the improved three-probe method [8] are utilized to measure the straightness of linear slides and radial errors of the spindle. According to the machine tool configuration, an error measurement platform was developed on the basis of the self-cut Φ 30 mm brass bar. A confocal probe was fixed on the manual rotation stage (M-UTR80S, Newport, 0.017° resolution). Two motorized miniature linear stages (MFA-CC, Newport, min. incremental motion 100 nm) hold the rotational stage to align the probe accurately. The in-house developed controller board was used for data synchronization among the machine tool controller, the confocal probe controller and the linear stage controller. The X and Z slide fed at 60 mm/min and the confocal probe worked at 1 kHz sampling rate in straightness error measurement. The scanning procedure repeated 20 times. The spindle radial and axial offset were measured three times at 60/120/180/240 RPM.

3. Results

Fig. 3 shows the results of the straightness error of X and Z slide. σ_{max} is the maxium deviation value. For X slide, the mean value of straightness error *Ezx* and *Eyx* are 25 nm and 45 nm respectively. The mean value of *Eyz* and *Exz* for Z slide are 43 nm and 33 nm respectively. As shown in Fig. 4 and Fig. 5, the axial motion errors of the spindle are within 20 nm, while the radial errors are less than 80 nm under all tested spindle speeds. The metrology results agree well with the machine tool specification.

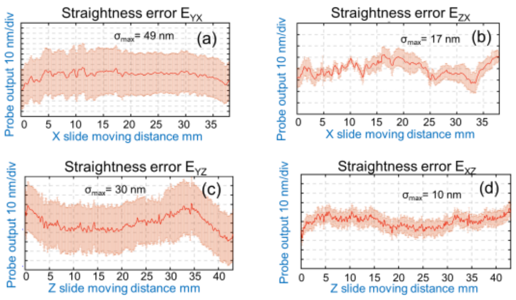

Figure 3. The straightness error of (a) E_{YX} (b) E_{ZX} (c) E_{YZ} (d) E_{XZ}

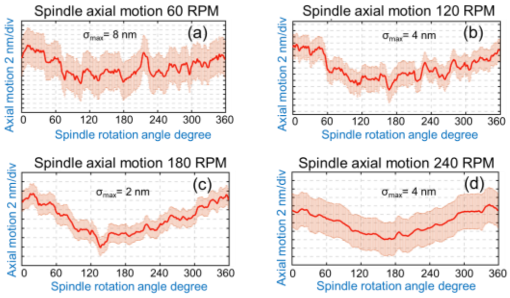

Figure 4. Spindle axial offset under (a) 60 RPM (b) 120 RPM (c) 180 RPM (d) 240 RPM

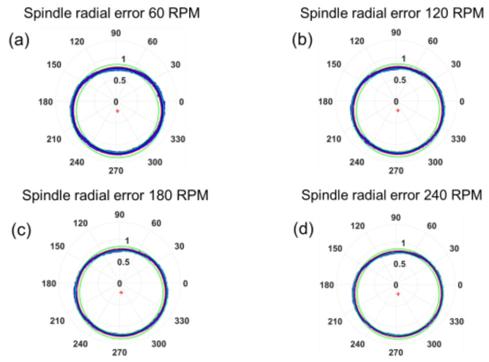

Figure 5. Spindle radial errors under (a) 60 RPM (b) 120 RPM (c) 180 RPM (d) 240 RPM

4. Summary and conclusions

A geometric error measuring method has been developed to measure the major motion errors of a XZC type ultra-precision machine tool. Crucial geometric errors have been identified through global sensitivity analysis and measured through self-developed metrology platform. The measurement results will be used to develop a closed-loop error measurement and compensation of ultra-precision grinding in the future work.

Acknowledgments

The authors gratefully acknowledge the UK’s EPSRC funding of Future Metrology Hub (Ref: EP/P006930/1), the UK’s STFC Innovation Partnership Scheme (STFC-IPS) project under grant agreement No. ST/V001280/1, the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 767589, and the China Scholarship Council (CSC).

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