A machining test to evaluate geometric errors of five-axis machine tools with its application to thermal deformation test

Soichi Ibaraki*, Yusuke Ota

Dept. of Micro Engineering, Kyoto University, Katsura, Kyoto 615-8530, Japan

* Corresponding author. Tel.: +81-75-383-3676; fax: +81-75-383-3676. E-mail address: ibaraki@prec.kyoto-u.ac.jp

Abstract

This paper proposes a machining test to calibrate position-dependent geometric errors, or “error map,” of rotary axes of a five-axis machine tool. At given sets of angular positions of rotary axes, a simple straight side-cutting using a straight end mill is performed. By measuring geometric errors of the machined test piece, position and orientation of rotary axis average lines (location errors), as well as position-dependent geometric errors of rotary axes, can be numerically identified based on the machine’s kinematic model. Furthermore, by repeating the proposed machining test consequently, one can quantitatively observe how the position and the orientation of rotary axes change with respect to the tool spindle due to thermal deformation induced mainly by tool spindle rotation. Experimental demonstration is presented.

© 2014 Published by Elsevier B.V. Open access under CC BY-NC-ND license. Selection and peer-review under responsibility of the International Scientific Committee of the 6th CIRP International Conference on High Performance Cutting

Keywords Five-axis machine tools, machining test, geometric errors, kinematic model, touch-triggered probe

1. Introduction

Machine tools with two rotary axes to tilt/rotate a tool and/or a workpiece, in addition to three orthogonal linear axes, are collectively called five-axis machine tools. On five-axis machine tools, error motions of each linear/rotary axis, as well as its alignment (assembly) errors, are accumulated in the positioning error of a tool relative to a workpiece. For efficient measurement of these errors, many “indirect” measurement methodologies, i.e. schemes to separately identify each error component from a set of measured tool center position (TCP) profiles, have been studied [1, 2]. ISO/DIS 10791-1 [3], currently under a revision process in ISO/TC 39/SC 2, contains quasi-static tests with a main interest in calibrating position and orientation errors of rotary axis average lines. The application of the ball bar to rotary axis dynamic measurements has been studied by many researchers [4,5] and is now included in ISO/DIS 10791-6 [6], also currently under a revision process in ISO/TC 39/SC 2. The R-test [7,8] is also in ISO/DIS 10791-6 [6]. A touch-trigger probe can be applied analogously to the ‘chase-the-ball’ test [9,10] and commercial probe-based calibration systems are now available.

Although it is important to evaluate geometric errors of rotary axes by such a non-cutting measurement, typical machine tool users consider more the machine's accuracy when it performs actual machining. Non-cutting tests are sometimes performed when the machine is "cold." In the machine's normal operating conditions, the spindle rotation, as well as environmental change, may potentially cause significant thermal deformation. In such a normal operating condition, the machine's geometric errors may be significantly different from those in 'cold' condition.

NAS (National Aerospace Standard) 979 [11], Clause 4,3.3.8.1, describes a cone frustum five-axis machining test. Since it is only standard well known describing a five-axis machining test, it is widely accepted by many machine tool builders as one of final performance tests. ISO/TC 39/SC 2 is currently discussing the inclusion of the cone frustum machining test in the revision of ISO 10791-7 [12]. Although it gives a good demonstration of the machine's overall machining performance, it is generally difficult to diagnose error sources from the measured geometry of the finished test piece [13,14].

The objective of this paper is to propose a new five-axis machining test such that geometric errors of rotary axes can be
Soichi Ibaraki and Yusuke Ota  /  Procedia CIRP 14 (2014) 323 – 328

separately identified by evaluating the geometric error of the machined test piece. In [15], a part of the authors presented a machining test to identify position and orientation errors of the axis average line of two rotary axes. This paper presents its extension to the calibration of position-dependent geometric errors, or “error map,” of rotary axes.

Furthermore, the paper will present its application to the observation of thermal influence on geometric errors of rotary axes. Experimental demonstration will be presented.

2. Proposed machining test

This paper considers a five-axis machine configuration with a titling rotary table (driven by B- and C-axes) depicted in Fig. 1. In principle, the basic idea of this paper can be straightforwardly extended to any five-axis configurations.

The proposed machining test is illustrated in Fig. 2. At $B_i=C_j=0^\circ$, a square-shaped step is machined by simple side-cutting using a straight end mill by driving X- and Y-axes only. The square step is machined at different heights at each combination of $C_j=0, 90, 180, 270^\circ$ ($j=1$ to 4) and $B_i=0, -90, 90^\circ$ ($i=1$ to 3). Total $4 \times 3=12$ finish cuts are made. Figure 3 shows an example of the nominal geometry of the finished test piece (adopted in the experiment in Section 4). The finishing condition must be properly chosen such that the influence of tool deflection or surface finish on the geometric measurement becomes sufficiently small. It is recommended to repeat the finishing with zero radial depth of cut (“zero cut”).

Then, the finished test piece’s geometry is measured. Figure 4 shows an example of probed points. The measurement coordinate system is set up based on the position and the orientation of the uppermost step, machined at $B_i=C_j=0^\circ$.

3. Identification of rotary axes geometric errors

3.1. Geometric error parameters to be identified

In ISO 230-1 [16], the axis average line of a rotary axis is defined as “the straight line representing the mean location and orientation of its axis of rotation.” Position and orientation errors of a rotary axis average line, called location errors in ISO 230-7 [17], are clearly among the most fundamental error factors in the five-axis kinematics. Table 1 shows location errors sufficient to describe the kinematics for the configuration in Fig.1 [16, 18].

It is to be noted that they only represent ‘average’ position or orientation of a rotary axis. The axis of rotation may change its position and orientation with its rotation. Such an error motion can be parameterized by position-dependent geometric errors [13]. Table 2 shows position-dependent geometric errors for B-axis.

It is important to note that this paper assumes geometric errors of linear axes are negligibly small compared to those of rotary axes. Many five-axis error calibration methodologies, briefly reviewed in Section 1, are based on the measurement of the TCP relative to the table, and it is therefore not possible
in principle to separate error motions of rotary axes and linear axes. Error motions of linear axes must be separately pre-calibrated by conventional measurement (e.g. ISO 10791-1 [3]).

3.2. Calculation of position/orientation of each step

For each square-shaped step machined at \(B_i\) and \(C_i\), denote the \(k\)-th measured position in the measurement coordinate system by \(p(i,j,k)\text{e}R^3\). Suppose that its nominal position is given by \(\hat{p}(i,j,k)\text{e}R^3\). Denote the displacement of the machined step from its nominal position by \((\Delta x(i,j), \Delta y(i,j), \Delta z(i,j))\) in \(X, Y,\) and \(Z\) directions. Denote its orientation error by \((\Delta a(i,j), \Delta b(i,j), \Delta c(i,j))\) around \(X, Y,\) and \(Z\) axes. They can be calculated by solving the following minimization problem:

\[
\min_{\Delta x(i,j), \Delta y(i,j), \Delta z(i,j)} \sum |\Delta p(i,j,k) - n(i,j,k)|^2
\]

(1)

where \(n(i,j,k)\text{e}R^3\) is a unit vector representing the normal direction to the target surface. This term is needed since a touch-trigger probe is sensitive only to this direction.

\[
\Delta p(i,j,k) = p(i,j,k) - \hat{p}(i,j,k)
\]

(2)

and

\[
[\hat{p}(i,j,k)]_1 = D(\Delta x(i,j))D(\Delta y(i,j))D(\Delta z(i,j))
\]

(3)

\[
D(\Delta a(i,j))D(\Delta b(i,j))D(\Delta c(i,j))\]

The calculation algorithm in Sections 3.2 and 3.3 is analogous to the one presented in our previous work on probing-based geometric error calibration [19].

3.3. Calculation of geometric error parameters

When the nominal point in the workpiece coordinate system is given by \(w_i^q\text{e}R^3\), its actual position, \(q_i\text{e}R^3\), when there exist location errors in Table 1, is given by:

\[
[w_i^q]_1 = (T_w)^{-1} \cdot \tau_q \cdot [w_i^q]_1
\]

(3)

where \(w_i^q\text{e}R^3\) is the homogeneous transformation matrix (HTM) representing the transformation from the workpiece coordinate system to the machine coordinate system:

\[
\begin{align*}
\tau_{w} &= \tau_a \cdot a_{w} \\
\tau_{a} &= D_1(E_{x0B})D_2(E_{y0C})D_3(E_{z0B}) \\
\tau_{w} &= D_1(E_{x0B}D_2(E_{y0C}D_3(E_{z0B})(-B_i)) \\
\end{align*}
\]

(4)

where \(D_1(*):\text{e}R^3\times R^4\times R^4\) denotes the HTM representing the translation in \(X, Y\) or \(Z\) or the rotation around \(X, Y,\) or \(Z,\)

| Symbol [16] | Description |
|-----------------|-----------------|
| \(E_{x0B}\) | Position error of \(B\)-axis average line in \(X\) |
| \(E_{y0C}\) | Position error of \(C\)-axis average line in \(Y\) |
| \(E_{z0B}\) | Position error of \(B\)-axis average line in \(Z\) |
| \(E_{x0B}E_{y0C}E_{z0B}\) | Position of \(C\)-axis from \(B\)-axis in \(X\) |
| \(E_{x0B}\) | Orientation error of \(B\)-axis avg line around \(X\) |
| \(E_{y0C}\) | Initial angular positioning error of \(B\)-axis |
| \(E_{z0B}\) | Orientation error of \(B\)-axis avg line around \(Z\) |
| \(E_{x0B}E_{y0C}E_{z0B}\) | Squares error of \(C\)- to \(B\)-axis |

Such a five-axis kinematic model can be found in numerous references, e.g. [2,8,18]. \(w_i^q\text{e}R^3\times R^4\times R^4\) represents the nominal transformation:

\[
\tau_{w} = D_1(-B_i)D_2(-C_i)
\]

(5)

As is presented in [8], the kinematic model (4) can be rewritten as:

\[
[w_i^q]_1 = D_1(\Delta X)D_2(\Delta Y)D_3(\Delta Z)D_4(\Delta A)D_5(\Delta B)D_6(\Delta C)[w_i^q]_1
\]

(6)

where

\[
\begin{align*}
\Delta X &= -(E_{x0B}\cos B_i + E_{z0B}\sin B_i + E_{z0B}\sin C_i + E_{y0C}\sin C_i) \\
\Delta Y &= -(E_{x0B}\cos B_i + E_{z0B}\sin B_i + E_{x0B}\sin C_i - E_{y0C}\cos C_i) \\
\Delta Z &= E_{x0B}\sin B_i - E_{z0B}\cos B_i \\
\Delta A &= -(E_{x0B}\cos B_i + E_{z0B}\sin B_i + E_{y0C}\sin C_i + E_{y0C}\sin C_i) \\
\Delta B &= -(E_{x0B}\cos B_i + E_{z0B}\sin B_i + E_{y0C}\sin C_i - E_{y0C}\cos C_i) \\
\Delta C &= E_{x0B}\sin B_i - E_{z0B}\cos B_i \\
\end{align*}
\]

The relationship of position/orientation errors of each machined step, \(\Delta x(i,j)\) to \(\Delta c(i,j)\), to location errors, can be derived from the formulation above. Recall that each step's position and orientation, \(\Delta x(i,j)\) to \(\Delta c(i,j)\), are measured in reference to those of the reference step, machined at \(B_i = C_i = 0^\circ\). In other words, \(\Delta x(i,j)\) to \(\Delta c(i,j)\) must be zero at \(B_i = C_i = 0^\circ\). This must be taken into account (see [19]).

Each location error can be identified from \(\Delta x(i,j)\) to \(\Delta c(i,j)\) by applying the least square fit to this model. The algorithm can be straightforwardly extended to the identification of position-dependent geometric errors in Table 2 (see [19,8]).
4. Experiment

4.1. Test setup

The proposed machining test is conducted on a machining center of the configuration in Fig. 1. Table 3 shows major machining conditions. Figure 5 shows the test setup.

Although it is preferable to measure the finished test piece’s geometry by a coordinate measuring machine (CMM), on-machine measurement using a touch-trigger probe was used in this experiment, assuming sufficiently high volumetric accuracy of machine tool's linear axes. OMP-400 by Renishaw is used (unidirectional repeatability: 0.35 μm (max 2σ value with 100 mm stylus), probe sphere: 66 mm (ruby)). The machining center's positioning resolution is 1 μm on all the linear axes; the probe's measurement resolution is also 1 μm.

With the machine’s B- and C-axes fixed at B=0°, points shown in Fig. 4 are probed. Note that error motions of B- and C-axes do not influence this measurement.

4.2. Test results

Figure 6 shows the measured geometry of four steps on the test piece's top face, each of which is machined at B=0°, and C=0, 90, 180, 270°, respectively. Figures 6 (a) and (b) respectively show the projection onto the XY and XZ planes. In Fig. 6, the dots (•) represent the nominal probed position, \( p(i,j,k) \), and the circles (o) represent the measured position, \( Pm(i,j,k) \). The error between measured and nominal positions is magnified 1,000 times. The position and the orientation of each step, represented by \( \Delta t(i,j) - \Delta c(i,j) \), is calculated as shown in Section 3.2. In Fig. 6, the painted bold-line square represents calculated position and orientation of each step (those in Fig. 6(a) are calculated from probed points on side faces of each step, and those in Fig. 6(b) are calculated from probed points on the bottom face).

From Fig. 6, many intuitive observations can be made on location errors or error motions of C-axis (at B=0°), e.g.,

- In Fig. 6(a), the square machined at C=-180° is shifted by about +8 μm in X-direction, and +3 μm in Y-direction. This is mostly caused by the position error of the C-axis average line, \( E_{3OC} \) and \( E_{2OC} \).
- In Fig. 6(b), the bottom surface of each step is tilted toward both X- and Y-directions. This is mostly caused by the orientation error of C-axis to X- and Y-directions.

The measured geometry of steps on the test piece's side faces, machined at \( Bc=-90° \) and 90°, can be plotted analogously, but omitted here.

Then, location errors, shown in Table 1, are identified as shown in Fig. 7. Figure 8 shows position-dependent geometric errors of B-axis, shown in Table 2, identified from the measured geometry. While location errors in Fig. 7 represent 'average' position and orientation of rotary axes, Fig. 8 shows how the B-axis position and orientation vary from their average values with the B-axis angular position, \( Bc \).

4.3. Uncertainty analysis

The calculation in Section 3 assumes negligibly small error motions of linear axes. It is, therefore, practically important to assess the uncertainty in identified geometric error parameters due to, especially, linear axis error motions. In the present analysis, other potential contributors, e.g. the uncertainty associated with probing and machining process, are regarded relatively small.

Table 4 shows assessed uncertainty contributors in linear axis error motions. Statistical uncertainty analysis based on the Monte Carlo simulation, analogous to the one presented in [20], is applied. The modelling of uncertainty contribution of linear axis error motions in [20] is adopted. In Fig. 7, error bars represent the standard uncertainty \( (k=1) \) calculated from uncertainty contributors in Table 4.

5. Application to thermal test

5.1. Objective

For five-axis machines, even when thermal deformation, typically caused by heat generation from spindle rotation (possibly also from linear/rotary axes or environment), causes simple translational errors, it often changes the position of rotary axes with respect to the machine coordinate system defined by linear axes. As a result, thermal deformation more likely causes the machined workpiece's geometric errors in five-axis machining. Thermal deformation may also influence rotary axis position/orientation directly. ISO 230-3:2007 [21] only describes tests to investigate thermal influence of spindle...
rotation, linear drives, and environment. The importance of thermal tests for rotary axes has been discussed only lately in the literature. Recent works include the application of R-test [22, 23, 24].

By repeating the proposed machining test consequently on the same machine, one can evaluate thermal influence on position and orientation of rotary axes. This section presents such an application of the proposed machining test.

5.2. Test procedure

The test procedure is described as follows:
1. Mount the unmachined workpiece on the machine's work table. Perform spindle warm-up (e.g. 30 min in our test).
2. Rough cutting (about 25 min in our test).
3. Finishing as described in Section 2 (about 25 min).
4. Dismount the finished test piece, and repeat the procedure 1 to 3 (total three times in our test).
5. After the machine sufficiently cools down, the three finished test pieces are measured on the machine as presented in Section 2.

5.3. Test results

Figure 9 shows position and orientation errors of B- and C-axis average lines (location errors, Table 1) identified by the geometry of each of three finished test pieces. Notable gradual change can be observed in the Y-position of the C-axis average line, \( E_{Y0C} \), and the Z-position of the B-axis average line, \( E_{Z0B} \). The variation in other error parameters is smaller. This likely indicates the thermal deformation of the spindle-side machine structure mainly toward Z- and Y-directions (see the machine configuration in Fig.1). Such a simple linear deformation (at tool tip) causes geometric errors of finished test piece in five-axis machining.

To validate location errors estimated from the machined test pieces, the position errors of C-axis average line, \( E_{ABC} \) \( = E_{AB0} + E_{MB0} \) \( E_{0BC} \), were directly measured by using a dial gauge, attached to the spindle, and a test piece fixed on the table. This measurement was conducted right after the machining of each test piece was finished. Figure 10 compares the estimates and direct measurements. The validity of the estimates can be observed.

6. Conclusion

In the proposed machining test, a simple square-shaped step is finished by a straight (radius) end mill at given sets of B- and C-axis angular positions. By examining the position and the orientation of each step on the finished test piece, geometric error parameters of B- and C-axes, both location errors and position-dependent errors, can be identified.

By repeating the proposed machining test, time-dependent variation in geometric error parameters can be observed, which is mostly caused by thermal deformation induced by spindle rotation or environmental change. In the machine configuration in Fig.1, the heat from tool spindle rotation mainly displaces the tool spindle. This deformation changes the relative position (and possibly the orientation) of rotary axes to the tool spindle. In five-axis machining, from our experience, thermally-induced variation in rotary axis location errors is often among the most critical factors for potentially significant geometric errors of finished workpiece. The proposed machining test is effective to evaluate the machine's thermal stability.

The machine's geometric errors are sometimes evaluated when the machine is 'cold' (e.g. static tests [3] at assembly/inspection sites in machine tool builders). Such a test is
clearly not good when the machine may be under significant thermal influence. The proposed machining test is effective to evaluate geometric errors when the machine is in normal operating conditions.

References

[1] Schwenke H, Knapp W, Hattjema H, Weckemann A, Schmitt R, Deltressine F. Geometric error measurement and compensation of machines -- An update. CIRP Annals Manuf. Tech. 2008; 57-2: 560-575.

[2] Ibaraki S, Knapp W. Indirect Measurement of Volumetric Accuracy for Three-axis and Five-axis Machine Tools: A Review. Int'l J. of Automation Technology 2012; 6-2: 110-124.

[3] ISO/DIS 10791-1:2013, Test conditions for machining centres -- Part 1: Geometric tests for machines with horizontal spindle and with accessory heads (horizontal Z-axis).

[4] Kakino Y, Ibara Y, Sato H, Otsubo H. A Study on the motion accuracy of NC machine tools (7th report) -- Measurement of motion accuracy of 5-axis machine by DDB tests. J. of Japan Society for Precision Engineering 1994; 60-5: 718-723 (in Japanese).

[5] Tsumitani M, Saito A. Identification and compensation of systematic deviations particular to 5-axis machining centers. Int'l J. of Machine Tools and Manufacture 2003; 43-8: 771-780.

[6] ISO/DIS 10791-6:2012, Test conditions for machining centres -- Part 6: Accuracy of speeds and interpolations.

[7] Weikert S. R-Test, A New Device for Accuracy Measurements on Five Axis Machine Tools. CIRP Annals -- Manufacturing Technology 2004; 53-1: 429-432.

[8] Ibaraki S, Oyama C, Otsubo H. Construction of an error map of rotary axes on a five-axis machining center by static R-test. Int'l J. of Machine Tools and Manufacture 2011; 51-3: 190-200.

[9] Erkan T, Mayer JRR, Dupont Y. Volumetric distortion assessment of a five-axis machine by probing a 3D reconfigurable uncalibrated master ball artefact. Precision Engineering 2011; 35: 116–125.

[10] Matsushita T, Oki T. Identification of Geometric Errors in Five-axis Controlled Machine Tool with Touch Trigger Probe. Proc. of the 2010 Spring JSPE Semiannual meeting 2010, 1105-1106 (in Japanese).

[11] NAS 979-1969. Uniform cutting test -- NAS series, metal cutting equipment specifications; 34-37.

[12] ISO/DIS 10791:2001-10:2001, Test Conditions for Machining Centres -- Part 7: Accuracy of a Finished Test Piece.

[13] Hong C, Ibaraki S, Matsubara A. Influence of position-dependent geometric errors of rotary axes on a machining test of cone frustum by five-axis machine tools. Precision Engineering 2011; 35-1: 1-11.

[14] Bossoni S, Geometric and Dynamic Evaluation and Optimization of Machining Centers, Ph.D. dissertation, ETH Zurich, 2009.

[15] Ibaraki S, Sawada M, Matsubara A, Matsushita T, Machine tests to identify kinematic errors on five-axis machine tools, Precision Engineering 2010, 34-3: 387-398.

[16] ISO 230-1:2007, Test code for machine tools -- Part 1: Geometric accuracy of machines operating under no-load or quasi-static conditions.

[17] ISO 230-7:2006, Test code for machine tools -- Part 7: Geometric accuracy of axes of rotation.

[18] Inakasu I, Kuwahara K, Sakamoto S, Sugimoto N, Takeuchi T, Tanaka F, Shaper generation theory of machine tools -- its basis and applications, Tokyo: Yokendo; 1997 (in Japanese).

[19] Ibaraki S, Sawada M, Matsubara A, Matsushita T. Calibration of location errors of rotary axes on five-axis machine tools by on-the-machine measurement using a touch-trigger probe, Int'l J. Machine Tools and Manufacture 2012, 58: 44-53.

[20] Bringmann B, Besuchet JP, Rohr L, Systematic evaluation of calibration methods, CIRP Annals Manufacturing Technology 2008, 57: 529-532.

[21] ISO 230-3:2007, Test code for machine tools -- Part 3: Determination of thermal effects.

[22] Hong C, Ibaraki S, Observation of Thermal Influence on Error Motions of Rotary Axes on a Five-Axis Machine Tool by Static R-Test, Int'l J. of Automation Technology 2012, 6-2: 196-204.

[23] Gebhardt M, Cube P, Knapp W, Wegener K, Measurement set-ups and -cycles for thermal characterization of axes of rotation of 5-axis machine tools, Proc. the 12th euromech Int'l Congr., 2012.

[24] Gebhardt M, Capparelli S., Ess M, Knapp W, Wegener K, Physical and phenomenological simulation models for the thermal compensation of rotary axes of machine tools, Proc. the 13th euromech Int'l Congr., 2013.