Special Issue on Flexible Automation

Paper

Identification of Rotary Axis Location Errors under Spindle Rotation by using a Laser Barrier Tool Measurement System —Experimental Comparison with R-Test*

Soichi IBARAKI† and Eita YANAI†

Position and orientation errors of rotary axis average lines are often dominant error sources in the five-axis machining. Many schemes have been studied, and some are now commercially available, such that they can be identified on-machine, and then numerically compensated, by a machine tool user. Many conventional schemes install a measuring instrument or a measured target in a machine spindle, and thus cannot be performed when the spindle is rotating. Rotary axis location errors are often influenced by the machine's thermal deformation. When the spindle is not rotating, they can be different from actual machining operations. This paper presents the application of a non-contact laser barrier tool measurement system to the identification of rotary axis location errors, when the spindle rotates in the same speed as in actual machining applications. An experimental thermal test is presented to observe the change in rotary axis location errors under continuous machine warm-up by spindle rotation and reciprocal linear axis motions. Experimental comparison with the R-Test, a typical conventional scheme that can be performed only when the spindle does not rotate, shows that rotary axis location errors change quickly after the machine warm-up is terminated.

1. Introduction

Position and orientation errors of rotary axis average lines are often dominant error sources in the five-axis machining. *The axis average line* of a rotary axis represents the average position and orientation of the axis of rotation over its full rotation (the term in ISO 230-1[1]). They are sometime referred to as *the location errors*[2] or position-independent geometric errors[3] of rotary axes. They are primarily caused by machine assembly errors, and thus it is important for machine tool builders to assess these errors in machine accuracy inspection, and then to perform mechanical adjustment or numerical compensation if they do not meet the tolerance. For such a purpose, ISO 10791-1[4] describes static tests to measure position and orientation errors of rotary axis average lines for five-axis machining centers. ISO 10791-6[5] describes interpolation tests with a main focus on their assessment.

While such an accuracy inspection by machine tool builders is indispensable, it alone cannot ensure the permissible accuracy over the entire life of the machine. Thermal deformation of machine structure, typically caused by the heat generation in a spindle, feed drive motors or environmental temperature change, is clearly among major error sources for any machine tools. As reviewed in[6–8], numerous efforts have been reported on the measurement, modelling and compensation of thermal errors. To ensure a machine tool's accuracy under thermal influence, it should be assessed not only by its manufacturer, but also by its user periodically, and numerical compensation should be updated based on it. Numerical compensation for the position and orientation errors of rotary axis average lines is possible on many commercial CNC systems[9,10]. For such a purpose, many machine tool builders commercialized a scheme to assess rotary axis location errors on-machine. A typical one is based on the measurement of the three-dimensional (3D) position of a precision sphere, installed on a machine table, by using a touch-trigger probe[11]. The R-Test[12–14] is also based on the 3D displacement measurement of a sphere but uses a set of thee displacement sensors. The application of the ball bar has been also studied by many researchers[15,16].

All of them install a measuring instrument or a measured target (a sphere) in a machine spindle. Thefore, they cannot be performed when the spindle is rotating. Rotary axis location errors are often influenced by the machine's thermal deformation. When the spindle is not rotating, they can be different from actual machining operations. Ibaraki et al.[11] experimentally investigated such an influence by a machining test. The standards[1,5] require a user to perform sufficient machine warm-up before performing accuracy tests, such that a machine can be tested under a thermal steady-state. In practice, the machine may

* Manuscript Received Date: August 24, 2020

† Graduate School of Advanced Science and Engineering, Hiroshima University; Kagamiyama 1-4-1, Higashi-Hiroshima 739-8527, JAPAN

Key Words: machine tool, metrology, thermal deformation, error calibration, five-axis, tool measurement.

be quickly cooled down immediately when the spindle stops, no matter how long the warm-up is performed. One of this paper's original contributions is on experimental demonstration of this issue.

To identify position and orientation errors of rotary axis average lines under spindle rotation, Ibaraki et al.[17] proposed a scheme using a laser light barrier tool measurement system. A laser light barrier tool measurement system (the term in ISO 230-10[18]) is an instrument to measure tool dimensions and geometries, e.g. the tool radius or length, by detecting light interruption by a rotating tool. Many products are commercially available, and are widely accepted by machine tool users. Ref.[17] used it to measure the position of a rotating tool with respect to the work table, when the work table is indexed at various angular positions, and presented an algorithm to identify rotary axis location errors from this test. Its crucial advantage is that it can be performed when the spindle rotates in the same speed as in actual machining processes, with exactly the same tool as the one used in actual machining processes.

Compared to [17], this paper's original contributions are as follows: 1) this paper presents the application of the proposed scheme to a thermal test, where the machine is continuously warmed up by spindle rotation and reciprocal linear axis motions, and the change in rotary axis location errors are periodically observed. 2) An experimental comparison with the R-Test is presented. The R-Test can be performed only when the spindle is stopped. The experiment shows that rotary axis location errors can quickly change when the spindle stops. Therefore it is difficult for the R-Test to capture rotary axis location errors in machining processes. 3) Ref.[17] employed a laser light barrier system with a single opto-electronic receiver to detect light interruption. This paper employs a laser tool measurement system with CMOS (Complementary Metal Oxide Semiconductor) sensor arrays to measure the 2D position of a rotating tool interrupting the light. The proposed scheme requires the tool measurement when the measuring system is rotated by 90° (at $B = -90°$). In such a setup, the laser tool measurement system with sensor arrays can have lower measurement uncertainty, since it can directly measure the 2D position of the tool.

This paper is based on our work presented in the conference paper[19]. A large portion of this paper is completely rewritten from [19]: Section **1** is completely rewritten to clarify a novelty of this paper compared to past works. Section **2.1** is newly added to describe the measuring instrument. The algorithm presented in Section **2.3** is re-organized and the presentation of the test results in Section **3.3** is modified.

2. Proposed Measurement Procedure

2.1 Measuring Instrument

This paper employs a laser light barrier tool measurement system with CMOS opto-electronic sensor arrays. Figure 1 shows its outlook (Dyna Line by Big Daishowa Seiki Co., Ltd.). Figure 2 illustrates its measuring principle. When a rotating tool blocks the laser beam, its vertical or horizontal position is measured by vertical or horizontal CMOS sensor arrays. Its typical applications contains the measurement of tool length or radius, by comparing with a reference cylinder of the calibrated geometry. Its signal sampling rate is sufficiently high to measure the run-out of a rotating tool. Table 1 shows major specifications of Dyna Line by Big Daishowa Seiki Co., Ltd.

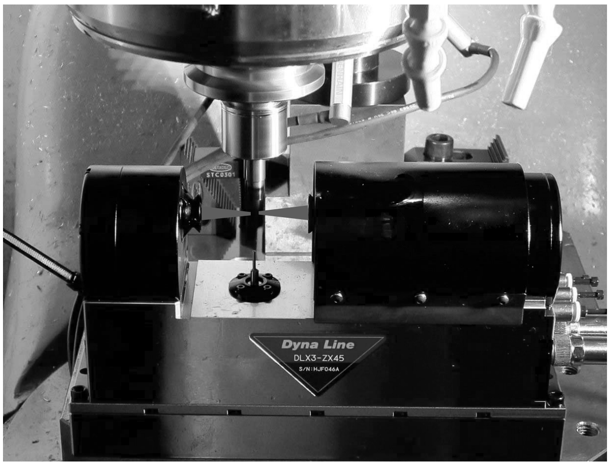


Fig. 1 Outlook of the laser light barrier tool measurement system (Dyna Line by Big Daishowa Seiki Co., Ltd.)

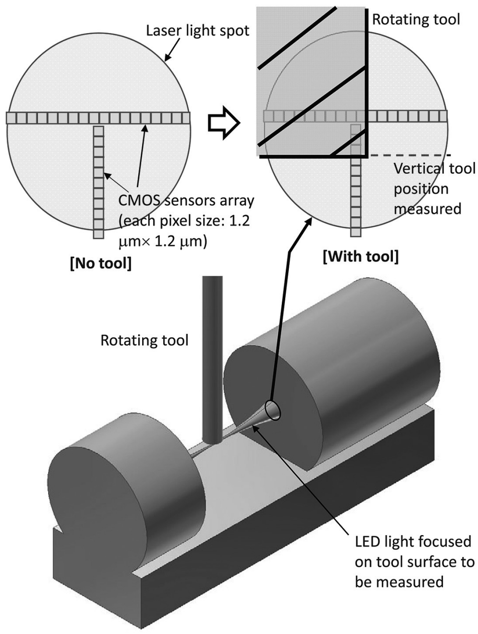


Fig. 2 Measuring principle of the laser light barrier tool measurement system with CMOS sensor arrays (Dyna Line by Big Daishowa Seiki Co., Ltd.). The LED light is focused at the tool surface. When the rotating tool interferes with the light (upper-right diagram), the vertical sensor array measures the vertical position of the tool's bottom face.

Table 1 Major specifications of the laser light barrier tool measurement system (Dyna Line by Big Daishowa Seiki Co., Ltd.)

Light source	LED (green)
Measurement resolution	0.1 μm
Repeatability in static tool radius measurement	0.12 μm (2σ)
Repeatability in static tool length measurement	0.12 μm (2σ)
Measurable range of sensor arrays	3.2 mm (X), 1.4 mm (Z)

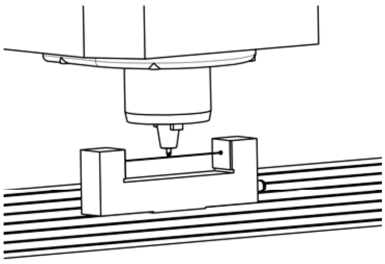


Fig. 3 A conventional laser light barrier tool measurement system [18]. The light interruption is detected by a single opto-electronic receiver.

More commonly used, conventional laser barrier tool measurement systems have a single light detector (see Fig. 3). When a rotating tool, fed to the laser beam in a constant low feedrate, blocks the laser beam, it is detected by the brightness measured by the sensor. Then its trigger signal is sent to the machine tool controller, where the machine position is logged. Unlike the one with sensor arrays in Fig. 2, the instrument itself does not measure the tool's position. It works as an optical switch when a defined degree of shading is reached. Potential advantages of the instrument employed in this paper (Fig. 2) over more common laser barrier tool measurement systems (Fig. 3) include:

- Similarly as a touch-trigger probe, a conventional laser barrier tool measurement system is influenced by the pre-travel, i.e. the distance between the point of the first interference of a tool to the laser beam and the point where the probe signal is generated[18]. This pre-travel often varies with the approaching direction. The instrument employed in this paper measures the tool position and thus is not influenced by the pre-travel at all.
- Since a conventional laser barrier tool measurement system has a single light detector only, actual distance from the laser spot center to the point where the trigger signal is generated most likely varies with the tool's approaching direction, due to the roundness error of the laser spot. This is not a critical issue for its typical applications to the measurement of tool dimensions, since the tool's approaching direction is usually the same. For the application presented in this paper, however, it can potentially be a significant uncertainty contributor.

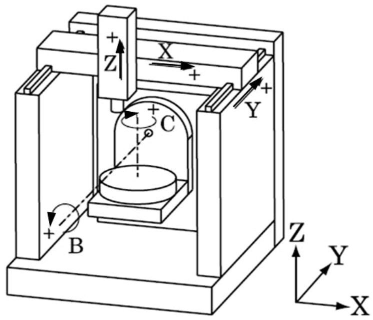


Fig. 4 Five-axis machine configuration considered in this paper

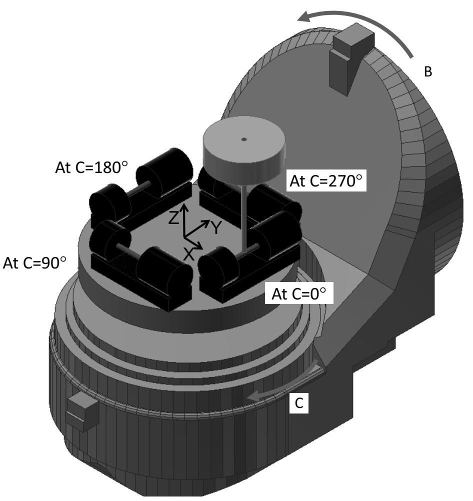
2.2 Test Procedure

This paper considers the five-axis configuration depicted in Fig. 4. It has two rotary axes, a rotary table C-axis mounted on a swivel axis B-axis, and their angular positions are respectively represented by b and $c \in \mathbb{R}$. The paper's basic idea can be extended to any five-axis configurations. A cylindrical end mill is attached to the machine spindle, and is rotated throughout the test. At $b = c = 0°$, the laser light barrier system is fixed on the machine table as shown in Fig. 5a (at "$C = 0°$"), where the laser beam is roughly aligned to the Y-direction and its focus is roughly at $Y = 0$ in the machine coordinate system (MCS). The MCS is the fixed coordinate system with its origin at the nominal intersection of B- and C-axes.

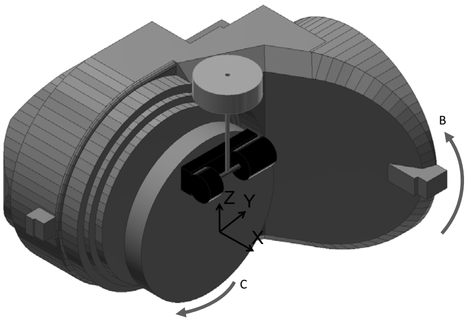
The following test procedure is basically the same as the one proposed in [17], except for that the measurement at $b = 90°$ is removed:

(1) At $b = c = 0°$ (see Fig. 5a), according to the instrument's recommended procedure, find (X, Y, Z) position to measure the tool's X position, and then to measure the tool's Z position. Typically, the tool's X position is measured at the position where the laser beam focuses roughly on the tool's side edge at the tangential YZ plane. Similarly, the tool's Z position is typically measured at the position where the laser beam focuses on one of the bottom edges. The Y position is not measured. Denote this command position in the workpiece coordinate system (WCS) by ${}^{w}p^{*}_{0,0} \in \mathbb{R}^3$. The WCS is a local coordinate system which is identical with the MCS at $b = c = 0°$, and rotates with B- and C-axes. At $b = c = 0°$, denote the tool's X- and Z-displacements respectively by ${}^{w}\Delta x_{0,0}$ and ${}^{w}\Delta z_{0,0} \in \mathbb{R}$, measured with respect to ${}^{w}p^{*}_{0,0}$ by the laser beam barrier system.

(2) Rotate the C-axis to $c = 90°$ (see Fig. 5a, $C = 90°$). Move the rotating tool to the command position in the MCS, ${}^{r}p^{*}(b,c) \in \mathbb{R}^3$, given by:



a)



b)

Fig. 5 Test procedure. a) at $b=0°$ and $c=0,90,180$ and $270°$. b) at $b=-90°$ and $c=180°$

$$\begin{bmatrix} {}^{r}p^{*}(b,c) \\ 1 \end{bmatrix} = D(-b)D(-c)\begin{bmatrix} {}^{w}p^{*}_{0,0} \\ 1 \end{bmatrix} \quad (1)$$

with $b=0$ and $c=90°$. Throughout this paper, $D_{*}(*)\in\mathbb{R}^{4\times4}$ represents the homogeneous transformation matrix (HTM) representing the translation to X, Y, or Z direction (∗=x, y, z) or the rotation around X, Y, or Z axis (∗=a,b,c). Their formulation is given in many publications, e.g.[13,20]. The left-hand side superscripts, w and r, respectively represent a vector in the WCS and the MCS.
Then, measure the tool's displacement in the X and Z directions in the WCS, respectively denoted by ${}^{w}\Delta x_{0,90}$ and ${}^{w}\Delta z_{0,90}$.

(3) Analogous tests are performed at $c=180°$ to measure (${}^{w}\Delta x_{0,180}$, ${}^{w}\Delta z_{0,180}$), and at $c=270°$ to measure (${}^{w}\Delta x_{0,270}$, ${}^{w}\Delta z_{0,270}$).
(4) Analogous tests are performed at $b=-90°$ and $c=180°$ to measure (${}^{w}\Delta x_{-90,180}$, ${}^{w}\Delta z_{-90,180}$) (see Fig. 5b).

Remark: When the tool rotation has the run-out, the measured tool position moves in the XY plane of the WCS within a full rotation. The sampling time of the laser barrier tool measurement systems is typically sufficiently high to observe this run-out. In the test procedure above, the tool's mean X position is taken as ${}^{w}\Delta x_{b,c}$. The influence of spindle rotation speed on the measurement uncertainty of the tool's mean position is negligibly small.

Table 2 Position and orientation errors (location errors) of rotary axis average lines for the machine configuration in Fig. 4

Symbol[20]	Description
δx^{0}_{BR}	Position error of B-axis average line in X
δy^{0}_{BR}	Position error of C-axis average line in Y
δz^{0}_{BR}	Position error of B-axis average line in Z
δx^{0}_{CB}	Intersection error of C- to B-axis average line
α^{0}_{CR}	Squareness error of C- to Y-axis
β^{0}_{BR}	Squareness error of C- to X-axis at $B=0°$

2.3 Identification of Rotary Axis Location Errors

The objective of the proposed test is to identify position and orientation errors of rotary axis average lines (rotary axis location errors) shown in Table 2. Their definition is described in [1,20].
Remark: For the machine configuration in Fig. 4, eight parameters are sufficient to fully describe the position and the orientation of B- and C-axis average lines[1,20]. Among them, the parallelism error of B- to Y-axis around X-axis, α^{0}_{BR}, and the squareness error of B- to X-axis, γ^{0}_{BR}, are excluded in Table 2, since they do not impose distinguishable influence on the present test.

The five-axis kinematic model plays an essential role in many previous publications on rotary axis indirect measurement schemes[21]. Ibaraki[20] showed that the five-axis kinematic model can be rewritten in the following form: when the command tool center point (TCP) in the WCS is given by ${}^{w}p^{*}\in\mathbb{R}^{3}$, and B- and C-axes are respectively indexed at b and $c\in\mathbb{R}$, then the actual TCP position in the WCS, ${}^{w}p\in\mathbb{R}^{3}$, under the rotary axis location errors in Table 2, is formulated by:

$$\begin{bmatrix} {}^{w}p \\ 1 \end{bmatrix} \approx D_{x}(\Delta X)D_{y}(\Delta Y)D_{z}(\Delta Z) \cdot D_{a}(\Delta A)D_{b}(\Delta B)D_{C}(\Delta c)\begin{bmatrix} {}^{w}p^{*} \\ 1 \end{bmatrix} \quad (2)$$

$$\Delta X = -(\delta x^{0}_{BR}\cos b + \delta z^{0}_{BR}\sin b + \delta x^{0}_{CB})\cos c + \delta y^{0}_{BR}\sin c$$
$$\Delta Y = -(\delta x^{0}_{BR}\cos b + \delta z^{0}_{BR}\sin b + \delta x^{0}_{CB})\sin c - \delta y^{0}_{BR}\cos c$$
$$\Delta Z = \delta x^{0}_{BR}\sin b - \delta z^{0}_{BR}\cos b$$
$$\Delta A = -(\alpha^{0}_{BR}\cos b + \gamma^{0}_{BR}\sin b + \alpha^{0}_{CB})\cos c + \beta^{0}_{BR}\sin c$$
$$\Delta B = -(\alpha^{0}_{BR}\cos b + \gamma^{0}_{BR}\sin b + \alpha^{0}_{CB})\sin c - \beta^{0}_{BR}\cos c$$
$$\Delta C = \alpha^{0}_{BR}\sin b - \gamma^{0}_{BR}\cos b$$

Notice that Eq. (2) is particularly useful to formulate the relationship of tool positions measured in the proposed scheme and rotary axis location errors. For example, at $b=-90°$ and $c=180°$ (see Fig. 5b), the measured X displacement in the WCS, ${}^{w}\Delta x_{-90,180}$, is given by:

$$^{w}\Delta x_{-90,180} \approx \Delta X + \Delta B \cdot {}^{w}p^{*}_{0,0}(3) \tag{3}$$
$$^{w}\Delta z_{-90,180} \approx \Delta Z - \Delta B \cdot {}^{w}p^{*}_{0,0}(1) \tag{4}$$

where ΔX, ΔZ, and ΔB are given in Eq. (2) with $b=-90°$ and $c=180°$. ${}^{w}p^{*}_{0,0}(1)$ and ${}^{w}p^{*}_{0,0}(3)$ are the X and Z components of ${}^{w}p^{*}_{0,0}$. Note that the nominal Y-position at $b=c=0°$, i.e. ${}^{w}p^{*}_{0,0}(2)$, is assumed approximately zero. By substituting Eq. (2) into Eqs. (3)(4), we have:

$$^{w}\Delta x_{-90,180} = -\delta z^{0}_{BR} + \delta x^{0}_{CB} + \beta^{0}_{BR} \cdot {}^{w}p^{*}_{0,0}(3) \tag{5}$$
$$^{w}\Delta z_{-90,180} = -\delta x^{0}_{BR} - \beta^{0}_{BR} \cdot {}^{w}p^{*}_{0,0}(1) \tag{6}$$

The measured tool displacement at $(b,c)=(-90°,180°)$, $({}^{w}\Delta x_{-90,180},\ {}^{w}\Delta z_{-90,180})$, is evaluated with respect to the one measured at $b=c=0°$, $({}^{w}\Delta x_{0,0},\ {}^{w}\Delta z_{0,0})$. By analogously formulating $({}^{w}\Delta x_{0,0},\ {}^{w}\Delta z_{0,0})$, we have the 8th and 9th rows in Eq (7). Analogous formulation for each of $(b,c) = (0,0)$, $(0,90)$, $(0,180)$ and $(0,270)$, we have:

$$\begin{bmatrix} {}^{w}\Delta x_{0,90} - {}^{w}\Delta x_{0,0} \\ {}^{w}\Delta z_{0,90} - {}^{w}\Delta z_{0,0} \\ {}^{w}\Delta x_{0,180} - {}^{w}\Delta x_{0,0} \\ {}^{w}\Delta z_{0,180} - {}^{w}\Delta z_{0,0} \\ {}^{w}\Delta x_{0,270} - {}^{w}\Delta x_{0,0} \\ {}^{w}\Delta z_{0,270} - {}^{w}\Delta z_{0,0} \\ {}^{w}\Delta x_{0,90} - {}^{w}\Delta x_{0,0} \\ {}^{w}\Delta x_{0,90} - {}^{w}\Delta z_{0,0} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 0 & 1 & -{}^{w}p^{*}_{z} & {}^{w}p^{*}_{z} \\ 0 & 0 & 0 & 0 & {}^{w}p^{*}_{x} & -{}^{w}p^{*}_{x} \\ 2 & 0 & 0 & 2 & 0 & 2{}^{w}p^{*}_{z} \\ 0 & 0 & 0 & 0 & 0 & -2{}^{w}p^{*}_{x} \\ 1 & -1 & 0 & 1 & {}^{w}p^{*}_{z} & {}^{w}p^{*}_{z} \\ 0 & 0 & 0 & 0 & -{}^{w}p^{*}_{x} & -{}^{w}p^{*}_{x} \\ 1 & 0 & -1 & 2 & 0 & 2{}^{w}p^{*}_{z} \\ -1 & 0 & 1 & 0 & 0 & -2{}^{w}p^{*}_{x} \end{bmatrix} \begin{bmatrix} \delta x^{0}_{BR} \\ \delta y^{0}_{BR} \\ \delta z^{0}_{BR} \\ \delta x^{0}_{CB} \\ \alpha^{0}_{CR} \\ \beta^{0}_{CR} \end{bmatrix} \tag{7}$$

Error sources in Table 2 can be identified by solving Eq. (7), when the tool displacements in the left-hand side of the equation are measured.

2.4 Application to Thermal Test

By periodically applying the proposed test procedure, while the machine tool is subject to thermal influence of internal or external heat sources, one can observe how rotary axis location errors gradually change over the entire test. The past works[22,23] presented a thermal test for five-axis machine tools by periodically applying the R-Test, and now it is adopted in ISO 230-3 standard[24]. The R-Test installed a precision sphere (or the sensors nest) on a machine spindle, and thus cannot be performed when the spindle rotates. The proposed scheme is more advantageous for a thermal test, since it can be performed without stopping spindle rotation.

When the proposed test, described in Section **2.2**, is performed multiple times with the same nominal initial tool position, ${}^{w}p^{*}_{0,0}$, the tool displacement measured at each angular position should be evaluated with respect to the measured displacement at $b=c=0°$ in the first test. Suppose that the proposed test is performed N times $(k=1,\cdots N)$ and the measured tool displacements at the k-th test are denoted by ${}^{w}\Delta x_{b,c}(k)$ and ${}^{w}\Delta z_{b,c}(k)$. The rotary axis location errors identified at the k-th test are denoted with (k), e.g. $\delta x^{0}_{BR}(k)$. Then, for the k-th test, Eq. (7) is replaced by:

$$\begin{bmatrix} {}^{w}\Delta x_{0,90}(k) - {}^{w}\Delta x_{0,0}(1) \\ {}^{w}\Delta z_{0,90}(k) - {}^{w}\Delta z_{0,0}(1) \\ {}^{w}\Delta x_{0,180}(k) - {}^{w}\Delta x_{0,0}(1) \\ {}^{w}\Delta z_{0,180}(k) - {}^{w}\Delta z_{0,0}(1) \\ {}^{w}\Delta x_{0,270}(k) - {}^{w}\Delta x_{0,0}(1) \\ {}^{w}\Delta z_{0,270}(k) - {}^{w}\Delta z_{0,0}(1) \\ {}^{w}\Delta x_{0,90}(k) - {}^{w}\Delta x_{0,0}(1) \\ {}^{w}\Delta x_{0,90}(k) - {}^{w}\Delta z_{0,0}(1) \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & -{}^{w}p^{*}_{z} & 0 \\ 0 & 0 & -1 & 0 & {}^{w}p^{*}_{x} & 0 \\ 1 & 0 & 0 & 1 & 0 & {}^{w}p^{*}_{z} \\ 0 & 0 & -1 & 0 & 0 & -{}^{w}p^{*}_{x} \\ 0 & -1 & 0 & 0 & {}^{w}p^{*}_{z} & 0 \\ 0 & 0 & -1 & 0 & -{}^{w}p^{*}_{x} & 0 \\ 0 & 0 & -1 & 1 & 0 & {}^{w}p^{*}_{z} \\ -1 & 0 & 0 & 0 & 0 & -{}^{w}p^{*}_{x} \end{bmatrix} \cdot \begin{bmatrix} \delta x^{0}_{BR}(k) \\ \delta y^{0}_{BR}(k) \\ \delta z^{0}_{BR}(k) \\ \delta x^{0}_{CB}(k) \\ \alpha^{0}_{CR}(k) \\ \beta^{0}_{CR}(k) \end{bmatrix} - \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 0 \\ 0 & 1 \\ 1 & 0 \\ 0 & 1 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} -(\delta x^{0}_{BR}(1) + \delta x^{0}_{CB}(1)) - {}^{w}p^{*}_{z} \cdot \beta^{0}_{CR}(1) \\ -\delta z^{0}_{BR} + {}^{w}p^{*}_{z} \cdot \beta^{0}_{CR}(1) \end{bmatrix} \tag{8}$$

3. Experiment

3.1 Objective

The objectives of the experiment are: 1) To demonstrate a thermal test for a five-axis machine tool. By continuously generating the heat by spindle rotation and reciprocal motion of linear axes, and performing the present scheme periodically, the change in rotary axis location errors can be observed. 2) To experimentally compare the present test with the R-Test. The R-Test[12–14], described in ISO 10791-6[5], is a well-accepted scheme to evaluate rotary axis average lines. Its disadvantage is that it can be performed only when a spindle is stopped, since a sphere must be installed on the spindle. The R-Test is performed immediately before and after the machine warm-up, and its estimates are compared to those estimated during the warm-up cycles by the proposed scheme.

3.2 Experimental Setup and Procedure

The proposed test was performed on a five-axis machine, NMV3000DCG by DMG Mori Co., Ltd., of the configuration in Fig. 4. Figure 6 shows the experimental setup. The laser light barrier tool measurement system, Dyna Line by Big Daishowa Seiki Co., Ltd. (Table 1), and the R-Test sensors nest were installed on the machine table. The R-Test device has three tactile displacement sensors, and measures the 3D displacement of the precision sphere installed on the machine spindle. The details of the R-Test instrument, its test procedure, the algorithm to identify rotary axis location errors based on the R-Test, are given in [13,14]. The experimental procedure is as follows:

(1) First, without performing any machine warm-up cycles, the R-Test cycle was performed. The sphere was installed to the spindle (see Fig. 6c). The 3D sphere displacement was statically measured at $C=0,90,180,270°$ and $B=0°$, and then at $B=-90°$ and $C=180°$.
(2) Then, a cylindrical end mill (diameter: 10 mm, corner radius: 1 mm) was installed to the spindle and the spindle started rotating by 6,350 min^{-1}. Then, the proposed test procedure presented in Section **2.2** was performed (see Figs. 6 b and c). It took about 10 min. All the points were measured three times to check the measurement's repeatability.
(3) Then, at the retracted Z position, while the spindle kept rotating in the same speed, repeat the reciprocal motion of X, Y, and Z axes to the distance 200 mm for 15 min. This is the machine warm-up cycle.
(4) Repeat (2) and (3) six times. The total test took 125 min.
(5) When the thermal test was finished, the spindle was stopped, and the sphere was installed to the spindle. Then, the same R-Test cycle was performed. It was performed in about 10 min after the spindle stopped. Finally, the same R-Test cycle was again performed in about 30 min after the first R-Test cycle.

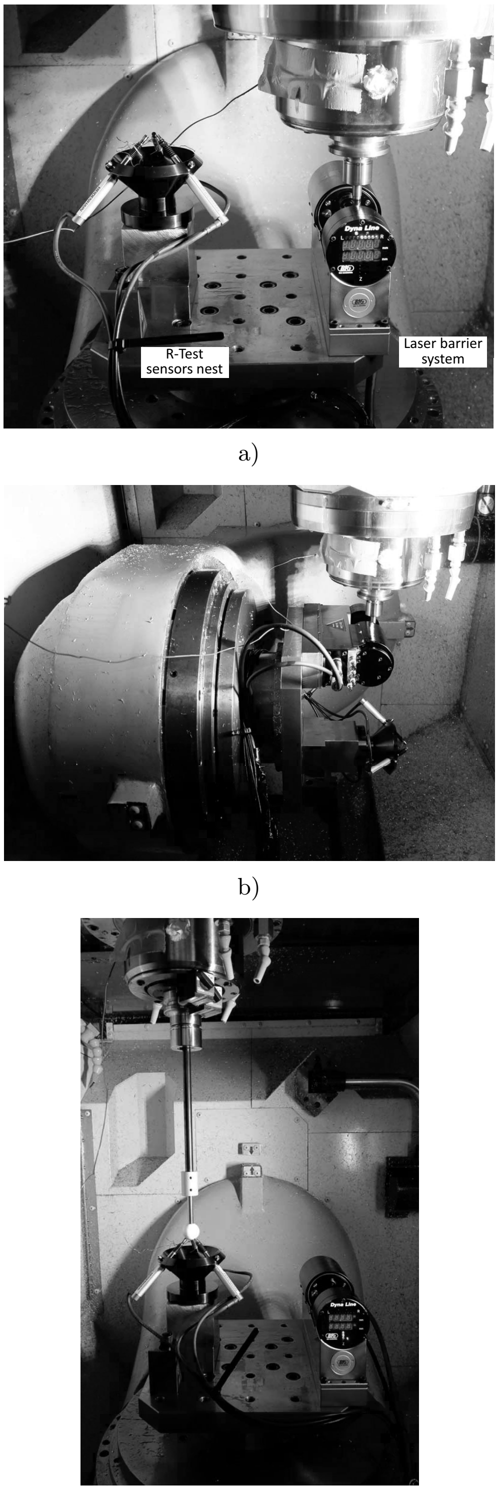
3.3 Thermal Influence on Rotary Axis Location Errors

Figure 7 show the rotary axis location errors identified by the proposed test (Step 2 in Section **3.2**) performed at every 25 min during the thermal test. It also shows those estimated by the R-Test before and after the thermal tests.

Figure 8 shows the temperatures measured by using thermocouples attached to a) the Z-axis servo motor frame, b) the spindle unit frame near its front bearing, and c) in the air near the test piece. The temperature on the Z-axis servo motor frame was increased by about 1.0 °C in 125 min, but no clear temperature increase was observed on the spindle frame. Note that only the temperature on the spindle unit frame, not its inside, was measured, which may not directly show the spindle's thermal deformation.

The following observations can be made on the test results:

(1) The Z-position of B-axis average line, δz_{BR}^0, was displaced by 12 μm by the machine warm-up for 125 min. It is typical for the heat generated by a spindle to cause its deformation to the Z-direction. When the spindle is displaced to -Z direction, it causes the positive Z-position error of B-axis average line with respect to the tool.
(2) Thermal displacement to X- or Y-direction was at maximum 2 μm. The orientation errors of the C-axis average line, α_{CR}^0 and β_{BR}^0, were changed by about 2×10^{-5} rad. Considering that the distance of the measured point to the C-axis centerline was about 120 mm, its influence on the tool's position

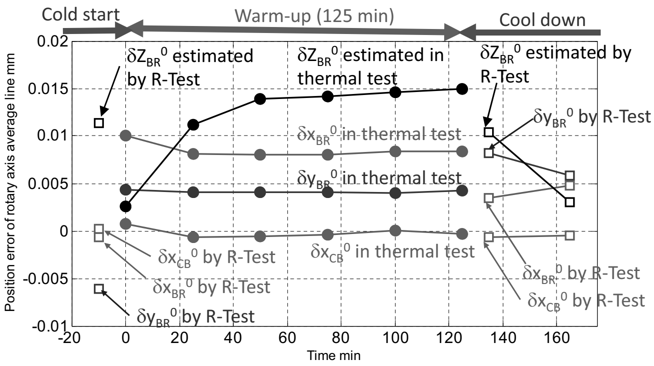


a)

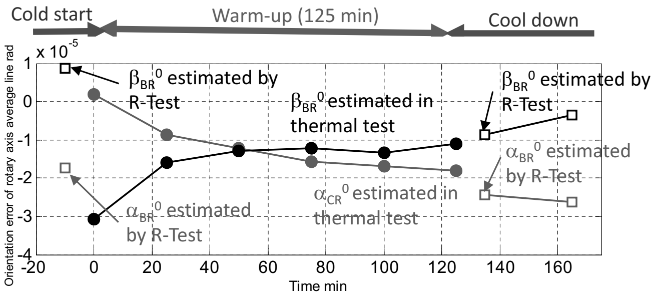
b)

c)

Fig. 6 Experimental setup. a) at $B=C=0°$, b) at $B=-90°$ and $C=180°$, c) R-Test setup at $B=C=0°$



a)



b)

Fig. 7 Rotary axis location errors estimated in the thermal test by the proposed scheme, in comparison with the estimates by the R-Test before and after the machine warm-up cycles. See Table 2 for the definitions of rotary axis location errors. a) position errors, b) orientation errors.

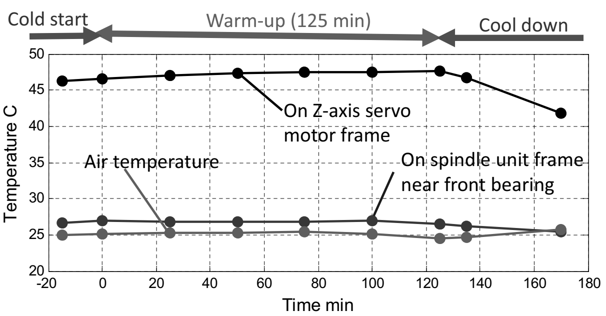


Fig. 8 Temperatures measured in the experiment

in the WCS is about 2 μm. These may not be significant, compared to the measurement uncertainty or the machine's repeatability.

(3) When the spindle was stopped, the Z-position of B-axis average line, δz_{BR}^0, measured by the R-Test, was reduced by 5 μm only in 10 min. In 40 min after the spindle stopped, δz_{BR}^0 was reduced to 4 μm, which is approximately the same as its initial value. This shows that the machine was quickly cooled down and deformed when the machine warm-up cycles were terminated, even after the machine was warmed up for 125 min.

The experimental result clearly shows that rotary axis location errors can be subject to a potentially significant influence of the heat generated by spindle and linear axes. Since rotary axis location errors can be a major contributor to the machining error, it is crucial to evaluate them in machining processes. The values estimated by the first R-Test, performed before the thermal test, have significant difference from the values when the machine is in thermal steady state by the warm-up cycles. Even when the R-Test was performed right after the 125 min warm-up cycles, Fig. 7a shows that the machine can quickly be cooled down when the spindle stops. This shows a critical issue with many conventional error calibration schemes. e.g. the R-Test, the ball bar tests, and probing-based schemes, which can be performed only when the spindle does not rotate.

4. Conclusion

The position and orientation errors of rotary axis average lines can change due to thermal influence or machine "aging". Many schemes are commercially available, e.g. a tough-trigger probe system with a precision sphere or the R-Test, to measure and then to compensate them. Their critical issue is that they can be performed only when the spindle does not rotate, and thus they may not capture rotary axis location errors in actual machining processes. This paper presented the application of a laser barrier tool measurement system to the identification of rotary axis location errors. An essential principle is common with conventional schemes; the position of a tool with respect to the work table is measured at various angular positions of rotary axes.

Since the present scheme can be performed with the spindle continuously rotating, it can be applied to a thermal test. The experiment showed the change in rotary axis location errors, when the heat is generated by spindle rotation and reciprocal motion of linear axes for 125 min. The comparison with the R-Test showed that rotary axis location errors quickly changed when the spindle stopped, even after 125 min warm-up cycles. This shows a potential effectiveness of the present scheme for compensating rotary axis location errors in machining processes.

Similarly as many conventional "indirect" rotary axis error calibration, the present scheme inherently cannot separately identify linear axis error motions. When the machine has significant linear axis error motions, they can be major uncertainty contributors. Ref.[17] presented the uncertainty analysis to assess the influence of linear axis error motions and an analogous analysis can be applied to this paper's scheme.

References

[1] ISO 230-1:2012, Test code for machine tools — Geometric accuracy of machines operating under no-load or quasi-static conditions

[2] ISO 230-7:2015, Test code for machine tools — Part 7: Geometric accuracy of axes of rotation

[3] H. Yang, X. Huang, S. Ding, C. Yu and Y. Yang: Identification and compensation of 11 position-independent geometric errors on five-axis machine

tools with a tilting head; *The International Journal of Advanced Manufacturing Technology Volume*, Vol. 94, pp. 533–544 (2018)

[4] ISO 10791-1:2015, Test conditions for machining centres — Part 1: Geometric tests for machines with horizontal spindle (horizontal Z-axis)

[5] ISO 10791-6:2014, Test conditions for machining centres — Part 6: Accuracy of speeds and interpolations

[6] J. Mayr, J. Jedrzejewski, E. Uhlmann, A. Donmez, W. Knapp, F. Hartig, K. Wendt, T. Moriwaki, P. Shore, R. Schmitt, C. Brecher, T. Würz and K. Wegener: Thermal issues in machine tools; *CIRP Annals — Manufacturing Technology*, Vol. 61, No. 2, pp. 771-791 (2012)

[7] M. Weck, P. McKeown, R. Bonse and U. Herbst: Reduction and compensation of thermal errors in machine tools; *CIRP Annals — Manufacturing Technology*, Vol. 44, No. 2, pp. 589–598 (1995)

[8] J. Bryan: International status of thermal error research; *Annals of the CIRP*, Vol. 39, No. 2, pp. 645–656 (1990)

[9] Y. Yamada: Compensation technology for volumetric error in machine tool; *Proc. of the 15th International Machine Tool Engineers' Conference* (2012)

[10] K. Wegener, S. Weikert and J. Mayr: Age of compensation — Challenge and chance for machine tool industry; *International Journal of Automation Technology*, Vol. 10, No. 4, pp. 609–623 (2016)

[11] S. Ibaraki and Y. Ota: Error calibration for five-axis machine tools by on-the-machine measurement using a touch-trigger probe; *International Journal of Automation Technology*, Vol. 8, No. 1, pp. 20–27 (2014).

[12] B. Bringmann and W. Knapp: Model-based 'Chase-the-Ball' calibration of a 5-axis machining center; *Annals of CIRP — Manufacturing Technology*, Vol. 55, No. 1, pp. 531–534 (2006)

[13] S. Ibaraki, C. Oyama and H. Otsubo: Construction of an error map of rotary axes on a five-axis machining center by static R-test; *International Journal of Machine Tool and Manufacture*, Vol. 51, pp. 190–200 (2011)

[14] S. Ibaraki, Y. Nagai, H. Otsubo, Y. Sakai, S. Morimoto and Y. Miyazaki: R-test analysis software for error calibration of five-axis machine tools — Application to a five-axis machine tool with two rotary axes on the tool side —; *International Journal of Automation Technology*, Vol. 9, No. 4, pp. 387–395 (2015)

[15] M. Tsutsumi and A. Saito: Identification and compensation of systematic deviations particular to 5-axis machining centers; *International Journal of Machine Tools and Manufacture*, Vol. 43, No. 8, pp. 771–780 (2003)

[16] H. Xia, W. Peng, X. Ouyang, X. Chen, S. Wang and X. Chen: Identification of geometric errors of rotary axis on multi-axis machine tool based on kinematic analysis method using double ball bar; *International Journal of Machine Tools and Manufacture*, Vol. 122, pp. 161–175 (2017)

[17] S. Ibaraki, H. Inui, C. Hong, S. Nishikawa and M. Shimoike: On-machine identification of rotary axis location errors under thermal influence by spindle rotation; *Precision Engineering*, Vol. 55, pp. 42–47 (2019)

[18] ISO/CD 230-10.2:2020, Test code for machine tools — Part 10: Determination of the measuring performance of probing systems of numerically controlled machine tools

[19] E. Yanai and S. Ibaraki: Measurement of five-axis kinematic errors under thermal influence by spindle rotation; *Proc. of 2019 Annual Meeting of JSPE Kyushu Branch*, National Institute of Technology, Sasebo College (2019) (in Japanese)

[20] S. Ibaraki: *Volumetric Accuracy of Machine Tools — Kinematic Modelling, Measurement and Compensation of 3D Motion Errors* —, Morikita Publishing Co., Ltd. (2017) (in Japanese)

[21] S. Ibaraki and W. Knapp: Indirect measurement of volumetric accuracy for three-axis and five-axis machine tools: A review; *International Journal of Automation Technology*, Vol. 6, No. 2, pp. 110–124 (2012)

[22] C. Hong and S. Ibaraki: Observation of thermal influence on error motions of rotary axes on a five-axis machine tool by static R-test; *International Journal of Automation Technology,*, Vol. 6, No. 2, pp. 196–204 (2012)

[23] M. Gebhardt, J. Mayr, N. Furrer, T. Widmer, S. Weikert and W. Knapp: High precision greybox model for compensation of thermal errors on five-axis machines; *Annals of CIRP — Manufacturing Technology*, Vol. 63, No. 1, pp. 509–512 (2014)

[24] ISO 230-3:2020 Test code for machine tools — Part 3: determination of thermal effects

Authors

Soichi IBARAKI (Member)

Soichi Ibaraki received the M.Sc. degree in precision engineering from Kyoto University, Kyoto, Japan, in 1996, and the Ph.D. degree in mechanical engineering from the University of California, Berkeley, CA, USA, in 2001. From 2001 to 2006, he was an assistant professor and from 2006 to 2016 he was an associate professor in the Department of Micro Engineering, Kyoto University. In 2016, he joined the Department of Mechanical Engineering Systems, Hiroshima University, as a professor. His current research interests include three-dimensional metrology for the motion of a machine tool and an industrial robot.

Eita YANAI

Eita Yanai received his Bachelor of Engineering degree from Hiroshima University in 2019. He is currently a master course student in Graduate School of Advanced Science and Engineering, Hiroshima University.