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Citation	Precision Engineering , 55 : 42 - 47
Issue Date	2019-01
DOI	10.1016/j.precisioneng.2018.08.005
Self DOI	
URL	https://ir.lib.hiroshima-u.ac.jp/00048777
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Relation	

On-machine identification of rotary axis location errors under thermal influence by spindle rotation

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Abstract
Position and orientation errors of rotary axis average lines are often among dominant error contributors in the five-axis kinematics. Although many error calibration schemes are available to identify them on -machine, they cannot be performed when a machine spindle is rotating. Rotary axis location errors are often influenced by the machine's thermal deformation. This paper presents the application of a non-contact laser light barrier system, widely used in the industry for tool geometry measurement, to the identification of rotary axis location errors, when the spindle rotates in the same speed as in actual machining applications. The effectiveness of the proposed scheme is verified by experimental comparison with the R-Test and a machining test. The uncertainty analysis is also presented.

Key words:
machine tool; metrology; thermal deformation; error calibration; five-axis; tool measurement

1. Introduction

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 [1,2,3], numerous efforts have been reported on the measurement, modelling and compensation of thermal errors. On a five-axis machine tool, the thermal deformation often changes the position and the orientation of rotary axis average lines with respect to the tool's position and orientation [4]. 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 [5]).

Many schemes have been reported to measure position and orientation errors of rotary axis average lines. Their review can be found in [6,7]. Typical ones use the ball bar [8], the R-Test instrument [9], and a touch-triggered probe [10]. The application of the ball bar and the R-Test to rotary axis accuracy tests are now included in ISO 10791-6 [11]. Numerical compensation for location errors of rotary axis average lines is now available in many latest CNCs [12]. Many latest five-axis machines have an automated calibration/ compensation system for position errors of rotary axis average lines by typically using a touch-triggered probe and a precision sphere.

All of them can be performed only when a machine spindle is stopped. The heat generated by spindle rotation can be a dominant contributor to rotary axis location errors. Ref. [10] showed an experimental machining test result showing that location errors of rotary axis average lines can be significantly different in machining operations from those identified when the spindle is stopped. Before performing accuracy tests, the standards [5,11] require a user to perform sufficient machine warm-up. In practice, however, since the tests themselves must be performed with the machine spindle stopped, it can be difficult to ensure that the machine is thermally at the steady-state, no matter how long the warm-up is performed. The machine may be quickly cooled down when the spindle stops for accuracy tests. A good practical example will be presented in Section 3.2.

This paper proposes a scheme to identify position and orientation errors of rotary axis average lines under spindle rotation. To measure the position of a swivelling rotary table at various angular positions with respect to a rotating tool, this paper employs a laser light barrier system, which is widely used in the industry as a tool geometry measurement system. Exactly the same tool as the one used in actual machining processes can be used as the target of the laser light barrier system. The experiment in Section 3.1 will show that some of the rotary axis location errors, estimated by the R-Test, are significantly different from those estimated by the machining test. This can be caused by the thermal deformation due to the spindle rotation during the machining test. The proposed scheme gives the estimates that are closer to those estimated by the machining test.

Thermal tests in ISO 230-3 [13] observe the thermal influence of heat generation in a spindle or a linear axis on the displacement of the tool center point positioned at a single point in the workspace. Numerous research works have been devoted to thermal characteristics of a machine tool spindle, and they mostly focus on the thermal influence on the tool's displacement [14, 15, 16]. In the five-axis kinematics, the thermal influence on the tool's position and orientation should be evaluated with respect to the position and the orientation of rotary axis average lines, since it can dominate the geometry accuracy of the machined workpiece. Some recent studies [17, 18, 19] reported the application of the R-Test to investigate the thermal influence on rotary axis average lines. They focus on thermal influence by the heat generated by the reciprocating motion of a rotary axis. In the R-Test, a machine spindle must have a sphere or a sensors nest, and thus it cannot be performed when the spindle rotates. ISO TC39/SC2 is currently discussing the revision of ISO 230-3 [13] to include the tests to evaluate thermal influence on rotary axis geometric errors by using the R-Test.

2. Proposed test procedure

2.1. Proposed test procedure

A laser light barrier system, the term in [20], is an opto-electronic device using a single light detector. It logs the machine position when a tool blocks the laser beam. In reference to a reference cylinder of the calibrated geometry, various properties of a rotating tool can be measured, e.g. tool length and diameter. Many latest machine tools have a similar instrument as a default tool measuring system. Figure 1 shows a laser light barrier system used in our experiments.

This section considers the five-axis configuration depicted in Fig. 2a. The paper's basic idea can be extended to any five-axis configurations. A tool, which will be used in actual machining operations, is attached to the machine spindle, and is rotated in the same speed as in machining operations. At B=C=0°, the laser light barrier system is fixed on the machine table as shown in Fig. 3a ("At C=0°"), where the laser beam is roughly aligned parallel to

the X-direction. The machine coordinate system (MCS) is defined with its origin at the nominal intersection of B- and C-axes.

1) At C=0°, as shown in Figs. 3a and 3b ("At C=0°"), feed the rotating tool to the laser beam toward i) +Y direction and ii) -Z direction. The laser barrier system detects i) the Y-position in the MCS, denoted by $y_{0,0}$, and ii) the Z-position, $z_{0,0}$.
2) Analogous tests are performed at C=-90° to measure ($x_{0,-90}$, $z_{0,-90}$), at C=-180° to measure ($y_{0,-180}$, $z_{0,-180}$), and at C=-270° to measure ($x_{0,-270}$, $z_{0,-270}$) (see Figs. 3a and 3b).
3) Analogous tests are performed at B=-90° and C=-270° to measure ($x_{-90,-270}$, $z_{-90,-270}$) (see Fig. 3c).
4) Analogous tests are performed at B=90° and C=-90° to measure ($x_{90,-90}$, $z_{90,-90}$).

The proposed scheme uses a laser light barrier system to measure a tool's position with respect to a work table. This principle can be seen essentially the same as the R-Test. Unlike the R-Test, the tool position can be measured only in two directions. A strong advantage is that it can measure a rotating tool, not a non-rotating sphere as in the R-test.

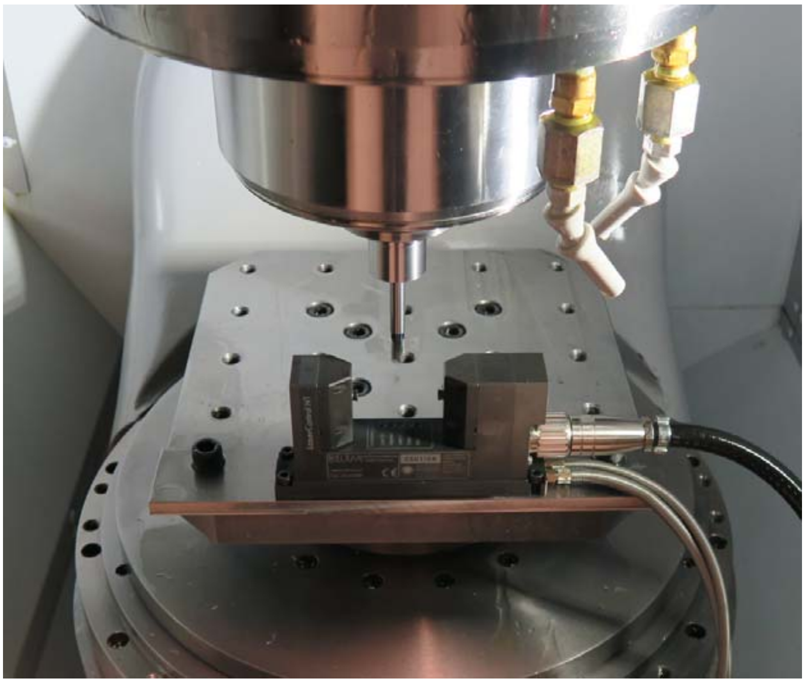


Figure 1. A laser light barrier system (Laser Control Nano NT by Blum- Novotest) and the experimental setup in Section 3.1.

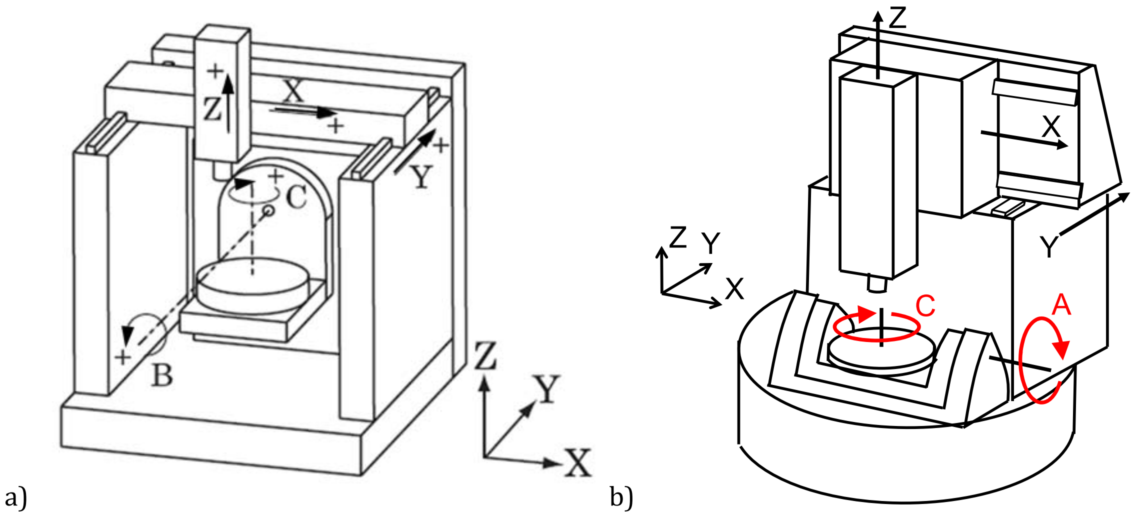


Figure 2. Machine configurations. a) The machine in Sections 2 and 3.1, b) the machine in Section 3.2.

2.2. Identification of location errors of rotary axis average lines

The objective of the proposed scheme is to identify position and orientation errors of rotary axis average lines shown in Table 1. Their definition is described in ISO 230-1 [5] (Table 1 employs different symbols from the ones in ISO 230-1, since they clarify more each symbol's definition in the kinematic model. See [6]). Analogously to many other rotary axis indirect measurement schemes reviewed in [6], geometric errors of linear axes are assumed pre-calibrated and sufficiently small. Their influence will be discussed in Section 4.

The relationship of tool positions measured in the proposed scheme and rotary axis location errors in Table 1 can be formulated as follows:

$$y_{0,0} + y_{0,-180} = 2\delta y_{CR}^{0} - 2z_{0,0}^{*} \cdot \alpha_{CR}^{0} \quad (1)$$

$$z_{0,-180} - z_{0,0} = -2y_{0,0}^{*} \cdot \alpha_{CR}^{0} \quad (2)$$

$$x_{0,-270} + x_{0,-90} = 2\left(\delta x_{BR}^{0} + \delta x_{CB}^{0}\right) + 2z_{0,0}^{*} \cdot \beta_{CR}^{0} \quad (3)$$

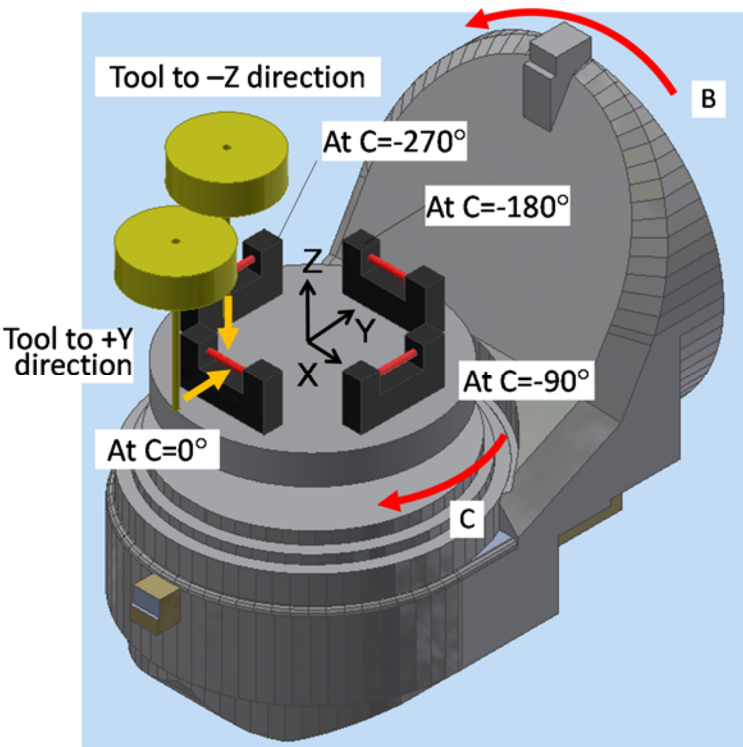
$$z_{0,-270} - z_{0,-90} = -2y_{0,0}^{*} \cdot \beta_{CR}^{0} \quad (4)$$

$$x_{90,-90} + x_{-90,-270} = 2(\delta x_{BR}^{0} - y_{0,0}^{*} \cdot \beta_{CR}^{0}) \quad (5)$$

$$z_{-90,-270} - z_{90,-90} = 2\delta x_{CB}^{0} \quad (6)$$

$$z_{-90,-270} + z_{90,-90} = -2(y_{0,0}^{*} + r^{*}) + 2\delta z_{BR}^{0} \quad (7)$$

where $(y_{0,0}^*, z_{0,0}^*) \in \Re^2$ represents the laser spot's nominal position on the tool at B=C=0° (small error in it would not influence much the estimation of rotary axis location errors). $r^* \in \Re$ represents the tool radius, which should be pre-calibrated by using the same laser light barrier system. By solving Eqs. (1) to (7), rotary axis location errors in Table 1 can be identified. Eqs. (1) to (7) can be derived by using the rigid-body five-axis kinematic model, which has been used as the basis of many previous works, e.g. [4,8,9,10,14,15,16].



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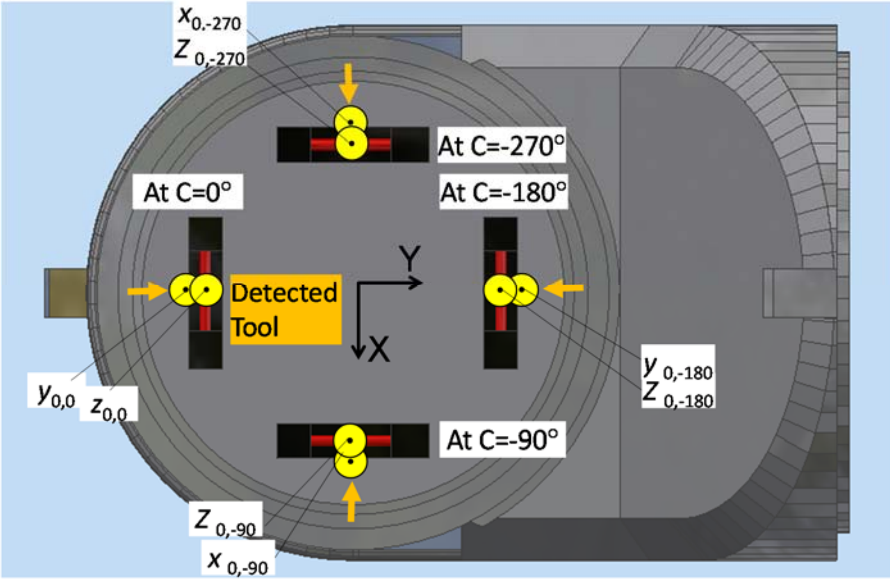
b) 

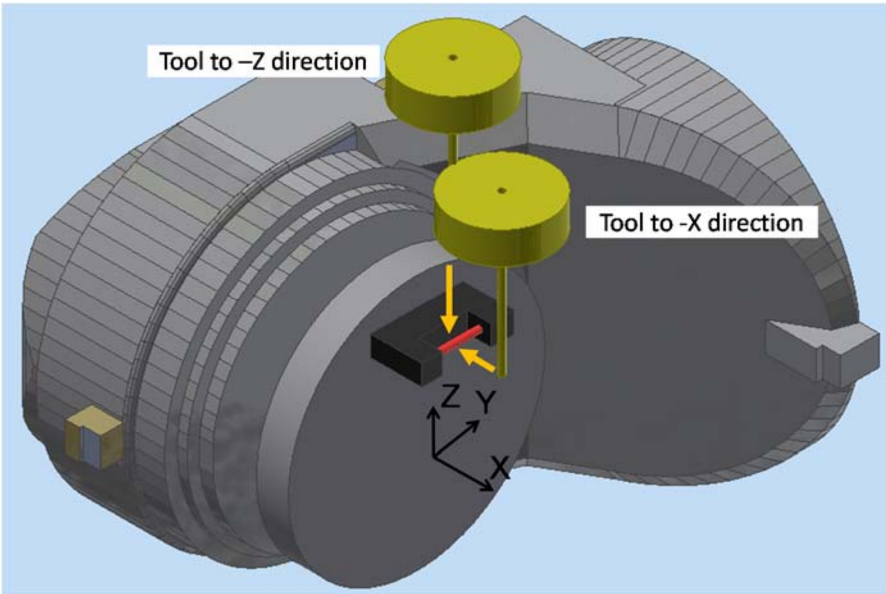
c) 

Figure 3. Proposed test setup. a) at B=0° (C=0, -90, -180, and -270°), b) at B=0° shown in the XY plane, c) at B=-90° and C=-270°.

3. Experiments

3.1. Comparison with the static R-test and the machining test

The proposed test was performed on a five-axis machine in Fig. 1a. Figure 1 shows the experimental setup. A cylindrical end mill of the diameter 8 mm (with corner radius R0.5 mm) was used. The tool length was L=105.66 mm. The spindle speed was 12,000 min^{-1} and the feed per revolution was 0.25 μm in the laser barrier system measurement. The positioning resolution of the machine, and thus the measurement resolution, was 1 μm. The tool's nominal position at B=C=0° was ($y_{0,0}^*$, $z_{0,0}^*$)= (-142, 77) mm in the MCS. Table 1 (the column "Identified by proposed scheme") shows the estimated rotary axis location errors.

For experimental comparison, the R-Test cycle was performed on the same machine to identify the same location errors in Table 1 (the column "Identified by R-test"). The R-Test setup is shown in Fig. 4. The measuring instrument, the measurement procedure, and the algorithm to identify rotary axis location errors, are presented in [9, 21, 22]. No spindle warm-up was performed before the R-Test cycle.

Finally, to estimate rotary axis location errors under actual machining operations, the pyramid-shaped machining test, proposed in [4, 23], was performed. Figure 5 illustrates the machining procedure [4]. Figure 6 shows the machining test setup and the finished test piece. The rotary axis location errors are identified by the measured geometry of the finished test piece as shown in Table 1 (the column "Identified by machining test").

All the estimates in Table 1 indicate that this machine did not have significant rotary axis location errors, and thus the difference was not very clear. Still, there are larger difference between the estimates by the R-test and the machining test; larger difference is with δz_{BR}^0 (9.4 μm) and α_{CB}^0 (29.7 μrad). In the R-test, the spindle was fixed. This difference is likely caused by thermally-induced change in the Z-position of the tool center point, as well as the orientation of the spindle axis around the X-axis. Many estimates by the machining test are closer to the ones by the proposed scheme: the maximum difference was 3.6 μm in δx_{BR}^0. To experimentally clarify the contribution of thermal deformation to the uncertainty in the R-test, the spindle's thermal deformation under spindle rotation can be actually measured by the test described in ISO 230-3 [13]. Further investigation on the thermal influence on the uncertainty in the R-Test will be left for our future research.

Table 1. Definition of rotary axis location errors and their estimates by the proposed scheme, the R-test, and the machining test.

Symbol [6]	Description	Identified by proposed scheme	Identified by R-test	Identified by machining test
δx_{BR}^0	X-position of B-axis average line	-1.2 μm	0.3 μm	-4.8 μm
δz_{BR}^0	Z-position of B-axis average line	2.4 μm	-9.1 μm	0.3 μm
δy_{CR}^0	Y-position of C-axis average line	-0.5 μm	-9.3 μm	0.0 μm
δx_{CB}^0	Intersection error of C- to B-axis	1.5 μm	0.7 μm	0.3 μm
α_{CR}^0	Squareness of C- to Y-axis	-7.1 μrad	-31.4 μrad	-1.7 μrad
β_{CR}^0	Squareness of C- to X-axis	-5.7 μrad	-15.7 μrad	-1.7 μrad

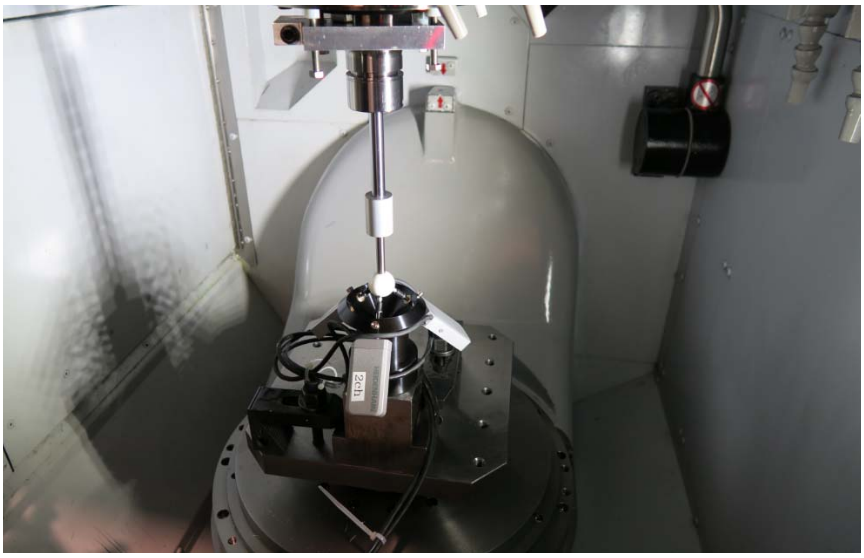
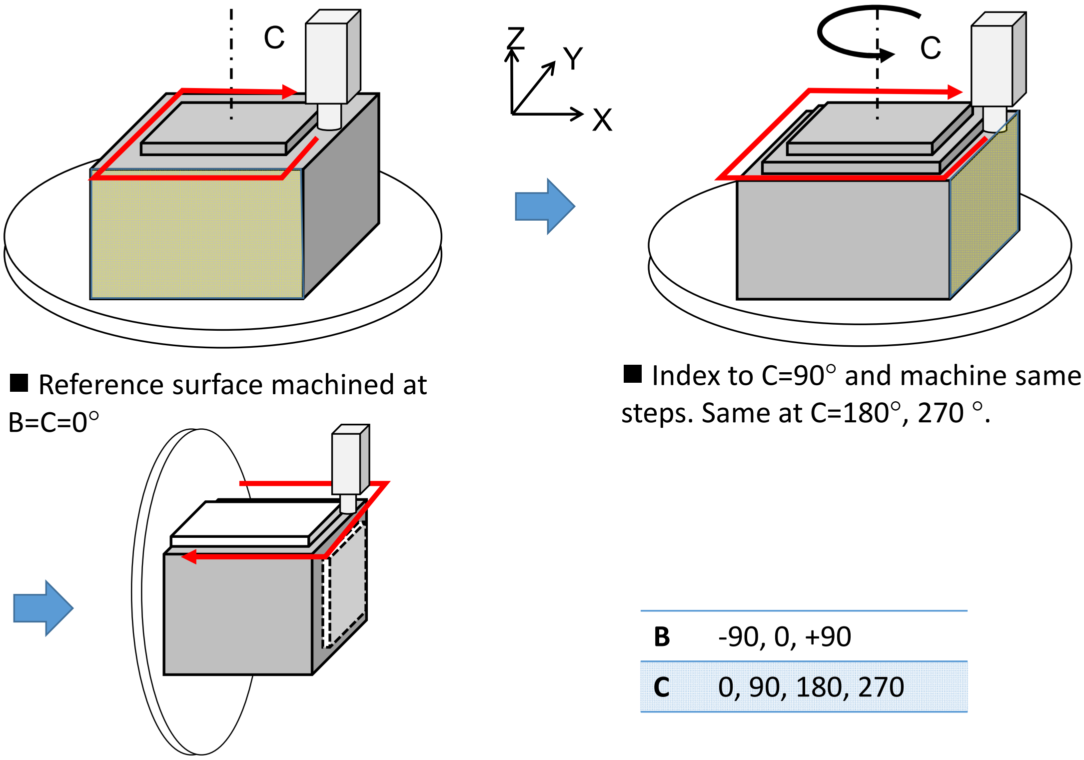


Figure 4. R-Test setup.



B	-90, 0, +90
C	0, 90, 180, 270

Figure 5. Machining test procedure [4]

Figure 6. Machining test setup (at B=0°)

3.2. Thermal deformation test

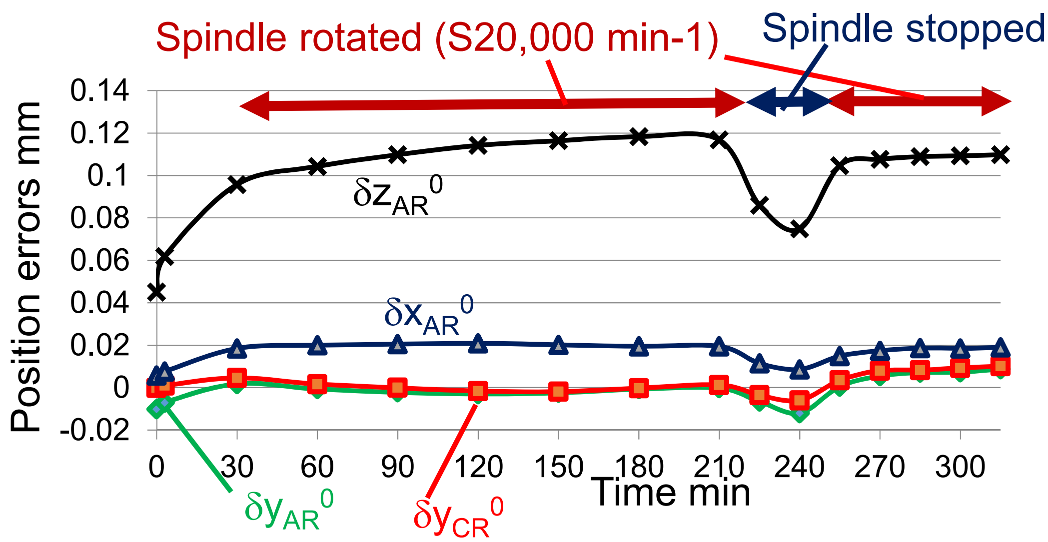
This subsection demonstrates a thermal test to evaluate the influence of continuous spindle rotation on rotary axis location errors. A five-axis machine of the configuration in Fig. 2b was measured. The same laser light barrier system was used. A cylindrical end mill of the diameter 10 mm was used. All thermal compensations in the machine's controller was turned off.

The test procedure was as follows:

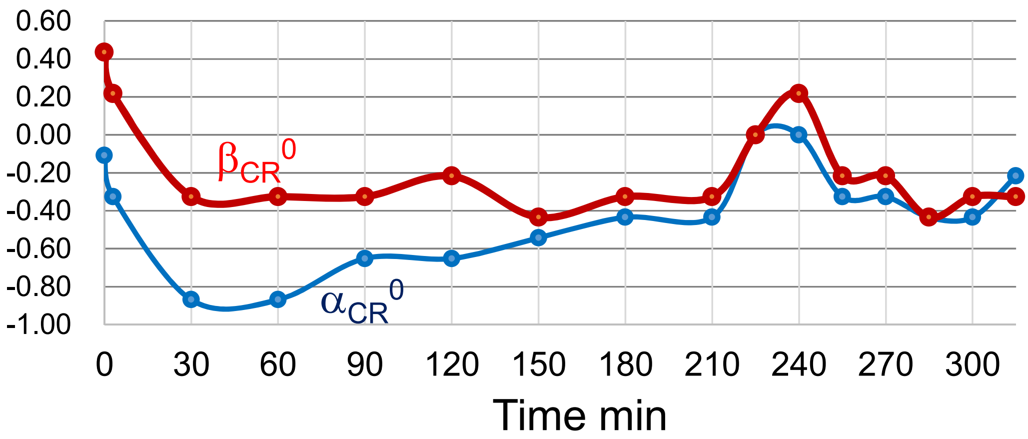
1) Start rotating the spindle in 20,000 min^{-1} for 30 min.
2) Then, while the spindle keeps rotating in the same speed, perform the proposed test in Section 2.1.
3) Repeat 1) and 2) for total 210 min.
4) Stop the spindle, and perform the proposed test 15 and 30 min later (the spindle rotates only during the proposed test).
5) Rotate the spindle again in 20,000 min^{-1} and perform the proposed test in every 15 min until 320 min.

Figure 7 shows rotary axis location errors estimated by the proposed scheme.

- The Z-position of A-axis average line, δz_{AR}^0, was displaced by about 80 μm by the spindle rotation for 210 min. This shows the spindle's thermal displacement to –Z direction.
- The spindle was also deformed to -X-direction by about 20 μm for 210 min (δx_{AR}^0). The thermal influence on the orientation of C-axis average line is also observed in Fig. 7b.
- When the spindle was stopped, δz_{AR}^0 was reduced by about 45 μm for 30 min. This shows that the machine was quickly cooled down and deformed when the spindle stopped, even after spindle was warmed up for 210 min.



a)



b)

Figure 7. Rotary axis geometric errors estimated in the thermal test. a) position errors, b) orientation errors.

4. Uncertainty analysis

The experiment in Section 3.1 only compares the three identification schemes within each scheme's measurement uncertainty. To validate the proposed scheme, this section presents the uncertainty analysis of the proposed scheme. The following uncertainty contributors are considered:

1) *Error motions of linear axes:* The proposed formulations in Section 2.2 assume negligibly small error motions of linear axes. Similarly as many "indirect" rotary axis error calibration schemes, linear axis error motions can be major uncertainty contributors [24]. The uncertainty contribution of each linear axis error motion is modelled in the same way as presented by Bringmann et al. in [24, 25]. Each linear axis error motion is modelled as a Fourier series. The standard deviation of each Fourier coefficient is given based on accuracy test results by the machine manufacturer. Its influence to the probed positions is calculated by the machine kinematic model.

2) *Probing uncertainty*: In the proposed scheme, the tool can be displaced from the laser light's focus point due to

rotary axis location errors and other error motions. The influence of the tool's position and orientation from the laser light focus point on the probing repeatability was experimentally investigated. When the tool's displacement is within 20 μm and the orientation error is within 10 mdeg, the repeatability of the laser light barrier system was u_{probe}=2.4 μm (k=2) (the machine's positioning resolution is 1 μm). When the tool's position and orientation are the same, its repeatability is 0.1 μm (2σ), according to the manufacturer's catalogue.

3) *Uncertainty in tool radius*: Eq. (7) contains the tool radius, r^*. Its uncertainty is mostly caused by the uncertainty in the reference tool's geometry.

Table 2 shows the expanded uncertainty (k=2) in the estimation of rotary axis location errors evaluated by using the Monte Carlo simulation [26] applied to the formulations in Section 2.2. The combined influence of randomly-given uncertainly contributors, described above, on each rotary axis location error, is represented as the normal distribution of the standard deviation equal to the half (k=2) of the uncertainty presented in Table 2.

Table 2. Uncertainty (k=2) in estimated rotary axis location errors.

Symbol	Uncertainty (k=2)	Symbol	Uncertainty (k=2)
δx_{BR}^0	6.3 μm	δx_{CB}^0	2.4 μm
δz_{BR}^0	10.7 μm	α_{CR}^0	20.0 μrad
δy_{CR}^0	2.8 μm	β_{CR}^0	19.6 μrad

5. Conclusion

This paper proposed a scheme to identify position and orientation errors of rotary axis average lines in a five-axis machine tool when a machine spindle continuously rotates. To the authors' knowledge, all the schemes proposed in the literature, except for the machining tests, e.g. the one tested in Section 3.1 [4, 23], can be performed only when the spindle is stopped. The experiment in Section 3.2 shows that, even after the spindle was warmed up for 210 min, some of rotary axis location errors significantly changed in 30 min, once the spindle was stopped. This example clearly shows a potential issue with previous schemes.

Similarly as many "indirect" rotary axis error calibration schemes proposed in the literature, linear axis error motions can be major uncertainty contributors. This paper studied their contribution to the uncertainty in the estimation of rotary axis location errors, as well as the contribution of probing uncertainty and the uncertainty in tool radius calibration.

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