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Extended discrete R-Test as on-machine measurement cycle to separate the thermal errors in Z-direction

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Abstract
This paper presents an on-machine measurement cycle based on the discrete R-Test, which separates the thermal errors of the different machine components in Z-direction. The error separation in Z-direction is particularly required for five-axis machining processes. The extended discrete R-Test separates the thermal position and orientation errors of a vertical rotation axis, the thermal errors of the machine table and the thermal position errors of the spindle and a horizontal rotation axis. The new measurement approach provides the foundation for more precise compensation results without requiring a more complex measurement setup.

Thermal error, on-machine measurement, error separation

1. Introduction

Five-axis machine tools are characterized by a high productivity for complex workpieces because of the reduced reclamping effort compared to 3-axis machine tools. However, this results in a more complex kinematic chain of the machine tool and a larger number of geometrical and thermal errors due to the two additional rotation axes. Among the different error sources, thermal errors have the most significant impact on the accuracy of machine tools [1].

Many different measurement strategies have been developed to evaluate the thermal behaviour of spindles and rotary axes. Commonly, the measurement setup described in ISO-230-3 [2] is applied to identify the thermal errors of spindles. Brecher et al. [3] propose an extension of this measurement setup to determine the thermal errors of a rotary axis and a spindle. The resulting measurement setup consists of five mandrels mounted on the machine table and a sensor setup with five displacement sensors fixed in the spindle. Furthermore, the R-Test developed by Weikert [4] is applicable to measure the thermal position and orientation errors of rotary axes. Ibaraki and Hong [5] propose a method based on the R-Test to evaluate the thermal influences on the error motions of a rotary axis. Gebhardt et al. [6] introduce a discrete R-Test to measure the thermal position and orientation errors of a vertical rotary axis and the thermal error of the machine table in axial and radial direction. Brecher et al. [7] developed a measurement method based on a dynamic R-Test to identify the volumetric thermal errors of five-axis machine tools. Ibaraki et al. [8] use a non-contact laser measurement system which is fixed on the rotary table to obtain the location errors of a rotary axis. This setup allows to measure the deviations at the same spindle speed as in the actual machining application.

Most of the measurement strategies for the thermal analysis of rotary axes need a specific measurement setup or expensive measurement devices. Therefore, Blaser et al. [9] present an on-machine measurement strategy for the discrete R-Test by using a touch trigger probe fixed in the spindle and a precision sphere mounted on the machine table. This on-machine measurement cycle identifies the thermal errors of a horizontal rotation axis which can be used for the Thermal Adaptive Learning Control (TALC) methodology [9,10].

The version of the on-machine measurement strategy described in [9] does not provide a detailed error separation in Z-direction between the different machine tool components. Consequently, the change of the effective direction of certain thermal errors is not considered for rotations of the swivelling axis. For robust thermal compensation results, it is required that the thermal errors are properly assigned to the different components so that they are also precisely compensated when the swivelling axis is rotated.

This paper presents an extended discrete R-Test for vertical rotation axes which enables a detailed error separation in Z-direction between errors with permanent and changing effective direction. Section 2 describes the methodology of the on-machine measurement approach and Section 3 presents the experimental results. To close the paper a conclusion and outlook is given in Section 4.

2. Methodology

The discrete R-Test for vertical rotation axes identifies the thermal position and orientation errors of a C-axis and the axial and radial thermal expansion of the machine table. Consequently, the axial thermal expansion of the machine table also includes the thermal error of the spindle and the position error of the horizontal rotational axis. In the case of the extended discrete R-Test the axial thermal growth of the machine table is clearly separated from the thermal error of the spindle and the thermal position error of the swivelling axis. Therefore, the extended discrete R-Test for vertical rotation axes enables to determine in total ten thermal errors, which are summarized in Table 1.

Table 1 Thermal errors identified by the extended discrete R-Test according to ISO 230-7 [11] with the addition of the machine table related errors according to [12]

Error	Description
E_{X0C}	Error of the position of C in X-axis direction
E_{Y0C}	Error of the position of C in Y-axis direction
E_{Z0T}	Position error of the table surface in Z-axis direction
E_{R0T}	Radial error of the functional surface table
E_{A0C}	Error of the orientation of C in A-axis direction: Squareness of C to X
E_{B0C}	Error of the orientation of C in B-axis direction: Squareness of C to Y
E_{C0C}	Zero position error of C-axis
E_{Z0S}	Error of the position of the spindle in Z-axis direction
E_{Y0A}	Error of the position of the A in Y-axis direction
E_{Z0A}	Error of the position of the A in Z-axis direction

2.1. Measurement cycle

The proposed measurement cycle combines laser measurement system and touch trigger probe measurements for a detailed separation of the thermal errors in Z-direction. Figure 1 illustrates the measurement procedure for the extended discrete R-Test. In the first step, the axial thermal error of the spindle is measured by a laser measurement system. However, the error separation between the spindle and the A-axis can only be realised if the laser measurement system is not mounted on the machine table. In the following, the measurements are performed using a touch trigger and a precision sphere placed on the machine table. The sphere is positioned at the circumference of the machine table to ensure a maximum distance from the rotational centre. The X-, Y-, and Z-positions of the sphere are measured at four positions reached by rotating the C-axis and two positions reached by additionally turning the A-axis. For the two A-axis measurements, the A-axis is turned to 90° and -90°. Thus, the proposed measurement cycle extends the standard discrete R-Test by a spindle measurement and two additional A-axis positions. The measurement time of the extended R-Test including all tool changes is around 2.5 minutes.

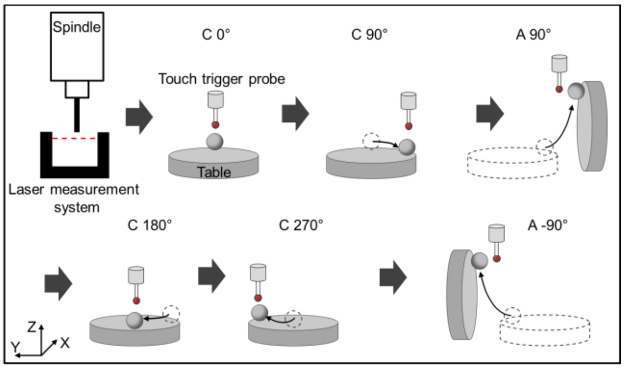

Figure 1. Measurement procedure of the extended discrete R-Test to identify the thermal position and orientation errors of the C-axis, the thermal errors of the machine table and the thermal position errors of the spindle and the A-axis.

2.2. Mathematical model

The calculation of the thermal position and orientation errors of the C-axis and the axial and radial thermal error of the machine table are described in [12]. The calculation of the axial thermal error of the machine table in Z-direction for the standard discrete R-Test is shown in Eq. (1).

$$E_{Z0T_i} = \frac{1}{4}\sum_{k=1}^{4} Z_{t_i,C_k} - \frac{1}{4}\sum_{k=1}^{4} Z_{t_1,C_k} \tag{1}$$

Compared to Eq. (1) the three additional measurement steps of the extended discrete R-Test allow a more accurate estimation of the thermal errors in Z-direction. The measurement of the laser measurement system is directly used to calculate the error E_{Z0S} as described in Eq. (2).

$$E_{Z0S,i} = -(Z_{t_i,laser} - Z_{t_1,laser}) \tag{2}$$

The thermal error of the spindle is defined at the tool side such that an elongation of the spindle results in an error in negative Z-direction. The thermal error of the spindle includes the thermal elongation of the spindle and the displacement of the laser measurement system due to thermal influences. The two additional measurement positions of the A-axis at 90° and -90° result in a reversal measurement in Y-direction, which enables an error separation between E_{Z0T} and E_{Y0A}. The thermal error E_{Z0T} changes its effective direction depending on the rotational angle of the A-axis. In contrast, the thermal error E_{Y0A} appears in the same direction at both rotation angles. Therefore, E_{Y0A} and E_{Z0T} can be separated by considering the Y-coordinate of the two additional positions. Eq. (3) defines the calculation of the thermal error E_{Z0T}.

$$E_{Z0T_i} = \frac{1}{2}\left(Y_{t_i,A_{-90}} - Y_{t_i,A_{90}}\right) - \frac{1}{2}\left(Y_{t_1,A_{-90}} - Y_{t_1,A_{90}}\right) \tag{3}$$

Eq. (4) is used to calculate the thermal error E_{Y0A}.

$$E_{Y0A_i} = \frac{1}{2}\left(Y_{t_i,A-90} + Y_{t_i,A90}\right) - \frac{1}{2}\left(Y_{t_1,A-90} + Y_{t_1,A90}\right) \tag{4}$$

The measurement data in Z-direction is required to determine the thermal error E_{Z0A}. However, the measurement results also depend on the thermal errors E_{R0T} and E_{Z0S}. These influences must be eliminated by subtracting them as shown in Eq. (5).

$$\begin{aligned} E_{Z0A_i} = \frac{1}{2}\left(Z_{t_i,A_{-90}} + Z_{t_i,A_{90}}\right) - \frac{1}{2}\left(Z_{t_1,A_{-90}} + Z_{t_1,A_{90}}\right) \\ + E_{Z0S_i} - E_{R0T_i} \end{aligned} \tag{5}$$

The thermal error E_{Z0A} describes the error between the laser measurement system and the position of the A-axis. However, a possible thermal zero position error of the A-axis has no influence on the identified E_{Z0A} because it is eliminated by the reversal measurement.

If no laser measurement system is available, it is not possible to separate the thermal errors of the spindle and A-axis in Z-direction. This separation is not required for the compensation but neglecting it results in a more complex compensation model for this thermal error due to a larger number of relevant inputs. For that case the calculation of the thermal error E_{Z0A} + E_{Z0S} is given in Eq. (6).

$$\begin{aligned} E_{Z0S_i} + E_{Z0A_i} = \frac{1}{2}\left(Z_{t_i,A_{-90}} + Z_{t_i,A_{90}}\right) \\ - \frac{1}{2}\left(Z_{t_1,A_{-90}} + Z_{t_1,A_{90}}\right) - E_{R0T_i} \end{aligned} \tag{6}$$

3. Experimental Results

The kinematic chain of the investigated machine tool can be described according to ISO 10791-2 [13] as following:

V [w – C' – A' – X' – b – Y – Z – S – t].

The laser measurement system of the considered machine tool is placed in the tool magazine. During the experiment, the spindle and the C-axis are rotated over 72 h with two randomly generated speed profiles. Figure 2 shows the speed variation for the spindle and the C-axis and the measured temperatures. The speed of the spindle varies between 159 and 10’884 rpm and the speed of the C-axis is between 9 and 117 rpm. During the experiment a five minutes thermal load case interval and the measurement interval alternate.

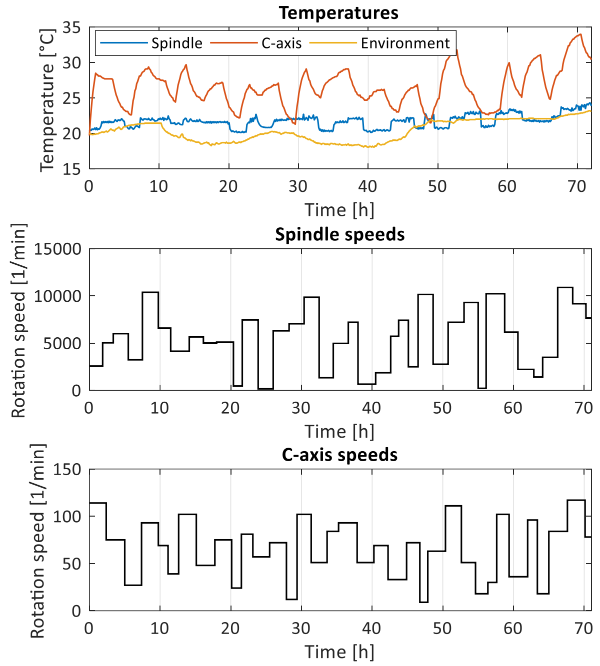

Figure 2. Speed profiles of the spindle and the C-axis and the measured temperatures.

Figure 3 presents the thermal error in Z-direction measured with the standard discrete R-Test for vertical rotation axis. Commonly, this error is described as thermal error of the machine table in axial direction. However, this represents the superposition of the thermal errors at the tool and the workpiece side. It is also apparent in Figure 2, that the underlaying source of the thermal error in Z-direction is a superposition of the two speed profiles and the changing environmental influences.

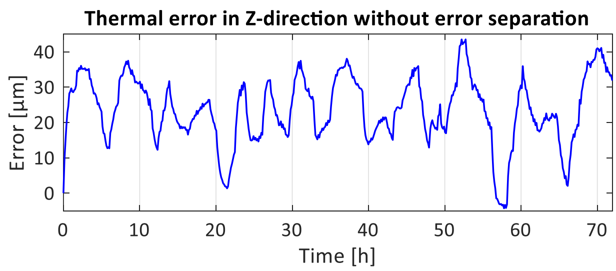

Figure 3. Error in Z-direction without separating the different influences.

Figure 4 illustrates the separated thermal errors in Z-direction obtained from the extended discrete R-Test. The thermal error E_{Z0S} relates to the speed variations of the spindle and the thermal error E_{Z0T} is mainly influenced by speed variations of the C-axis. The thermal error E_{Z0A} depends significantly on the environmental temperature. Consequently, the error separation enables a more detailed analysis of the thermal errors of the different machine components. Approximately one-half of the thermal error in Z-direction measured with the standard discrete R-Test corresponds to the spindle and the other half to the machine table. If the accumulated error in Z-direction was applied for thermal compensation, this would result in inaccurate compensation results when the swivelling axis is turned. This compensation error would be up to 26 µm in the conducted experiments.

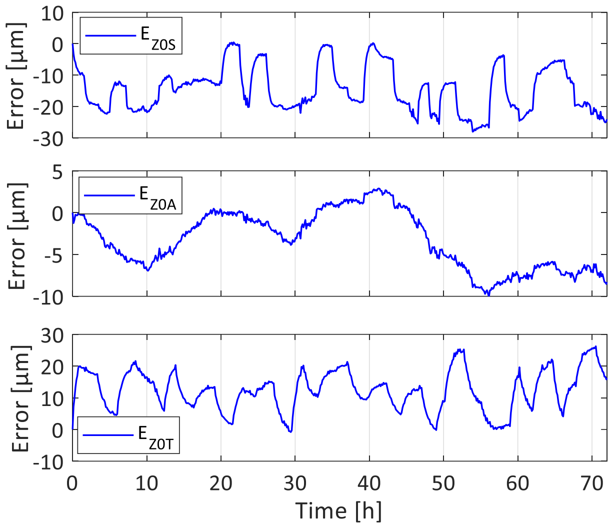

Figure 4. Separated errors in Z-direction of the spindle, A-axis and the table.

As described in Section 2.2 the extended discrete R-Test is also applicable if no laser measurement system is available on the considered machine tool. Figure 5 shows the error separation for this modified approach. The thermal error, which permanently appears in Z-direction, is the superposition of the thermal errors E_{Z0S} and E_{Z0A}. This thermal error must be compensated at the tool side and the thermal error E_{Z0T} should be compensated at the workpiece side.

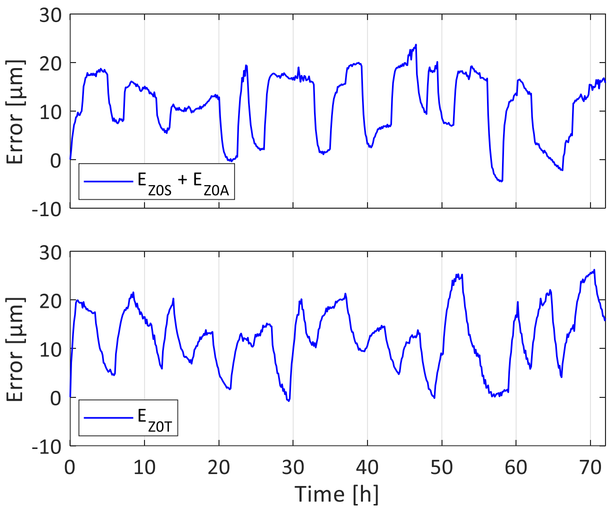

Figure 5. Separation of the errors in Z-direction without using the laser measurement.

4. Conclusion and Outlook

The extension to the discrete R-Test provides a detailed separation of the thermal errors in Z-direction so that the thermal errors are assigned to the correct machine components. This is especially important for five-axis machine tools when the swivelling axis is used in the machining process and a reorientation of the machine table takes place. The conducted experiments show exemplarily that in the case of the investigated machine tool a compensation without the error separation results in compensation values which are around 50 % off. In the future, the on-machine measurement approach will also be extended to the orientation errors of the A-axis.

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