Analysis of spatial and temporal dependencies of the TCP-dislocation measurement for the assessment of the thermo-elastic behavior of 3-axis machine tools

C. Brecher[1], M. Klatte[2], F.Tzanetos[2]
[1]*Machine Tool Laboratory (WZL), RWTH Aachen University, Germany*
[2]*Fraunhofer Institute for Production Technology, Germany*

Abstract

It is common to investigate the thermo-elastic behavior of machine tools by measuring the 3D-dislocation of the Tool Center Point (TCP) under several loading conditions. According to the ISO 230-3 standard, this can be achieved with extensive measurement procedures and expensive equipment. Based on the investigation framework stipulated by this standard and the R-Test measuring equipment, a novel method is applied that enables a holistic investigation of the thermal effects in an automated manner. This method automates the setup of the measuring instrument and simplifies the measurement in different positions in the workspace. The investigation of temporal and spatial dependencies of the TCP-dislocation is carried out on a 3-axis machine tool. Additionally, various loading modes are applied in accordance to the aforementioned standard. The strong influence of the tool position in the working space leads to the conclusion that zero offset and distortion are two different error types that should be discriminated from each other. This error separation enables a holistic as well as more intuitive understanding of the thermal effects on the machine tool. The possible sources of thermal-induced errors could thus be deduced for the investigated 3-axis machine tool and lead to anticipated conclusions for the particular construction.

1 Introduction

The assessment of the thermo-elastic behavior of machine tools has been a major topic in precision engineering and metrology, since Bryan first summarized the effects and measurement procedures of thermal errors in 1968 [1;2]. However, the increased demands for productivity and precision of the metal-cutting industry in the past 20 years have led to more dedicated and extensive research in this topic. According to Mayr et al. [3], the machine tool users have realized that "comparable machine tools can show significantly different thermal errors and that in some machine tools most of the energy supplied to the machine tool is used to stabilize the temperatures". This means that the task to ensure that the machine tools are performing to their quoted accuracy specifications is now of paramount importance, although still highly complex. Due to the increased awareness of the industry, both machine tool users and manufacturers carry out such assessment measurements [4]. This has led to a rapid development of new measurement techniques that are faster, more automated, easier, cheaper and more precise.

This extensive research has also led the scientific society to estimate that up to 75% of geometrical workpiece errors can be traced to thermal issues in machine tools, as it is summarized in [3]. This fact can be illustrated by the thermal distortion of a C-frame, typical for horizontal milling machines. Although for some levels of precision the thermal behavior can be ignored (e.g. due to the difference of the time constants of the process and of the thermal effects), when the accuracy of the workpiece becomes demanding, then the consequence of thermal effects dominates. The predominant distortion of a C-frame milling machine is the heating of the column, causing tool-workpiece relative errors. This will occur though after some time due to the massive casting comprising the C-frame. The importance of thermal errors for the industry demands therefore novel efficient solutions to investigate the thermo-elastic behavior of machine tools, which however still must comply with ISO 230-3 [5]. This paper proposes a novel approach based on R-Test measuring equipment. After reviewing the theoretical background of investigating thermal errors in machine tools in Chapter 2.1, as well as the state of the art in measurements based on the R-test equipment in Chapter 2.2, the new method is introduced in detail in Chapter 2.3. The measurement setup of the experimental investigations is described in Chapter 3. Then, measurements that were carried out with the proposed method are presented in Chapter 4. Interpretations of these measurements are also derived. Finally, the conclusions and the outlook for future research are summarized in Chapter 5.

2 Investigation of Thermal Errors in Machine Tools

According to ISO 1 [6], dimensions of objects are given only at 20°C. A change in temperature results in a change in dimension for most engineering materials. The role of metrology standards, such as ISO 230-3, is to determine the effect of temperatures other than 20°C on an object´s dimensions. The investigation of thermal errors in machine tools identifies these effects at the Tool Center Point (TCP), i.e. the point of contact between tool and workpiece, whose dislocation (translational and angular) characterizes the overall machine tool accuracy. The practical goal of this investigation is to determine whether a thermally induced error is large enough to be of concern. Hence, international standards are needed to stipulate universal acceptance criteria that must be met by all machine tools depending on the application.

The relevant standards developed within the past two decades to fulfill the necessary roles are: a) ISO 230-3 [5] published in 2007, prescribes a standardized methodology for the assessment of the thermo-elastic behavior of machine tools. b) ISO 10791-10 [7] published in 2007, specifies tests for the assessment of machining centers and their positioning systems, without defining acceptance criteria. c) ISO 13041-8 [8] published in 2004, specifies tests for turning centers and numerically controlled turning machines as well as acceptance criteria for the test results. ISO 10791-10 and ISO 13041-8 are both based on the stipulations of ISO 230-3 and are specific to the defined machine types. This paper is focused to

3-axis milling machines; hence the detailed consideration of solely the ISO 230-3 standard is henceforth sufficient.

2.1 Measuring Equipment, Setup and Procedures in ISO 230-3

Essentially the tests are concerned with monitoring the displacement of the high precision test mandrel which has been mounted in the spindle of the machine tool. With the five-probe configuration displacements may be monitored in XI, X2, Yl, Y2 and Z, providing radial error, axial error, and thermal tilt information for spindle test, or displacement and tilt error in case of tests without rotating spindle. The non-contact capacitive transducers are set up to ensure that they are operating at their mid-range point so that drifts either side of this mid-point can be observed. Ambient air temperature is also measured in the close vicinity of the machine and at the same elevation as the spindle nose, while temperatures may also be monitored on the machine table and as close as possible to the front spindle bearing. All displacements and temperature sensors are interfaced to the data acquisition equipment so that thermal distortions and temperature changes can be monitored and recorded over fixed time intervals.

The standard stipulates three kinds of tests: a) The Environmental Temperature Variation Error (ETVE). b) The determination of the thermal distortion caused by rotating spindle. c) The determination of the thermal distortion caused by moving linear axes. In the first test of ETVE, the effects of environmental temperature changes on the machine tool are slow, but they affect the entire working space, thus leading to global and not only local deformation. They are indicative to the suitability of location of the machine, since this is an important communication topic between machine tool manufacturer and operator. Machine tools are suggested to be sited in an area where the temperature of the environment can be accurately controlled to 20°C and that the machine should be protected from external radiations such as sunlight. The second test is performed to identify the effects of the internal heat source of the spindle. Most of the interest in thermally induced errors in machine tool systems is directed to the behavior of spindles, since they generally operate at high speeds for various time periods and various loads depending on the nature of the part and the process. The third test is performed to identify the effects of the internal heat source of the linear axes.

The internal heat sources have the following properties that differentiate them from external heat sources analyzed with the ETVE-tests: a) Characteristic of local deformation of the machine tool structure, hence leading to displacements that affect only partially the working volume. b) Change faster than those in the ETVE-tests. c) Less predictable, due to their complexity and versatility.

Usually a test mandrel is clamped in the spindle and a measurement setup with five displacement measurement devices is fixed onto the workpiece table. In the case of linear-axis tests, two sensor nests are required. The following recommendations are given concerning the test equipment: a) A displacement measuring system with adequate range, resolution and accuracy. b) Temperature sensors with sufficient resolution and accuracy. c) Precision test mandrel, preferably made of steel. d) Fixtures or sensor nests in which to mount the displacement transducers, constructed also from steel.

2.2 State of the Art of Measurements Based on R-Test Equipment

The intensive focus of both research and industry in the past two decades has already led to several alternative measuring devices and setups that promise faster results and more information content [9]. As Mayr et al. [3] also explain, the challenges inflicted on all novel concepts are especially high. All relevant geometric parameters of the machine tool have to be measured, which means that already 21 error parameters have to be determined for the linear axes of a three-axis machine. The spindle exhibits further errors which can have a significant influence on accuracy. The measurements have to be carried out along the entire working volume to catch all spatial dependencies. Similarly, the time span of the measurements has to be kept as short as possible, in order that the loading conditions are not interrupted for long and thus catch the temporal dependencies with satisfactory precision. The measuring equipment has to exhibit low measurement uncertainty.

The R-Test equipment has been developed for measuring geometric errors of five-axis machine tools [10-13]. The main component is a measuring probe with three displacement sensors. With this measuring device, the dislocation relative to a reference ball can be probed. This design is also suitable for other applications, also for three axis machines, such as checking the positioning accuracy of linear and rotary axes [13-15]. Similarly, the equipment can be used for thermal characterization of machine tools. The reference balls can be placed almost freely in the working volume. In this way, the TCP-displacement at the ball positions can be determined by repeated measurements. A large number of probing positions can be realized with low effort, since not the number of sensors is increased, but the number of reference balls. This is certainly a limiting factor for measurement methods based on test mandrels and sensor nests, since the number of sensors has to be increased for each added position. New designs of the R-test utilize wireless data transmission. Therefore, the probe can be easily changed like a regular tool or touch probe. Even complex measurement procedures can be automated, since no manual operation is required after the probe has been properly set up in the respective machine. Examples of using R-Test equipment for thermal characterization can already be found in research [16;17]. In contrast to former methods, which utilize 5-axis kinematics in order to cover a large working volume, the approach in this paper is to simplify the measurement process, so that independent information about the thermal behavior can be obtained in a short time window.

2.3 Novel Approach Based on R-Test Equipment

In order to achieve this, a cross configuration of reference balls is beneficial (see Figure 1). Four reference balls are placed on the machine’s working table, so that a cross is shaped, which covers the whole working plane. The reference balls can be probed with a single probe (R-Test device) in the tool holder in regular time intervals, determining TCP dislocation in X-, Y- and Z-direction. As a trade-off, at each position the tilt errors cannot be determined.

Between the probing cycles, the machine can be thermally loaded, cooled or be tested according to an ETVE test. Not only linear axis motion, but also spindle rotation can be used as thermal load, since the probe can be loaded into the spindle just for measuring.

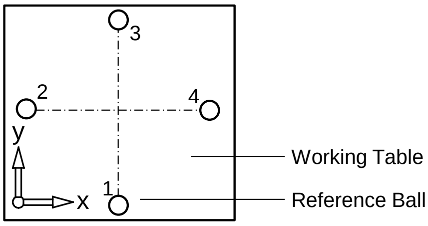

Figure 1: Proposed cross configuration of reference balls on working table

The zero-point shift can be calculated by determining the center of geometry of the dislocation values, where N is the number of measured positions and δ_i are the individual dislocation measurements at each position.

$$\vec{\delta}_{NP} = \frac{1}{N}\sum_{i=1}^{N}\vec{\delta}_i$$

The distortion error can, in the case of a cross-configuration of the measurement points, be calculated by taking the relative dislocation of opposing balls into account. The following formulae can be used to obtain the distortion errors in X- and Y-direction for the given measuring configuration. The variables l_i are the respective distances between the measuring positions.

$$d_x = \frac{\delta_{4,x} - \delta_{2,x}}{l_x}$$

$$d_y = \frac{\delta_{3,y} - \delta_{1,y}}{l_y}$$

The indices 1 to 4, x, y refer to the reference balls, as well as to the direction of the distortion error in X- or in Y-direction respectively (see Figure 1).

3 Measurement Setup and Procedure

Exemplary measurements have been obtained from a thermo-symmetric 3-axis machining center. The measurement setup is shown in Figure 2. Four reference balls were mounted on the machine’s working table. Regarding the XY-plane, they were placed in the proposed cross configuration (see Figure 2 a). A wireless probe is used in order to determine the dislocation of the reference balls (Figure 2 b).

The spindle and linear axis have been used as heat sources under finishing conditions according to ISO 230-3, however the activation time of the heat sources has been reduced from four hours to one to two hours, which is considered sufficient in order to demonstrate the measurement method. In order to show the different volumetric error characteristics, the load cases of loading spindle and X-axis are compared. For each experiment, the respective heat source was active for at least one hour. The X-axis was moved repeatedly at rapid feed of 80 m/min for the full travel distance available. The spindle was rotated at 18,000 RPM, respectively maximum spindle speed.

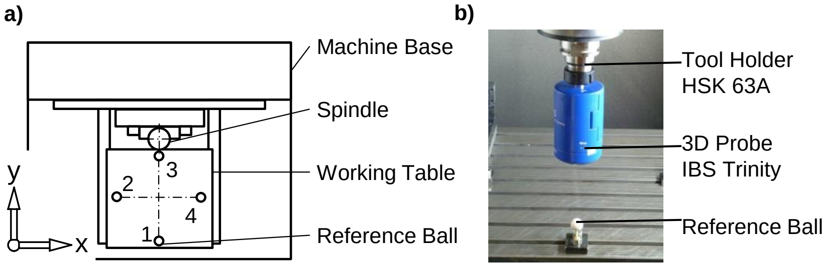

Figure 2: a) Scheme of measurement setup for the new method in vertical machining centre; b) 3D-probe and reference ball.

The displacement was measured approximately every fifteen minutes with two measurements taken at each reference ball. After the loading phase, the cooling phase was observed for additional six hours. The temperature of the machine structure is recorded during the experiment. Special care is taken of the table temperature, which is kept constant within 1°C for the duration of the experiments.

4 Results and Discussion of the Proposed Method

4.1 Spatial Dependencies Based on One Reference Ball

Figure 3 shows the measured TCP dislocation for the two loading cases at a single position (Ball 1) in the working volume. It is evident that the characteristics of each load case are different. In case of the loaded X-axis the dominant dislocation error is in Y-direction, whereas in case of the loaded spindle the Z-direction is more sensitive. In both cases the dislocation in X-direction is minimal, since the reference ball is placed in the plane of thermo-symmetry. Apart from the missing information about tilt errors, this representation of results is common, e.g. in ISO 230-3.

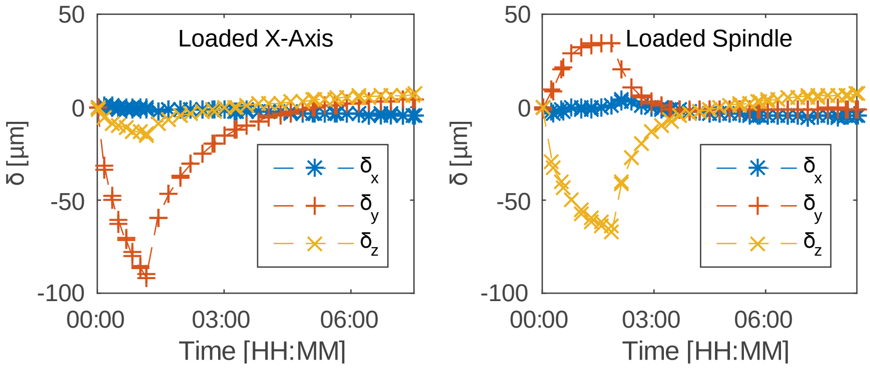

Figure 3: Measured TCP-dislocation at single position for two load cases

4.2 Spatial Dependencies Based on Four Reference Balls

When considering all four positions in the working volume, the new method shows additional thermal characteristics of the machine (see Figure 4). This plot shows a spatial representation of the TCP dislocation. The examined plane is the XY-plane, according to the setup sketch of Figure 2. Therefore, the trace of dislocation at each ball position can be observed. The initial location at each position is marked as initial state in the figure. Each trace is spaced according to the ball positions in the working volume. In this way the traces can be analyzed in detail for each reference ball.

It is clearly visible that, depending on the loading conditions, the dislocation at each position in the working volume can differ. In case of the loaded X-axis, a distortion in X and Y direction can be clearly observed; the traces diverge since the working volume grows in these directions. This is not as clearly visible in the case of spindle loading. Here, the traces at each point in the working volume are very similar. This information is not available when only considering one or two points in the working volume.

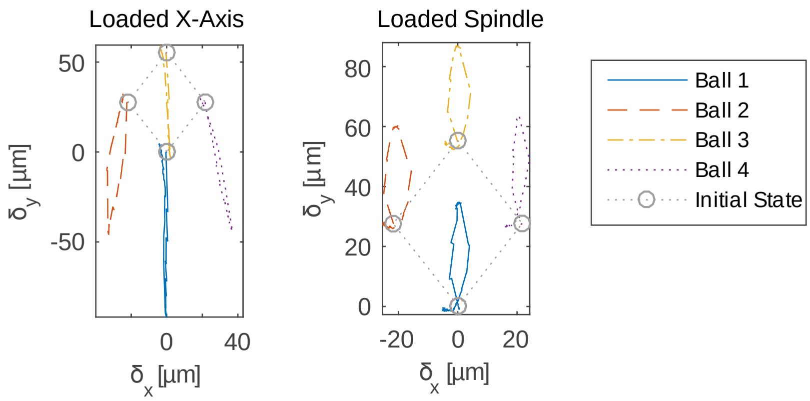

Figure 4: Spatial representation of TCP-dislocation at multiple positions in working volume for exemplary load cases

4.3 Temporal Dependencies

In order to have a clearer understanding of the distortion of the workspace, it seems reasonable to use the dislocation data in order to extract error parameters. Therefore, in Figure 5, the time-based representation of extracted error parameters is shown. With the example of the X-axis, there is a clear distinction between a zero-point shift and a distortion error. When considering the thermal behavior of a machine tool, the zero-point shift can be interpreted as a shift of the linear scale of the machine, while the distortion error can be interpreted as thermal growth of the linear scale [10]. Accordingly, these errors can have a different impact on the produced parts.

It is apparent that in each case, the zero point shift is very similar to the dislocation at a single point in the working volume (compare Figure 3). However, in the case of X-axis heating the distortion error shows additional information of significance. It is observable, that distortion is present in multiple directions, also lateral to the axis motion. The distortion error reaches ca. 60 µm/m in X- and Y-direction. In contrast, the spindle has a minor influence on distortion with less than 12 µm/m. This information cannot be obtained when only taking into account one or two positions in the working volume.

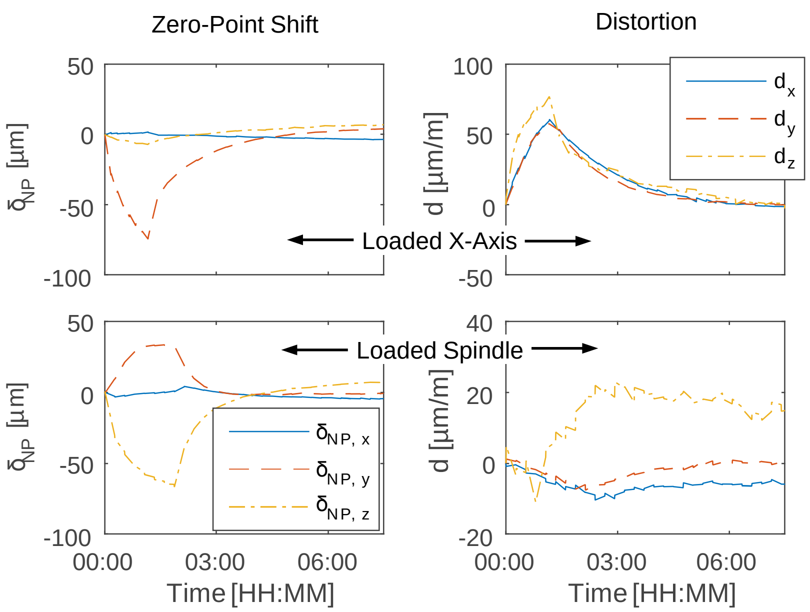

Figure 5: Extracted error parameters for exemplary load cases

5 Estimation of Measurement Uncertainty

In order to estimate the measurement uncertainty of the method u_m in the exemplary load cases the following influences are considered: a) uncertainty of probing single point u_p, b) influence of temperature changes on measuring device u_t, c) change of position of reference balls during the measurement u_b. The uncertainty budget is listed in Table 1. The uncertainty of probing a single point u_p has been determined with 0.5 µm, including repeatability of the test machine as well as the tool change. Both u_t and u_b are dependent on temperatures. While u_t is negligible due to a very low thermal coefficient of the sensors of 0.01%/°C, the change of position of reference balls can be significant. With a table material of cast with α_{th}=11 µm/(m*K) and a maximum distance of the balls on the table of 500 mm, a 1°C temperature change of the table material during the experiments leads to up to 5.5 µm of distance change. The derived uncertainty u_b therefore is 3.18 µm. The total budget leads to a combined uncertainty u_m of ca. 3.2 µm.

Table 1: Contributions to measurement uncertainty

Source	**Probing**	**Device**	**Ball Position**	**Combined**
Value	1 µm	$4*10^{-4}$ µm	5.5 µm	-
Distribution	Normal (k=2)	Rectangular	Rectangular	-
Divisor	2	√3	√3	-
Sensitivity	1	1	1	-
Uncertainty	**0.5 µm**	**$2.3*10^{-4}$ µm**	**3.18 µm**	**3.2 µm**
Symbol	u_p	u_t	u_b	u_m
Method	Measured	Estimated	Estimated	Estimated

6 Conclusions and Outlook

In conclusion, the proposed method exhibits the following properties: a) No practical limitation on the number of measuring points in the workspace, hence enabling more detailed recordings of the spatial dependency of the TCP-dislocation. b) The setup and the communication of the measuring instrument ensure high flexibility. c) Additional information about spatial dependency of TCP-dislocation can be extracted, such as the distortion lateral to axis motion. The trade-off is that tilt errors (A and B distortions) cannot be determined with this method.

All measuring equipment is structured as a three-component system [2;10], consisting of: a) The probe to be measured. b) The master for which the dimensions are known. c) The comparator, i.e. the device that measures the difference between the probe and the master.

The most important impact on the precision of the measurement lies on the thermal environment in which these three components are in. The three components will have the same temperature only after they all have reached equilibrium with the ambient. If ambient air temperature is varying, then their temperature will vary as well according to their individual thermal time constants. The design of the measuring equipment is therefore of great importance for precise measurements. All structures have different thermal resonance frequencies, since they demonstrate a different response to similar loading conditions. This is evident in Figure 4 in the hysteresis of the deformation progress between loading and cooling down. However, the following potential could be identified for future work: a) Are the zero-point displacement and the distortion independent from each other? b) How can the method or sensor technology be advanced so that tilt motion of the tool can be identified?

Comparison of results with proven methods from ISO 230-3 as long as with other novel alternative methods [18-22] should be conducted. In order to assess the quality of the proposed procedure however, it is important to determine the measurement uncertainty, as stipulated in [5] and analyzed in [23]. A common method to determine the uncertainty is prescribed in [24] and makes use of calibrated artifacts, similar to the reference balls used in the proposed method of this paper.

7 Acknowledgements

This work is funded by the DFG (German Research Foundation) within the framework of the trans-regional special research field SFB/TR96 “Thermo-energetic Design of Machine Tools” subproject C03 “Structurally Integrated Sensors”.

References

[1] Bryan, J.B. International status of thermal error research. CIRP Ann-Man. Techn. 1968; 16(2):203-215.

[2] Bryan J. B., McClure E. R., Brewer W., Pearson J. W. Thermal effects in dimensional metrology. ASME Prod. Eng. Conf. Rept. 1965; 65-PROD-13.

[3] Mayr J., Jedrzejewski J., Uhlmann E., Donmez M.A., Knapp W., Härtig F., et al. Thermal issues in machine tools. CIRP Ann- Man. Techn. 2012; 61(2):771-791.

[4] Brecher C., Brockmann B., Daniels M., Wennemer M. Herausforderungen bei der meßtechnischen Untersuchung von Werkzeugmaschinen. ZWF, Carl Hanser Verlag; 2014.

[5] ISO 230-3. Test code for machine tools - part 3: Determination of thermal effects. 2007.

[6] ISO 1. Geometrical product specifications (GPS) - Standard reference temperature for the specification of geometrical and dimensional properties. 2016.

[7] ISO 10791-10. Test conditions for machining centres - part 10: Evaluation of thermal distortions. 2007.

[8] ISO 13041-8. Test conditions for numerically controlled turning machines and turning centres - part 8: Evaluation of thermal distortions. 2004.

[9] Kwasny, W, Turek, P, Jedrzejewski, J. Survey of machine tool error measuring methods. J. of Mach. Eng. 2011; 11(4):7-38.

[10] Weck M., Brecher C. Werkzeugmaschinen meßtechnische Untersuchung und Beurteilung. 6. Auflage, Springer Verlag, 2006.

[11] Bringmann, B., Knapp W. Model-based ‘Chase-the-ball’ calibration of a 5-axes machining centre. CIRP Ann- Man. Techn. 2006.

[12] Lei, W.T., Hsu Y.Y. Accuracy test of five-axis CNC machine tool with 3D probe-ball. Part I: Design and modeling. Int. J. Mach. Tools Manuf. 2002; 42(Compendex): 1153-1162.

[13] Schwenke H, Knapp W, Haitjema H, Weckenmann A, Schmitt R, Delbressine F. Geometric error measurement and compensation of machines: an update. CIRP Ann- Man. Techn. 2008; 57(2):660–675.

[14] Weikert S., Knapp W. R-test, a new device of accuracy measurements of five axis machine tools. CIRP Ann- Man. Techn. 2004.

[15] Bitar-Nehme E., Mayer J.R.R. Thermal volumetric effects under axes cycling using an invar R-test device and reference length. Int. J. Mach. Tools Manuf. 2016; 105:14–22.

[16] Morávek, M. Bureš, J., Horejš, O. Volumetric measurement of machine tool thermal deformation using an MT-Check probe - In: Laser Metrology and Machine Performance XI. Bedfordshire: euspen. 2015: 305-313.

[17] Gomez-Acedo, E.; Olarra, A.; Orive, J.; Lopez de la Calle, Luis Norberto. Methodology for the design of a thermal distortion compensation for large machine tools based on state-space representation with Kalman filter. Int. J. Mach. Tools Manuf. 2013; 75: 100–108.

[18] Kuric I., Košinár M., Cisár M. Measurement and analysis of CNC machine tool accuracy in different location on work table. Proc. in Manuf. Syst. 2012; 7(4): 259-264.

[19] Brecher C., Fey M., Wennemer M. Volumetric thermo-elastic machine tool behavior. Prod. Eng. 2015; 9(1): 119–124.

[20] Du, Z., Zhang, S., Hong, M. Development of a multi-step measuring method for motion accuracy of NC machine tools based on cross grid encoder. Int. J. Mach. Tools Manuf. 2010; 50(3): 270–280.

[21] Yang S. H., Kima K. H., Park Y.K. Measurement of spindle thermal errors in machine tool using hemispherical ball bar test. Int. J. Mach. Tools Manuf. 2004; 44(2–3): 333–340.

[22] Jiang, Z.; Song, B.; Zhou, X.; Tang, X.; Zheng, S. On-machine measurement of location errors on five-axis machine tools by machining tests and a laser displacement sensor. Int. J. Mach. Tools Manuf. 2015; 95(1–12).

[23] Knapp W., Measurement uncertainty and machine tool testing, institute for machine tools and manufacturing (IWF), Swiss Federal Institute of Technology (ETH), Zurich, Switzerland.

[24] Li S., Zhang Y., Zhang G. A study of pre-compensation for thermal errors of NC machine tools. Int. J. Mach. Tools Manuf. 1997; 37(12):1715–1719.