euspen's 19th International Conference & Exhibition, Bilbao, ES, June 2019
www.euspen.eu

Thermal errors of a 5-axis CNC milling centre equipped with different spindle units

Otakar Horejš[1], Martin Mareš[1], Jan Hornych[1]

[1] *Czech Technical University in Prague, Faculty of Mechanical Engineering, Department of Production Machines and Equipment, RCMT, Horská 3, 128 00 Prague, Czech Republic*

O.Horejs@rcmt.cvut.cz

Abstract
Thermally induced errors are dominant sources of inaccuracy and are often the most difficult types of errors to reduce today. Software compensation of thermally induced displacements at the TCP is a widely employed technique to reduce these errors due to its cost-effectiveness and ease of implementation. Furthermore, machine tool manufacturers frequently offer a particular type of machine tool in multiple versions, where each version is equipped with a different spindle unit. This leads to different thermal deformation behaviour depending on the specific spindle unit mounted in the machine tool. To demonstrate this difference, an experimental research on a three 5-axis CNC milling centres of the same type equipped with three different spindle units is presented in this paper. Experimentally obtained thermal errors at the TCP from 3 machine tools with different mounted spindle units are mutually compared, showing a significant variation in thermal errors in the Z direction depending on the spindle unit. This fact should be taken into consideration in development of thermal error compensation models, as shown in the case of a modelling approach using transfer functions for a tested 5-axis CNC milling centre.

Thermal error, Spindle unit, Accuracy, Compensation

1. Introduction

Thermal error is one of the primary factors affecting the machining accuracy of a machine tool [1]. The spindle is the core component of CNC machine tools. Of all the heat sources that lead to thermal distortions, the spindle is an important contributor to total thermal errors due to the large amount of heat from its high-speed revolutions. As such, studies on thermal deformations of the spindle are indispensable to reduction of total thermal errors [2].

There are various design solutions for the main spindle of a machine tool (belt-driven spindle units, direct coupling and motorized spindle units). However, the overwhelming majority of machine tools are equipped with motorized spindles (also called electrospindles) nowadays [3]. Furthermore, general trends in the machining industry are characterized by increasing globalization of the sector with standardization of components and systems. For that reason, motorized spindles are often available as cartridge or block units which makes it possible to equip machine tools with different spindle units without excessive structural modifications of the machine tools. Thus, machine tool manufacturers have the opportunity to fulfil various customers' requirements.

Firstly, this paper is focused on thermal error evaluation of different motorized spindle units placed in multifunctional 5-axis CNC milling centres. Experiments on three 5-axis CNC milling centres of the same type equipped with three different spindle units were carried out. Secondly, a thermal error compensation model based on transfer functions is presented in [4]. The compensation model was calibrated using experimental data from tests with only one motorized spindle unit (herein referred to as SP1). The model was applied to complex experiments obtained from machine tools equipped with three different spindle units.

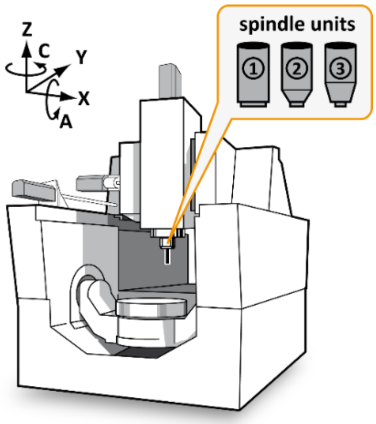

Figure 1. Multifunctional 5-axis CNC machining centre equipped with different motorized spindle units (SP1, SP2 and SP3)

2. Experiments

All of the experiments were performed on a 5-axis CNC milling centre (Fig. 1) with a rotary table (diameter of 630 mm) with 3 different motorized milling spindles from the Kessler Group (for spindle specification see Tab. 1).

Table 1. Specification of tested milling spindles (SP1, SP2 and SP3)

n.	Spindle model (Kessler)	Max. speed [rpm]	Power [kW] S6-40%	Torque [Nm] S6-40%
SP1	DMS 112.56.8.FOS	10,000	26	340
SP2	DMS 100.46.4.FHS	18,000	35	120
SP3	DMS 100.46-666.393	12,000	48	200

Tests for thermal distortion caused by rotating spindles were carried out according to ISO230-3 [5] (without machining).

The spindles were run at constant spindle speed (500 rpm or 9,000 rpm) to steady state followed by a cooling phase. The machining centres were equipped with several temperature probes (Pt100, Class A, 3850 ppm/K) placed as close as possible to the thermal sinks and sources. A test mandrel was clamped into the spindle. A measurement setup with five displacement measurement devices was fixed onto the table of the machining centres (Fig. 2). Eddy current sensors were employed for noncontact sensing of displacements at the TCP in the directions X, Y and Z (sensor type: PR6423, produced by Emerson).

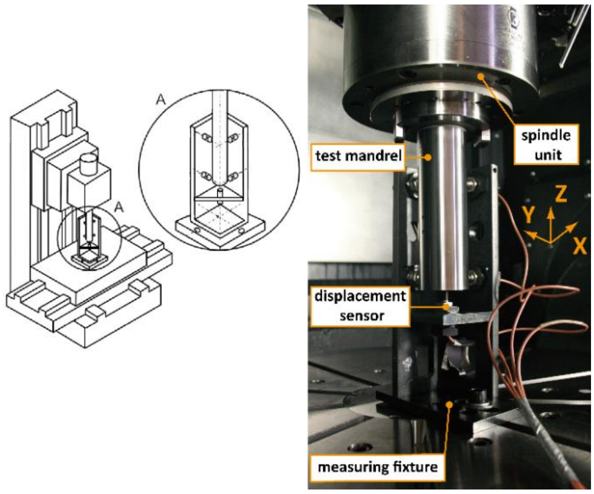

Figure 2. Experimental setup per ISO 230-3 (left) and its implementation in a 5-axis CNC milling centre (right)

A programmable automation controller (PAC) cRIO 9024 (National Instruments) with LabVIEW software was used for data acquisition (the sampling rate was 1 sec). Along with the additional temperatures and displacements mentioned above, NC data such as effective power, electric current, torque, feed rate, etc. were logged using Profibus DP communication between the machine controller and the PAC. Recently, nearly every spindle is equipped with sensors to monitor the motor temperature and often additional sensors to monitor the bearing temperature. Both types of temperature sensors were built into the tested spindles according to Tab. 1. Data acquisition of these temperatures during tests was also implemented via the Profibus DP.

2.1. Constant spindle speed of 500 rpm

The bearing temperature behaviours of the measured spindles are shown in Fig. 3.

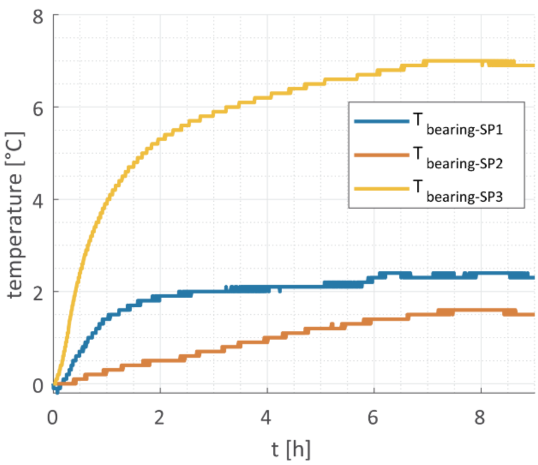

Figure 3. Spindles bearing temperatures during 500 rpm tests

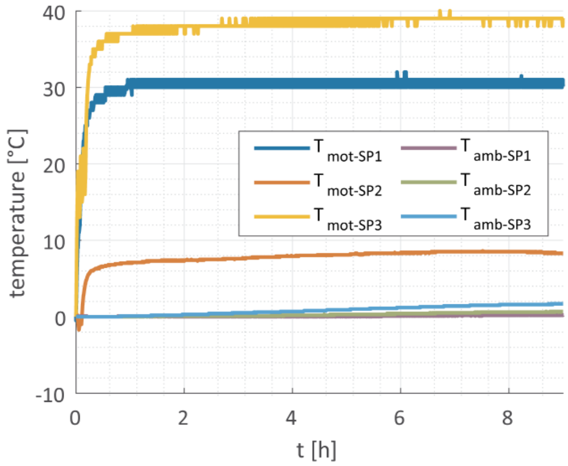

Figure 4. Spindles motor temperatures and ambient temperatures during 500 rpm tests

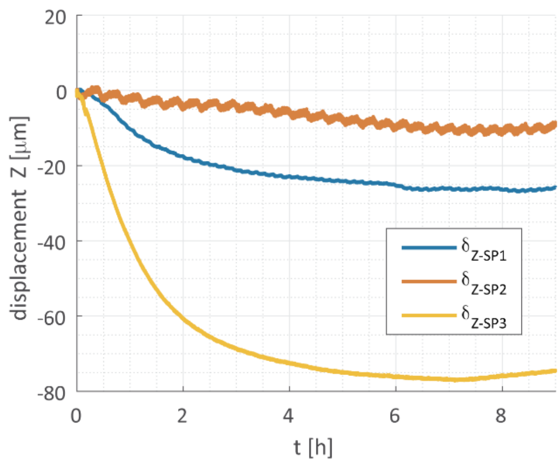

Figure 5. Thermally induced displacements in the Z direction of 5-axis CNC milling centres equipped with three different spindle units during 500 rpm tests

Figure 4 depicts the spindles' motor temperature and ambient temperature behaviour over time with different spindle units according to Tab. 1 during 500 rpm tests. Thermally induced displacements in the Z direction of 5-axis CNC milling centres equipped with three different spindle units during 500 rpm tests are shown in Fig. 5.

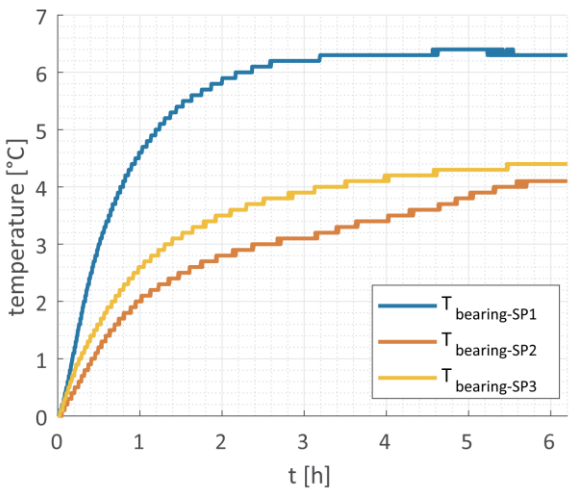

Figure 6. Spindle bearing temperatures during 9,000 rpm tests

2.2. Constant spindle speed of 9,000 rpm

The bearing temperature behaviours of the measured spindles are shown in Fig. 6. Figure 7 depicts the spindles' motor temperature and ambient temperature behaviour over time with different spindle units according to Tab. 1 during 9,000 rpm tests. Thermally induced displacements in the Z direction of 5-axis CNC milling centres equipped with three different spindle units during 9,000 rpm tests are shown in Fig. 8.

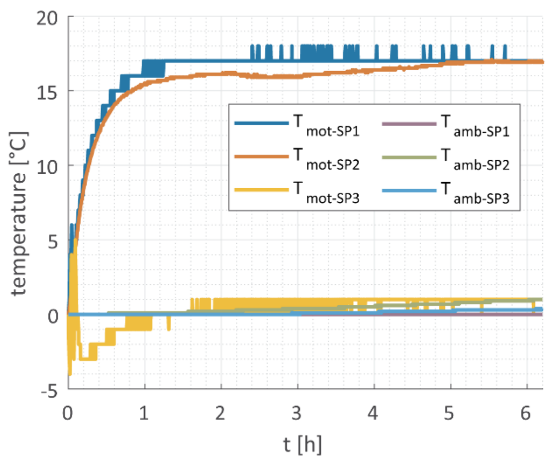

Figure 7. Spindle motor temperatures and ambient temperatures during 9,000 rpm tests

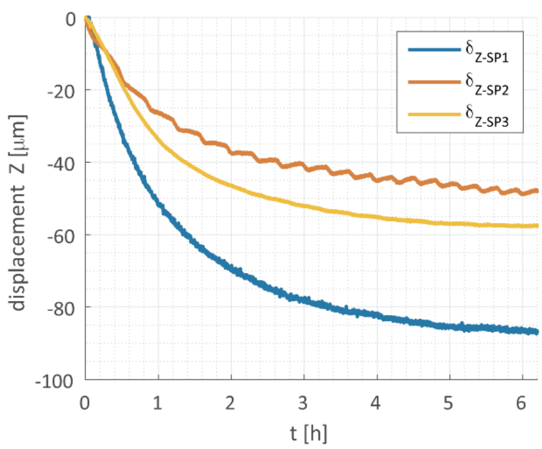

Figure 8. Thermally induced displacement in the Z direction of 5-axis CNC milling centres equipped with three separate spindle units during 9,000 rpm tests

3. Thermal error compensation

Thermal error compensation is considered a convenient, effective and cost-efficient way to reduce the thermal error compared to other thermal error control and reduction methods. Therefore, a thermal error compensation algorithm for the investigated 5-axis CNC milling centre (Fig. 1) based on transfer function modelling was developed in [4]. The transfer function reflects the nature of heat transfer principles. Thus, the calibration of empirical parameters is simple and the model is in addition more reliable with untested inputs and it can even be used reliably to extrapolate data, since it forces the data to conform to the same mathematical form as the real process.

The applicability and robustness of the software compensation based on transfer functions were verified on 3 different machine tool structures in [6].

The compensation model in [4] was calibrated using experimental data from tests with only one motorized spindle unit (herein referred to as SP1).

Generally, a discrete transfer function is used to describe the link between the excitation and the response

$$y(t) = \varepsilon.u(t) + e(t), \tag{1}$$

$$y(t) = \frac{a_n z^{-n} + \cdots + a_1 z^{-1} + a_0 z^0}{b_m z^{-m} + \cdots + b_1 z^{-1} + b_0 z^0} u(t);\ where\ m > n, \tag{2}$$

where *u(t)* in equations (1) and (2) is the transfer function input vector in the time domain, *y(t)* is the output vector in the time domain, ε represents the transfer function in the time domain, *e(t)* is the disturbance value, a_n are weight factors of the transfer function input and b_m are weight factors of the transfer function output.

The differential form of the transfer function in the time domain is defined as

$$y(k) = \frac{u(k-n)a_n + \cdots + u(k-1)a_1 + u(k)a_0 - y(k-m)b_m - \cdots - y(k-1)b_1}{b_0}, \tag{3}$$

where *k-n (k-m)* means the *n*-multiple (*m*-multiple) delay in the sampling frequency. Linear parametric models of ARX (autoregressive with external input) or OE (output error) identifying structures are used.

The advanced compensation model based on transfer functions in [4] predicts thermally induced displacements at the TCP in the Z direction caused by spindle rotation and varying ambient temperature. Thus, the model consists of 2 transfer functions

$$\delta_Z = \Delta T_{bearing}.\varepsilon_1 + \Delta T_{amb}.\varepsilon_2, \tag{4}$$

where $\Delta T_{bearing}$ is the spindle bearing temperature difference, ΔT_{amb} is the ambient temperature difference, ε_1 represents the transfer function approximating thermal errors due to spindle rotation and ε_2 represents the transfer function approximating thermal errors due to changes in ambient temperature (see Table 2).

Table 2 Coefficients of identified transfer functions

ε_1	a_0	a_1	a_2	
	-0.0337	0.0332	0	
	b_0	b_1	b_2	b_3
	1	-1.3009	-0.3263	0.6273
ε_2	a_0	a_1	a_2	
	-0.0337	0.0332	0	
	b_0	b_1	b_2	b_3
	1	-1.9985	0.9985	0

The error of approximation is expressed by *residue* (µm), which represents the fictive thermal displacements at the TCP in the Z direction (thermal errors) obtained after implementing the compensation algorithm into the machine tool control system

$$residue = \delta_{Z-EXP} - \delta_{Z-\mathrm{SIM}}, \tag{5}$$

where the δ_{Z-EXP} value represents the measured output (thermal displacement in the Z direction) and δ_{Z-SIM} is the simulated/predicted thermal displacement obtained by applying the transfer function model (4). Herein, an approximation quality of the identified models is also expressed by the *fit* value (normalized Root Mean Squared Error expressed as a percentage, see [7]). Figure 9 depicts the predicted thermal displacements of the 5-axis CNC milling centre equipped with 3 different spindle units obtained from the transfer function model (4) for 500 rpm tests. The residual errors in the Z direction obtained from the transfer function model for 500 rpm tests with 3 different spindle units are shown in Fig. 10.

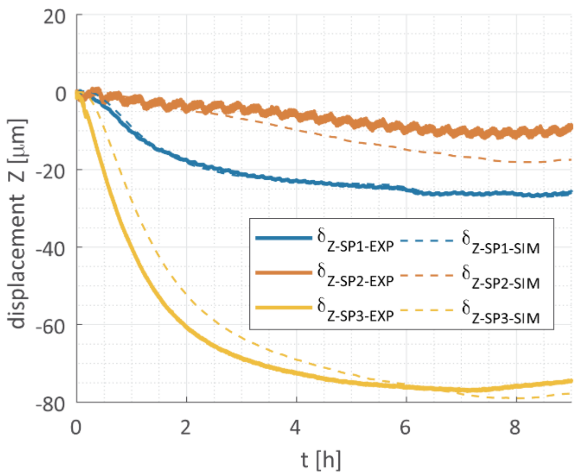

Figure 9. Model results applied on 500 rpm tests with 3 different spindle units

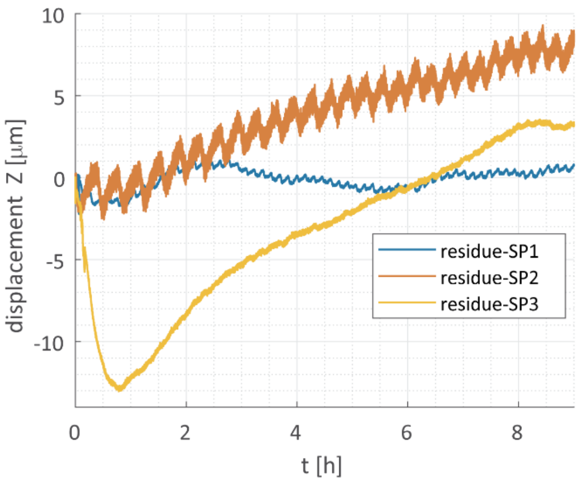

Figure 10. Residual errors in the Z direction obtained from the transfer function model for 500 rpm tests for 3 different spindle units

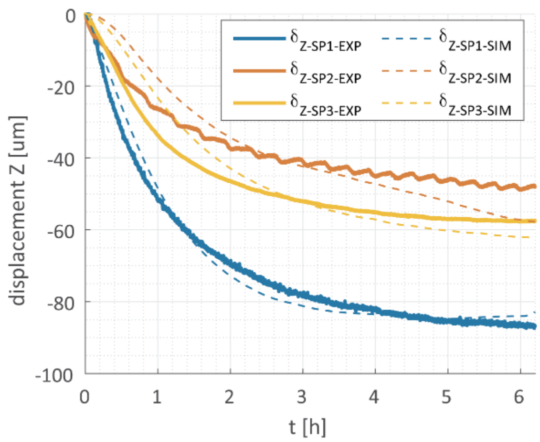

Figure 11. Model results applied on 9,000 rpm tests with 3 different spindle units

Table 3 Approximation quality of the transfer function model (4) expressed by the *fit* value for tests with 3 different spindle units

Test (constant spindle speed)	*fit* [%]		
	SP1	SP2	SP3
500 rpm	90.7	-44.7	68.0
9000 rpm	86.2	49.1	64.8

Analogous graphs for tests at 9,000 rpm are shown in Fig. 11 and Fig. 12, respectively.

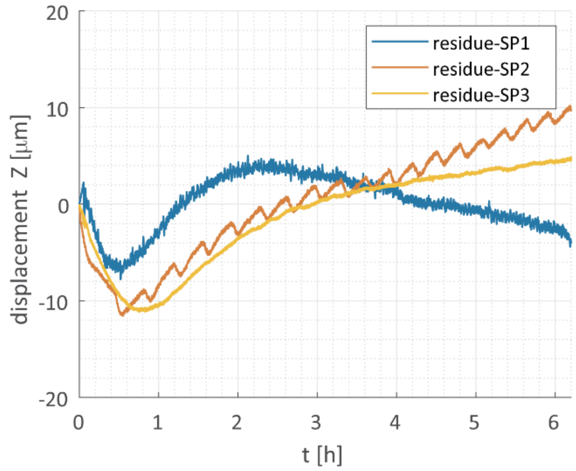

Figure 12. Residual errors in the Z direction obtained from the transfer function model for 9,000 rpm tests for 3 different spindle units

4. Summary

Experiments on three 5-axis CNC milling centres of the same type equipped with three different spindle units were carried out. The thermal errors obtained at the TCP in the Z direction in the experiments with 3 machine tools with different mounting of spindle units were compared, showing significant variation of thermal errors in the Z direction depending on the spindle unit. The maximum difference in thermal errors in the Z direction is 65 µm for the 500 rpm tests (see Fig. 5) and 39 µm for the 9,000 rpm tests (see Fig. 8).

This fact should be taken into consideration if a thermal error compensation model is developed as shown in the case of the modelling approach using transfer functions for the tested 5-axis CNC milling centre (Fig. 9 and Fig. 11). The approximation quality of the compensation model calibrated using experimental data from tests with only one motorized spindle unit (herein referred to as SP1) deteriorates if the model is applied on different spindle units (SP2, SP3) as shown in Fig. 10 and Fig. 12 (or see the *fit* values in Tab. 3).

Acknowledgements

This research (Thermal errors of a 5-axis CNC milling centre equipped with different spindle units) has received funding from the Technology Agency of the Czech Republic (Project (TE01020075).

References

[1] Mayr J et al. 2012 Thermal issues in machine tools *CIRP Annals – Manufacturing Technology* **61 (2)**, 771–791.

[2] Haitao Z, Jianguo Y and Jinhua S 2007 Simulation of thermal behaviour of a CNC machine tool spindle, *Int. J. Mach. Tools Manuf.* **47(6)** 1003–1010

[3] Abele E, Altintas Y and Brecher C 2010 Machine tool spindle units *CIRP Annals - Manufacturing Technology* **59 (2)** 781–802

[4] Mareš M, Horejš O and Hornych J 2017 Modelling of cutting process impact on machine tool thermal behaviour based on experimental data *Procedia CIRP* **58** 152–157

[5] ISO 230-3 2007 Test Code for Machine Tools – Part 3: Determination of Thermal Effects, Genf, Switzerland.

[6] Horejš O, Mareš M and Hornych J 2014 A general approach to thermal error modelling of machine tools, *In: Machines et usinage à grande vitesse (MUGV)*, Clermont Ferrand, France.

[7] Ljung L 2018 System Identification Toolbox™ User's Guide, The MathWorks, Inc., 3 Apple Hill Drive Natick, MA. https://ww2.mathworks.cn/help/pdf_doc/ident/ident.pdf