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Real-time compensation of a 5-axis CNC milling centre thermal errors considering different spindle units

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Abstract

Thermal errors of machine tools are the main contributor to geometrical inaccuracies of machined workpieces. Successful reduction in thermal errors has been realized through thermal error compensation techniques in the past few decades. The effectiveness of thermal error models directly determines the compensation results. However, most of the current thermal error models are empirical and highly rely on the collected data under specific working conditions, neglecting the insight into the underlying mechanisms that result in thermal deformations. On the contrary, the transfer function based correction method lead to promising results as was shown in past studies. Furthermore, machine tools manufacturers frequently offer the same type of the machine tool equipped with different spindle units. Consequently, it leads to different thermal behaviour depending on the specific spindle unit mounted in the machine tool. The research presented in this paper shows a dynamic approach for thermal error compensation of 5-axis CNC milling centres considering different spindle units. Experimentally obtained thermal errors at the TCP from milling centres with 3 different mounted spindle units were mutually compared, showing a significant variation in thermal errors in the Z direction depending on the specific spindle unit. System identification theory is applied to build the dynamic thermal error model for a single spindle unit based on calibration experiment. An industrial applicability of compensation models essentially depends on duration of calibration experiments and modelling effort to identify compensation model parameters. Therefore, the developed transfer function model is modified from the calibration effort point of view via multiplying original compensation model by a constant. Subsequently, model is applied on tests with other spindle units. Model performance evaluation through spindle spectra tests shows that up to 74% reduction in thermal errors in Z direction of milling centre equipped with 3 different spindle units was achieved after compensation.

Machine tool, Thermal error, Compensation, Spindle unit, Accuracy, System identification theory, Transfer function, 5-axis milling centre

1. Introduction

Thermal error is one of the primary factors affecting the machining accuracy of machine tools [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 and quick response inducing thermal errors at the TCP. 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.

An experimental research on a 5-axis CNC milling centres equipped with 3 different spindle units was carried out [4]. Experimentally obtained thermal errors at the TCP from milling centres with 3 different mounted spindle units were mutually compared, showing a significant variation in thermal errors in the Z direction depending on the specific spindle unit [4].

Furthermore, a thermal error compensation model of a 5-axis CNC milling centre thermal errors based on transfer functions is presented in [5]. The compensation model was calibrated using experimental data from tests with only one motorized spindle unit (herein referred to as SP1). The developed compensation model was applied to complex spindle speed spectra tests obtained from machine tools equipped with different spindle units. The approximation quality of the compensation model calibrated using experimental data from tests with only one motorized spindle unit deteriorates if the model is applied on different spindle units, see [4]. The research presented in this paper is focused on improving approximation quality of the existing compensation model for different spindle units using minimal additional modelling effort or calibration experiments.

2. Experimental setup

All of the experiments were performed on a gantry-type 5-axis milling centres with a rotary table (diameter 630 mm, no turning operations) with 3 different motorized milling spindles from the Kessler Group (for spindle specification see Table 1). Tests for thermal distortion caused by rotating spindles were carried out according to the ISO230-3 [6] (without machining). 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.

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

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. 1). 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).

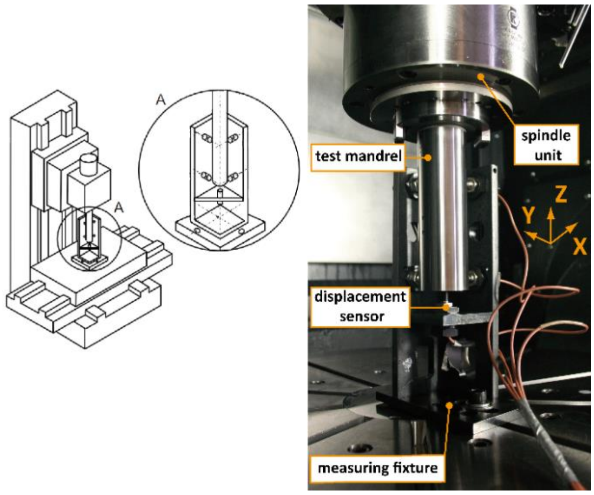

Figure 1. Experimental setup per ISO 230-3 (left) and its implementation in a 5-axis CNC milling centre (right)

A programmable automation controller cRIO 9024 (National Instruments) with LabVIEW software was used for data acquisition (the sampling rate was 1 sec). Recently, nearly every spindle is equipped with sensors to monitor the bearing temperature This bearing temperatures and other NC data such as effective power, electric current, torque, feed rate, etc. were also logged using Profibus DP communication between the machine controller and the PAC. Different test with constant spindle speed and spindle speed spectra tests has been designed to verify the validity of the compensation model for each of the spindle according to the Table 1 (see chapter 4).

3. Compensation model for thermal errors

System identification theory is applied to build the dynamic thermal error model for a one spindle unit (SP1) based on calibration experiment [5]. The transfer function reflects the nature of heat transfer principles. Thus, the calibration of empirical parameters is simple, 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 [7]. 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 difference 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 [5] 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 obtained from an environmental temperature variation error test (ETVE test) according to [6]. Coefficients of identified transfer functions ε_1 and ε_2 are introduced in [4]. The residual 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 [8]).

As mentioned above, the approximation quality of the compensation model calibrated using experimental data from tests with only one motorized spindle unit (SP1) deteriorates if the model is applied on different spindle units (SP2 and SP3). Therefore, the original dynamic TF model (4) is modified using multiplying spindle rotation part of the model by a constant *g* (gain) to improve approximation quality of the existing compensation model

$$\delta_Z = g.(\Delta T_{bearing} . \varepsilon_1) + \Delta T_{amb} . \varepsilon_2. \tag{6}$$

Thus, the thermal error compensation model for different spindle units do not requires neither additional calibration experiments nor high additional modelling effort.

4. Results

Figure 2 depicts the bearing temperature and ambient temperature behaviour over time during verification test (spindle speed spectrum) with spindle unit SP1. The grey curve plotted on Figure 2 represent variable spindle speed.

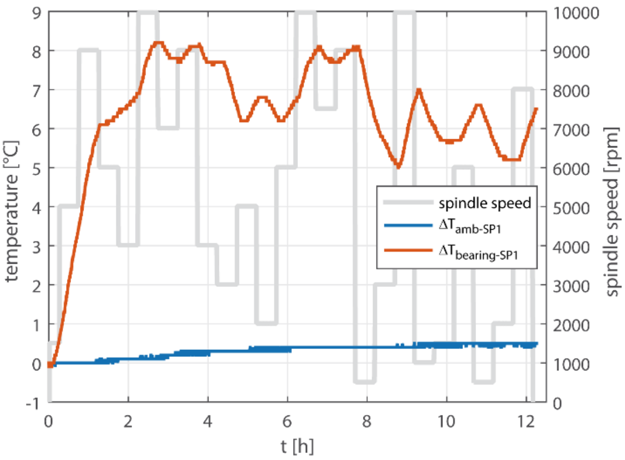

Figure 2. Spindle speed spectrum, ambient and spindle bearing temperatures during first spindle unit (SP1) verification test.

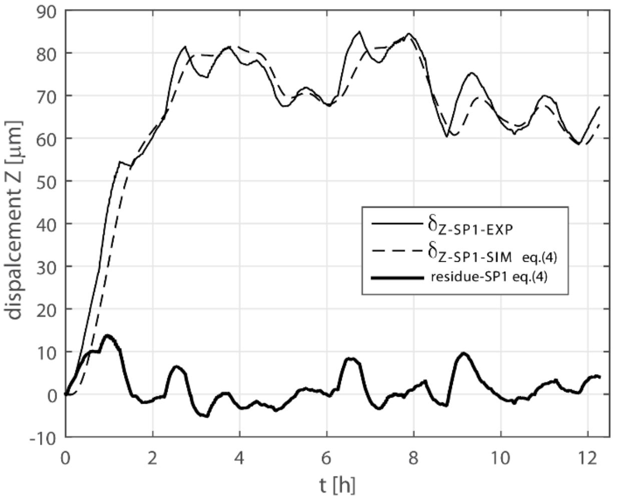

Figure 3. Measured, simulated and residual thermally induced displacements in the Z direction of 5-axis CNC milling centre equipped with first spindle unit (SP1) during verification test

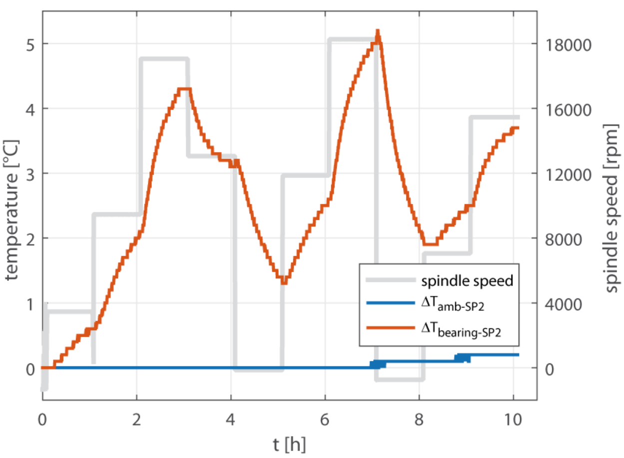

Figure 4. Spindle speed spectrum, ambient and spindle bearing temperatures during second spindle unit (SP2) verification test

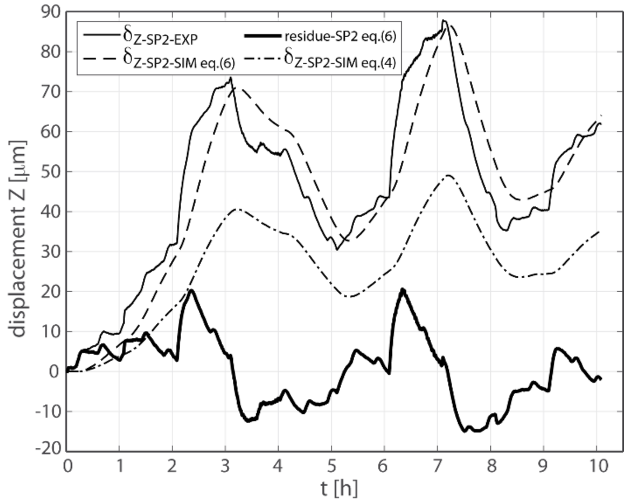

Figure 5. Measured, simulated and residual thermally induced displacements in the Z direction of 5-axis CNC milling centre equipped with second spindle unit (SP2) during verification test

Figure 3 depicts the measured (solid black curve) and predicted (dashed black curve) thermal displacements of the 5-axis CNC milling centre equipped with spindle unit SP1 obtained from the transfer function model (4) for the same verification test (spindle speed spectrum, see Figure 2). As the compensation model was calibrated based on experimental data with the spindle unit SP1, gain g is equal to 1. The thick solid black curve corresponds to the residual error (*residue*) of compensation model based on transfer function.

Analogically, Figure 4 and Figure 6 shows the bearing temperature, ambient temperature behaviour over time and variable spindle speed during test with spindle unit SP2 and SP3. Thermally induced displacements, its prediction by compensation model (6) and residual error expressed by *residue* for verification test with spindle unit SP2 is depicted in Figure 5. Similar graph for verification test with spindle unit SP3 is shown in Figure 7. Constant g in (6) is equal to 1.75 for verification test with SP2 and g = 1.25 for verification test with spindle unit SP3.

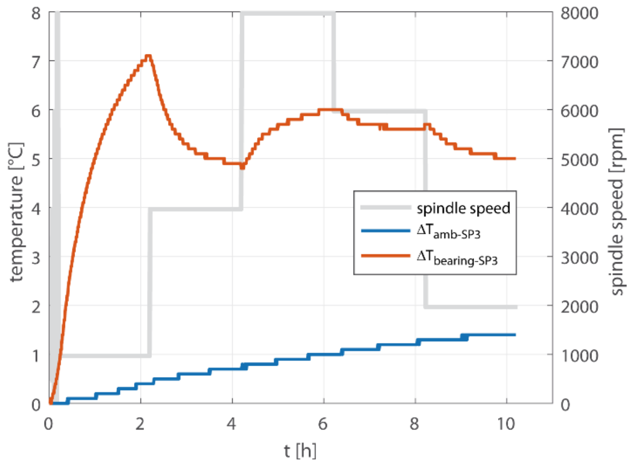

Figure 6. Spindle speed spectrum, ambient and spindle bearing temperatures during third spindle unit (SP3) verification test

Table 2 summarizes constant g (gain) and approximation quality of the transfer function model per (6) expressed by the *fit* value for 3 spindle speed spectra tests with different spindle units. It can be observed that constant g increases with a higher value of the maximum allowed spindle speed (by comparing Table 1 and Table 2).

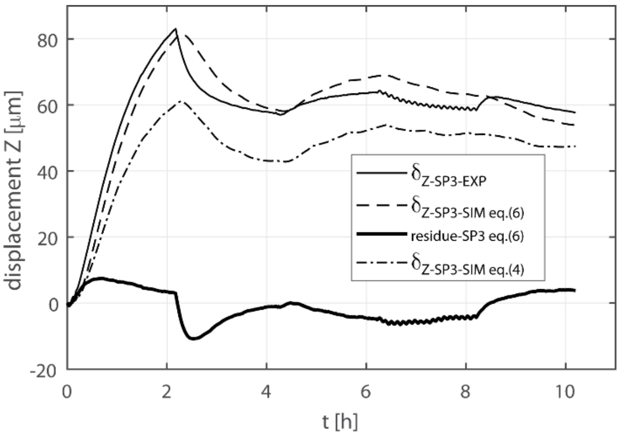

Figure 7. Measured, simulated and residual thermally induced displacements in the Z direction of 5-axis CNC milling centre equipped with third spindle unit (SP3) during verification test

Table 2. Gain and approximation quality of the transfer function model (5) expressed by the *fit* value and *residue* for 3 different spindle units

Verification test (spindle speed spectrum)	*g* [-]	*fit* eq. (6) [%]	*residue* [μm]	
			eq. (6)	eq. (4)
SP1	1	74	(-5;14)	(-5;14)
SP2	1.75	60	(-14;20)	(0;43)
SP3	1.25	66	(-6;8)	(-1;23)

The calculated *residue* (5) of developed models according to (4) and (6) are also summarised in Table 2.

5. Conclusions

Experiments on gantry-type 5-axis CNC milling centres of the same type equipped with 3 different spindle units were carried out. System identification theory was applied to build the dynamic thermal error model based on calibration experiment on milling centre equipped with motorized spindle unit (SP1), see equation (4).

Spindle spectrum tests with milling centre with spindle unit SP1 was employed to verify developed thermal error compensation model ability to reduce thermally induced errors at the TCP (in Z direction). A thermal errors reduction of 74% (expressed by the *fit* value) in Z direction of milling centre equipped with spindle units SP1 was achieved after compensation based on transfer function (see Figure 3).

Thereafter, the developed dynamic compensation model was applied to spindle speed spectra tests obtained from machine tools equipped with other spindle units (SP2 and SP3). However, the approximation quality of the compensation model calibrated using experimental data from tests with only one motorized spindle unit (SP1) deteriorates if the model is applied on milling centres equipped with other spindle units (SP2, SP3), see dash-dotted lines in Figure 5 and Figure 7 (calculated using model (4)) or previously published results in [4].

Therefore, the further research was focused on improving approximation quality of the existing compensation model for different spindle units. Generally, an industrial applicability of compensation models essentially depends on duration of calibration experiments and modelling effort to identify compensation model parameters. Hence, the developed model based on transfer function (4) is modified from the calibration effort point of view via simple multiplying indigenous compensation model by a constant *g*, see equation (6). Thus, the thermal error compensation model for different spindle units do not requires neither additional calibration experiments nor high additional modelling effort.

The prediction of modified compensation model is in good agreement with measured thermally induced displacements at the TCP as shown in Figure 5 for verification test with spindle unit SP2. Similarly, good agreement is accomplished for verification test (spindle speed spectrum) with spindle unit SP3 (see Figure 7). Thermal errors reduction (expressed by the *fit* value) was 60% in Z direction during the verification test (spindle speed spectrum) with spindle unit SP2 (see Table 2). A thermal errors reduction of 66% was achieved in case of verification test with spindle unit SP3. The minimisation of thermal errors is also evident by comparison of calculated *residue* of model (6) and former model (4) for spindle unit SP2 and SP3, see Table 2. Reduction of thermal errors (the approximation quality expressed by *fit* value) using modified compensation model slightly deteriorates if the model is applied on different spindle units (a reduction of 14% in case of spindle unit SP2, 8% in case of spindle unit SP3, see Table 2). Nevertheless, it can be concluded that successful reduction in thermal errors in Z direction of gantry-type 5-axis CNC milling centres has been realized through simple thermal error compensation model modification (multiplying spindle rotation part of the model by a constant *g*, see equation (6)).

Moreover, this approach enables rapid modification of the compensation model based on transfer functions using minimal additional modelling effort and without necessity of performing additional calibration experiments with machine tools equipped with other spindle units. A better approximation quality of the compensation model based on transfer function could be attained by developing independent thermal errors compensation models for each spindle units. However, it requires to carry out calibration tests with each spindle unit mounted in the gantry-type 5-axis CNC milling centre, which is time-consuming process. This is an issue for future research to explore.

The paper presents experiments which were carried under load-free rotation of the main spindle, save for the cutting process. The results in [5] showed that the thermal errors prediction of such compensation models (calibrated using non-contact test setup, see Figure 1) deteriorates in real cutting applications. However, the prediction accuracy of the proposed model (6) under real conditions (milling) can be improved using superposition principle (e.g. including tool elongation due to the impact of the cutting process as was shown in [5]).

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] Horejš O, Mareš M and Hornych J 2019 Thermal errors of a 5-axis CNC milling centre equipped with different spindle units, *In: euspen's 19th International Conference & Exhibition*, Bilbao, Spain
[5] 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
[6] ISO 230-3 2007 Test Code for Machine Tools – Part 3: Determination of Thermal Effects, Genf, Switzerland.
[7] 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.
[8] 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