

Portability of the thermo-mechanical compensation model of the milling center

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Abstract

Thermo-mechanical errors of machine tools (MT) are important element in inaccuracies of machined workpieces. In the past few decades, thermal errors have been successfully reduced by techniques of software compensation. For example, the multiple linear regression analysis, the finite element method, the neural network or the transfer function (TF) are used. Approximation model based on dynamic method of TF is used for compensation thermal errors in this publication. The approach respects basic mechanisms of heat transfer in the MT structures. Every single piece of produced MT is original due to manufacturing inaccuracies of MT components, assembly process (different preloads in bolts, deviation in the assembly and seating of components, etc.) or working environment of the MT (e.g. air-conditioned or common factory hall, etc.). Usually, MT producers offer the same type of the MT equipped with different components (e.g. spindle units) which leads to further differences in thermo-mechanical behaviour. The aim of the article is to define conditions and examine issues of transfer of existing thermal error compensation model between several machines of the same product line; taking into account manufacturing and assembly inaccuracies and changes in working environment. Selected machines were tested during non-stationary activity of the main heat sources: different spindle units and two linear axis movements.

Keywords: thermal errors, portability, software compensation

1. Introduction

One of the primary factors influencing the geometric accuracy of machine tools (MT) are thermal errors [1]. A spindle unit (as one of the based part of MT) has an important influence on this issue. Other elements influencing thermal behaviour of MT significantly are also motors of MT linear axes, movement mechanisms (bearings, lead screws, linear motion bearing, etc.) and changes in environmental temperature.

Several approaches how to address MT thermal errors with the help of compensation models exists e.g. multiple linear regression analysis, finite element method, neural network, or transfer function (TF) [2]. Experimental data driven model based on TF is used as a compensation approach in this article. At first calibration measurements are necessary to assemble the compensation model. That means identification of a function linking a change of temperature at input to a change of deformation at the output of thermo-mechanical system. The advantage of models based on TFs is possibility to solve each heat source influence contributing to overall MT thermal error separately. The resulting approximation is the sum of the solutions of the partial influences (single motors of MT linear axes, spindle unit, lead screws, ball screw nuts, bearings, environment, etc.). The compensation model based on TFs assembled in [3] is used within this article. The aim of the work is to apply the existing TF compensation model on another MTs of the same type, structure, and size and to analyse its approximation quality. First target machine is equipped with the same spindle unit (SP1; see *Table 1*) as identified MT in [3]. The second target machine dispose of the different spindle unit (SP2; see *Table 1*). Moreover, the compensation model was verified

and analysed on experiments consisting of Y and Z axis movements.

The second chapter describes the setup of the experiment and defined the location of the single sensors. The third chapter is focused on applied compensation model description and interpretation of an approximation quality. The fourth chapter summarises all the achieved results. Options of further MT accuracy enhancement are discussed in fifth chapter. All results are concluded and future work outlined in final section of the article.

Table 1 Specification of spindle units.

Named	Spindle model (Kessler)	Max. speed [rpm]	Power [kW]	Torque [Nm]
SP1	DMS 112.56.8.FOS	10 000	26	340
SP2	DMS 100.46-666.393	12 000	48	200

2. Experimental setup

All measurements were performed on two 5-axis milling centers of upper gantry type.

For measurement purpose were available 2 structurally identical machines placed in two different environments: MT producer's production hall and showroom for customers with relatively stable temperature conditions respectively. Each target machine is equipped with a different spindle unit (SP1 and SP2 respectively according to *Table 1*). Along with spindle speed and axis movements the temperature influence from the rough surrounding should be taken into account.

The thermo-mechanical behaviours of the target MTs are very extensive and complicated. Therefore, the article

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is focused on evaluation of portability simplified only to control predicted thermal errors in the most affected Z direction of the machine. *Table 2* shows the measurements performed on both target machines.

In measurement No. 1 (see *Table 2*) deformations in Z direction were measured as a function of the spindle speed over the time during the test No. 1a and No. 1b for target machines equipped with SP1 and SP2 respectively. Thermal errors caused by constant Y axis feed rates 15 m·min⁻¹ and 8 m·min⁻¹ for target machine 1 and 2 respectively are addressed in tests No. 2a and No. 2b. Similar setup is used for the tests No. 3a and No. 3b consisting of constant feed-rates in Z axes of both target machines.

Table 2 Performed experiments.

No.	Description	Heat source	Value
1a	SP1 speed spectrum	Spindle rotation	Variable
1b	SP2 speed spectrum	Spindle rotation	Variable
2a	Constant speed in the Y axis of target machine 1	Y feed drive	15 [m·min ⁻¹]
2b	Constant speed in the Y axis of target machine 2	Y feed drive	8 [m·min ⁻¹]
3a	Constant speed in the Z axis of target machine 1	Z feed drive	15 [m·min ⁻¹]
3b	Constant speed in the Z axis of target machine 2	Z feed drive	8 [m·min ⁻¹]

Measured temperatures and deformations are summarised in *Table 3*. Approximate positions of the sensors placed on the machine are schematically shown in *Fig. 1*. Temperature probes are part of machine control systems. Motor temperatures were recorded in control system in resolution of 1 °C and spindle and base temperatures in resolution of 0.1 °C. Temperatures are standardly connected in the control systems for other diagnostic purposes by the machine manufacturer. Deformations in the Z direction between TCP of clamped testing mandrel in the spindle and the machine table were measured with a non-contact eddy-current sensor PR6423 (Emerson). All measured data during the experiments were acquisitioned in CompactRio-9012 diagnostic control panel by National Instruments.

Table 3 Overview and description of used sensors.

Named	Placed (see Fig. 1)
T _Y	Temperature of Y axis feed drive
T _Z	Temperature of Z axis feed drive
T _{SP}	Spindle bearings temperature
T _{Ba}	Base (reference) temperature
δZ	Deformation of TCP in Z direction against the rotary table

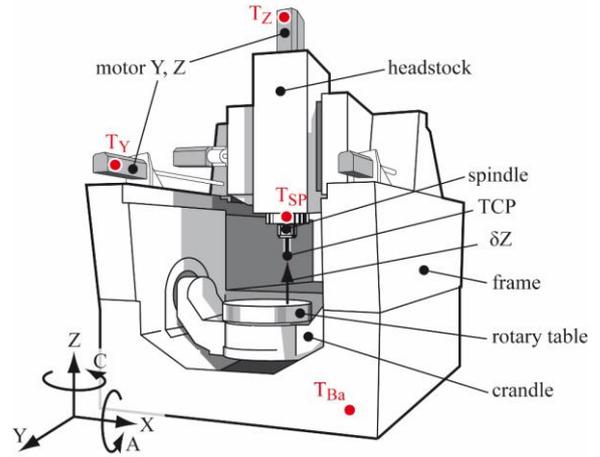


Fig. 1. Schema of target machine structures with approximate the positions of temperature and deformation sensors [3].

3. Compensation model of thermal errors

Software compensation is considered as suitable and cost-effective way to reduce the MT thermal errors compared to other methods of regulation and reduction. Therefore, compensation algorithm of thermal errors for the 5-axis milling center based on TFs was developed in [3]. TFs work with natural principles of heat transfer [2]. The applicability and robustness of software compensation based on TF was verified on 3 different MT structures in [4].

Prediction model of thermal deformations in the MT Z direction is represented by the mathematical expression in equation (1) [3]. Model approximates thermal errors caused by ambient temperature changing, spindle rotation and Y and Z axis movements. Model was calibrated in [3] on different machine from target machines 1 and 2 examined in this article.

$$\delta Z_{SIM} = \underbrace{\Delta T_{Ba} \cdot \varepsilon_{Z,amb}}_{ambient} + \underbrace{(\Delta T_{SP} - \Delta T_{Ba}) \cdot \varepsilon_{Z,SP}}_{spindle rotation} + \underbrace{(\Delta T_Y - \Delta T_{Ba}) \cdot \varepsilon_{Z,Y}}_{Y axis movement} + \underbrace{(\Delta T_Z - \Delta T_{Ba}) \cdot \varepsilon_{Z,Z}}_{Z axis movement} \quad (1)$$

The calibration conditions as well as coefficients of the four identified TFs for the approximation of thermal errors are summarised in [3]

The compensation model works with all temperatures listed in *Table 3*. The model was implemented in the control system (Heidenhain) of a calibrated machine using the Python programming language (the implementation principle is described in more detail in [3]).

The approximate quality of the simulated behaviour is expressed by equation (2). This value represents the percentage of the output deviation generated by the model [5]. The evaluation is based on the least squares approximation method. The value 100% expresses the complete agreement of the measured and simulated behaviour, in this case the time course of deformation. It is a global indicator of approximate quality.

$$fit = \left(1 - \frac{\|\delta Z - \delta Z_{SIM}\|}{\|\delta Z - \bar{\delta Z}\|}\right) \cdot 100 \quad (2)$$

The value $\bar{\delta Z}$ expresses the arithmetic mean at the time of the measured deformation. The vector norm used in equation (2) can generally be expressed by equation (3), where δ is a general vector of length r [5].

$$\|\delta\| = \sqrt{\delta_1^2 + \delta_2^2 + \dots + \delta_r^2} \quad (3)$$

The approximation error is also expressed in the article by the residue (equation (4)) representing a fictive thermal deformation obtained after implementation and activation of the compensation algorithm in the MT control system.

$$RES = \delta Z - \delta Z_{SIM} \quad (4)$$

4. Results

4.1. Target machine with SP1

Behaviours of measured temperatures over the time during measurement No. 1a (spindle SP1 speed spectrum, see Table 2) are shown in Fig. 2. The grey curve in Fig. 2 belongs to spindle speed behaviour over the time.

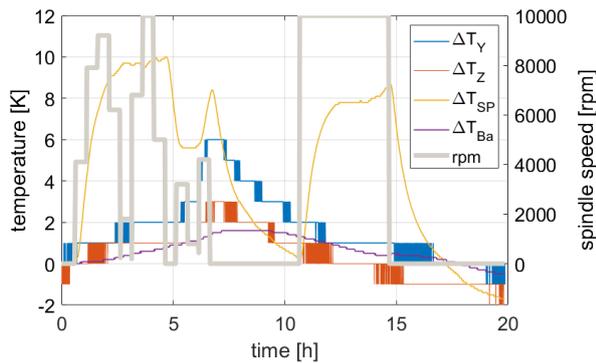


Fig. 2. Behaviours of measured temperatures and spindle SP1 speeds during test No. 1a.

Behaviours of measured and simulated deformations in Z MT direction along with their residue over the time during the test No. 1a are shown in Fig. 3.

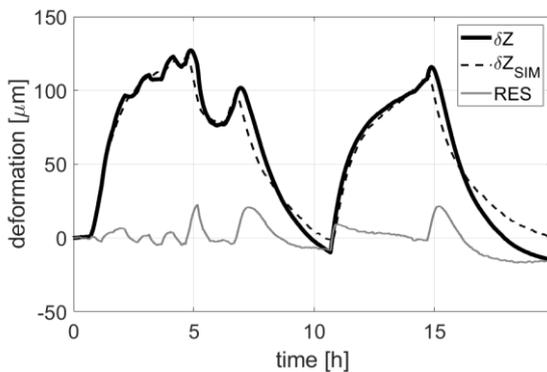


Fig. 3. Behaviours of measured, simulated and residual deformations during the test No. 1a.

Behaviours of measured temperatures over the time during measurement No. 2a (constant speed in the Y axis

of target machine 1) are depicted in Fig. 4. The grey curve shows the Y axis feed rate as a function of time.

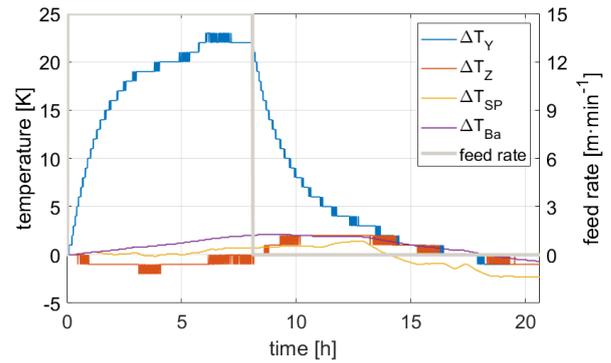


Fig. 4. Behaviours of measured temperatures and Y axis feed rate during measurement No. 2a.

Behaviours of the measured and simulated deformation in the Z direction of the machine and residual deformations as a function of time during the test No. 2a are shown in Fig. 5.

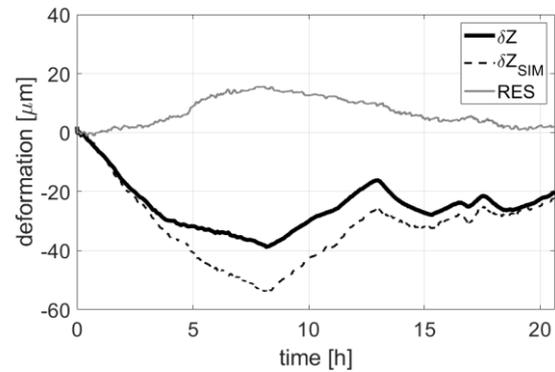


Fig. 5. Behaviours of measured, simulated and residual deformations during the test No. 2a.

Behaviours of measured temperatures over the time during experiment No. 3a (constant speed in the Z axis of target machine 1) are depicted in Fig. 6. The grey curve shows the feed rate in the Z direction of machine as a function of time.

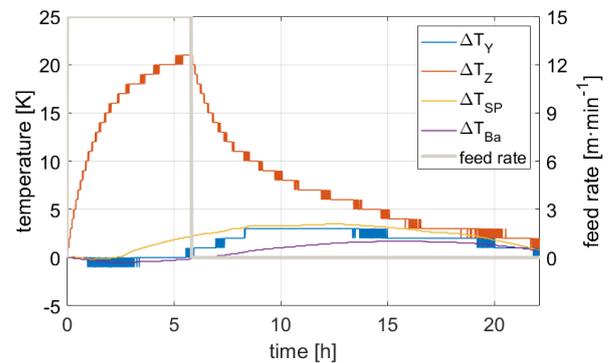


Fig. 6. Behaviours of measured temperatures and Z axis feed rate during test No. 3a.

Behaviours of the measured and simulated deformation in the machine Z direction and their residue over the time during the test No. 3a is shown in Fig. 7.

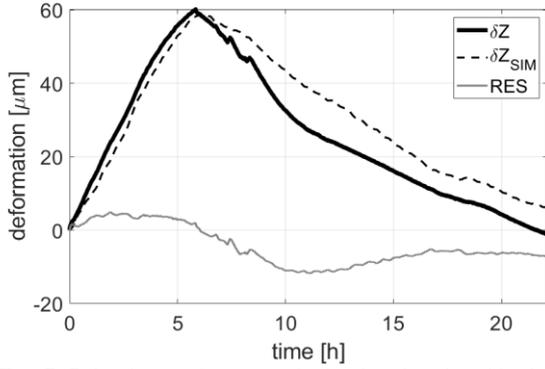


Fig. 7. Behaviours of measured, simulated and residual deformations during the test No. 3a.

4.2. Target machine with SP2

Behaviours of measured temperatures over the time during experiment No. 1b (spindle SP2 speed spectrum) is shown in Fig. 8. The grey curve depicts the spindle speed. Measured and simulated deformations along with their residue are depicted in Fig. 9.

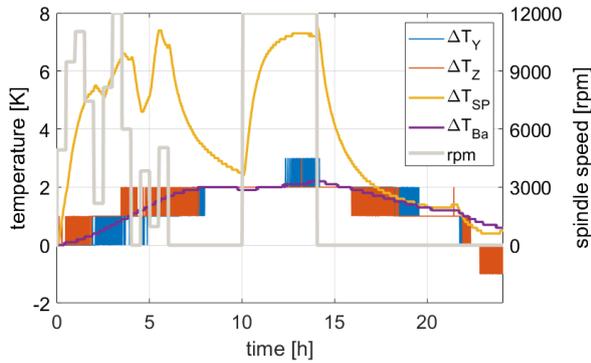


Fig. 8. Behaviours of measured temperatures and spindle speeds during test No. 1b.

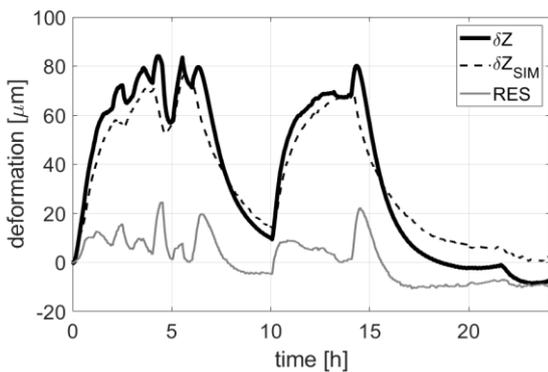


Fig. 9. Measured, simulated and residual deformations during test No. 1b.

Behaviours of measured temperatures over the time and curve of Y axis feed rate during the test No. 2b (constant speed in Y axis) for target machine 2 are shown in Fig. 10. Measured and simulated deformations along with their residue are depicted in Fig. 11.

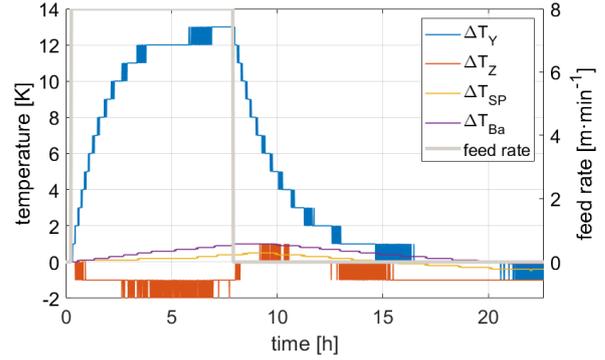


Fig. 10. Behaviours of measured temperatures and Y axis feed rate during test No. 2b.

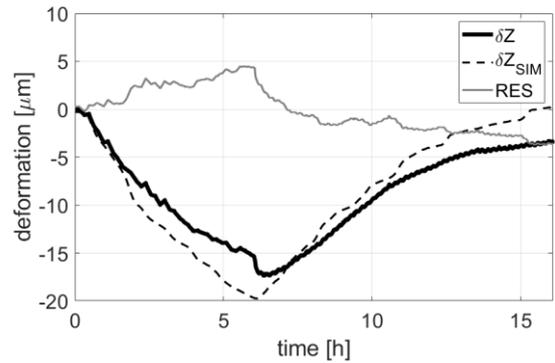


Fig. 11. Measured, simulated and residual deformations during the test No. 2b.

Behaviours of measured temperatures over of time and curve of Z axis feed rate during test No. 3b (constant speed in Z axis) are shown in Fig. 12. Measured and simulated deformations along with their residue are depicted in Fig. 13.

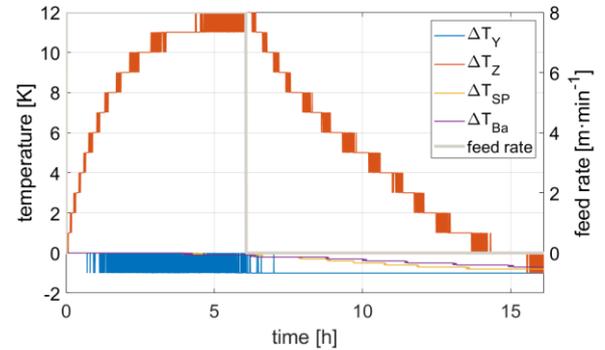


Fig. 12. Behaviours of measured temperatures and Z axis feed rate during test No. 3b.

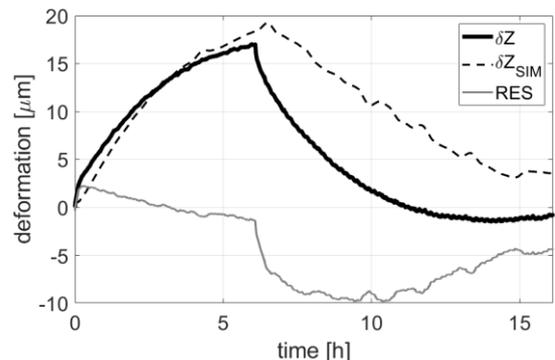


Fig. 13. Measured, simulated and residual deformations during the test No. 3b.

Table 5 lists the resulting *fit* values for the individual experiments carried out on target machines 1 and 2. The minimum and maximum values of the measured deformations and residual deformations are also given to compare the achieved improvement by application of the thermal error compensation model.

Table 5 An overview of the resulting values of *fit* and the minimum and maximum values of the measured and residual deformations.

Experiment	<i>fit</i> [%]	δZ (min;max) [μm]	REZ (min;max) [μm]
No. 1a	79	(-15;127)	(-17;22)
No. 2a	0	(-39;2)	(-1;15)
No. 3a	62	(-1;60)	(-12;5)
No. 1b	71	(-8;84)	(-11;24)
No. 2b	49	(-17;0)	(-4;4)
No. 3b	5	(-1;17)	(-10;2)

4.3. Result discussion

Based on the results shown in Table 5 is observed that the application of the thermal error compensation model always increased the production accuracy of the MT within the performed measurements. The thermal error of the machine was reduced from 33% to 73% of its original (uncompensated) state without intervention into model structure or calibration coefficients. In general could be concluded that the thermal error compensation model of the milling center is transferable between several machines of the same product line. Production inaccuracies, changes in the working environment and the effect of changes in the main heat source in the form of a spindle unit are taken into account.

Thermal error compensation model showed better results in the heating phases (see Fig. 2 to Fig. 7). The independent solution for both heating and cooling phases could further increase the MT accuracy. In the case the greater final production accuracy is required, creation of new thermal error compensation models for each target machine is recommended. However, this approach leads to a more complex models and a longer time spent on their development as well as the time necessary for new calibration and verification experiments. A change in the excitation (model input) value for approximation of influences of motion axes could be also considered for further enhancement of resultant accuracy. This means to place temperature sensors e.g. on a ball screw nut or a screw bearing instead of feed drives.

5. Conclusion

Application of existing compensation model of thermo-mechanical behaviour of a 5-axis milling center was described in this article. Compensation model considered influences of rotation of different spindle units, movements in two linear machine axes (*Y* and *Z*) and the different environment within experimental examination of two machines. The target machines of the same production line differ from the calibrated one by the serial number and type of spindle unit. The model uses inputs only from the

MT control system. Deformations were measured in a single machine axes configuration (no spatial error was considered). The results presented in this article show good applicability of the existing compensation model based on TF to introduced target machines without intervention into model structure. Moreover, the article contains a proposal for a modification of the compensation model to further increase of production accuracy.

Thanks

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List of symbols

<i>fit</i>	approximation quality [%]
<i>RES</i>	residue – difference between measured and simulated value [μm]
T_i	measured temperature [$^{\circ}\text{C}$] ($i = Ba, SP, Y, Z$)
<i>TCP</i>	tool centre point tool
δZ	measured deformation [μm]
δZ_{SIM}	simulated deformation [μm]
$\varepsilon_{Z,i}$	TF in the time domain [1] ($i = amb, SP, Y, Z$)
ΔT_i	measured temperature in relative coordinates [K] ($i = Ba, SP, Y, Z$)

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