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ADVANCED THERMAL ERROR COMPENSATION OF A FLOOR TYPE MACHINING CENTRE ALLOWING FOR THE INFLUENCE OF INTERCHANGEABLE SPINDLE HEADS

Thermal errors caused by internal and external heat sinks and sources may cause more than 50% of machine tool (MT) total error. Demands on machining accuracy and machine time utilization are still increasing. Therefore, research on thermal behaviour of MT structures is crucial for successful manufacturing. Direct (measuring between tool and work-piece) and indirect (predictive models) approaches to compensation of thermo-dependent tool centre point (TCP) displacement can be used to reduce sensitivity to heat flow or temperature control of MT and its environment. Thermal error indirect compensation is one of the techniques widely employed to reduce thermal errors due to its cost-effectiveness and ease of implementation. This paper is a continuation of scientific work on the modelling of complex MT thermal behaviour using a dynamic method with a physical basis: thermal transfer functions (TF). Previously published works focusing on middle-sized MTs are extended here to include heavy-duty MT application. Particular attention is paid to issues concerning compensation of thermal errors caused by interchangeable spindle heads.

1. INTRODUCTION

Spindle speed and feed rate of machine tool assemblies entail higher and dynamically changing power losses. As a result, the precision of machine tools and their operation are affected by the generated heat and its accumulation in the machine tool structure (and its environment) and by heat transmission. Moreover, machine tools placed on ordinary shop floors (without additional air conditioning) are exposed to thermally varying surrounding environment. The continuously changing operating conditions of a machine and thermally varying surrounding environment have a dynamically changing relation with the thermal errors at the TCP and workpiece itself. Demands for machining accuracy have been increasing over the last years. Therefore, this topic has been the focus of significant research activities recently [1].

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Different approaches exist to minimize thermal errors. In general, it is possible to divide the thermal error issue into three basic groups [2]:

- Design of the machine tool system to reduce sensitivity to heat flow (e.g. thermally symmetrical machine tool structure, high-cost materials with low values of thermal expansion coefficient, thermal insulation etc.);

- Temperature control of the machine tool and its environment (e.g. control of the machine tool cooling system, thermal actuator, electric heater etc.);

- Compensation of thermal errors.

Thermal deformation of machine tool structure cannot be sufficiently eliminated at the design stage or by using temperature control without high additional costs. On the other hand, **indirect thermal error compensation** (readjustment of the axes positioning by the machine tool's control based on mathematical models) is becoming a cost-effective way to improve accuracy of machine tools. The principle of the discussed method is schematically shown in Fig. 1.
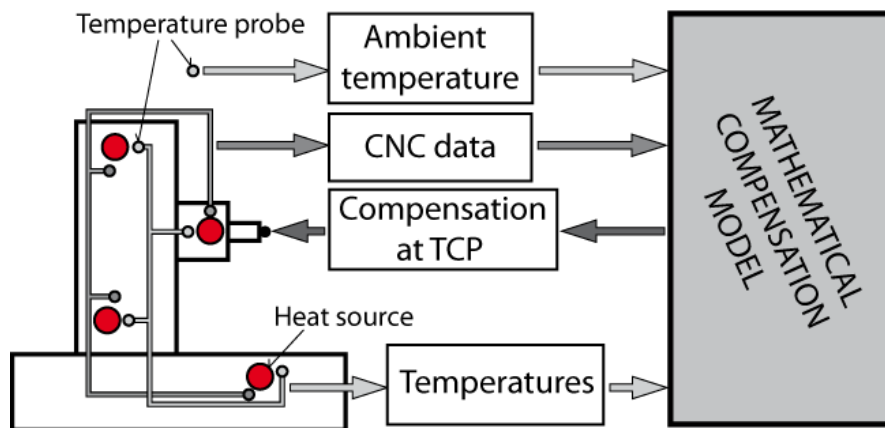

Fig. 1. Scheme of the indirect advanced compensation method

Many mathematical models have been developed to compensate thermal errors. The most common model for prediction of thermally induced displacements of MTs is obtained by multiple linear regression (MLR) [3]. These models, which are established in the form of an empirically calibrated polynomial expression, are overly restrictive since their coefficients are assumed to be constant for all operating conditions. While the processing time is short, the accuracy and reliability of the estimated thermal deflection are generally poor because the information from the unmeasured points on the structure is missing [4].

The TF contains the nature of the heat transfer principles. Thus, the calibration of the empirical parameters is simple, and the model is, in addition, more reliable with untested inputs. This modelling approach is dynamic and uses thermal history of the examined system. The modelling of thermally induced displacements of mechanical systems by using TF requires only few temperature probes in comparison with e.g. artificial neural network (ANN) [5] and provides comparable quality at least.

Conventional problems become unsolved when large part dimensions are involved [6]. Available literature dealing with thermal error models of heavy-duty MT (or its main components) has revealed the relationship between the thermal error and temperature from several different perspectives. These include inclusion of thermal deformation hysteresis fluctuation during seasonal weather into model structure [7], relation of thermal errors to temperature field, spindle speed and position in the workspace by finite element method (FEM) simulations leading to a semi-automatic thermal compensation solution [8], thermal error calculation relating temperature and current position of motion axis [9], precision cooling modelling for the heat exchanger of a heavy-duty MT based on FEM [10] or ram thermal error compensation also based on FEM [11]. Nevertheless, continuation work is seldom presented in the available literature, which has a direct connection with their robustness and lack of practical applicability. Moreover, time-consuming modelling methods [8],[10],[11] or static models [7],[9] are used for internal heat sinks and sources impact approximation in most cases.

This study concentrates on the evolution of extensive scientific work. An advanced modelling approach successfully applied to a number of middle-sized MTs [13],[14], [15],[16],[17],[18],[19] is tested here on a floor type machining centre. Two MT configurations (including interchangeable spindle heads) are taken into account. The identified approximation model is verified within the collective variation activity of calibrated thermal sinks and sources. Results of advanced model approximation quality are compared with a standard and current compensation model based on MLR.

2. EXPERIMENTAL SETUP

Data recording was performed with the National Instruments diagnostic devices and LabVIEW. The MT was equipped with 33 thermal probes (RTD) for a calibration measurement. The number of thermal probes was experimentally reduced to 3 favourable probes: $T_{bearings}$, $T_{spindle\ mot.}$ and $T_{reference}$ ($T_{bearings}$ is an external probe taking temperature of spindle bearings and $T_{spindle\ mot.}$ and $T_{reference}$ are probes from the MT control system taking temperature of the spindle motor and ambient temperature) for the prediction of thermal displacements. Schematic positions of the probes are depicted in Fig. 2.

Eddy current sensors were employed for noncontact sensing of displacements at the TCP. The paper focuses on thermal error compensation of the most affected direction − Z (*W1*) axis during the activity of heat sinks and sources caused by spindle rotation and ambient temperature. The second direction meant to approximate (*Y* axis) on the MT was solved similarly to the discussed Z direction with the same succession and without any demands on additional number of temperature probes. Thermal deformations occurred in the last direction (*X* axis) were negligible in comparison to the others. All Experiments were carried out at one point of the MT workspace.

Calibration and verification tests were executed for the MT in a **basic configuration** where spindle is directly equipped with a tool and a **configuration with a spindle head**.
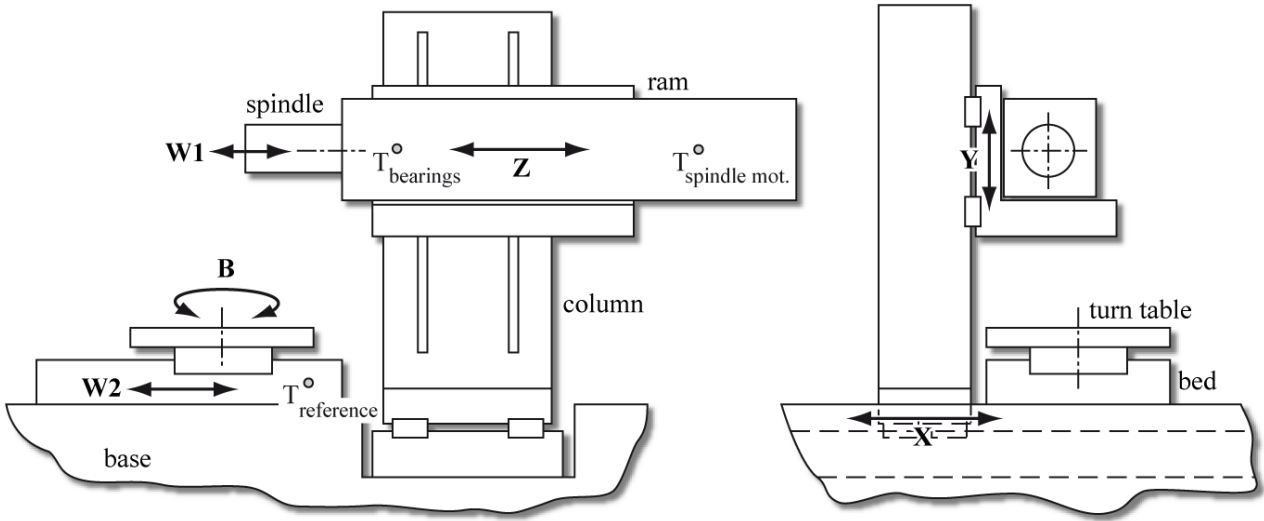
Fig. 2. Schema of a floor type machining centre

3. COMPENSATION MODEL OF THERMAL ERRORS

All data processing and TF identification, as well as MT thermal behaviour modelling and verification, were performed in *Matlab* and *Matlab Simulink*.

A discrete TF was used to describe the link between the excitation and its response. The differential form of the TF in the time domain is introduced in eq. (1):

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

where $u(k)$ is the TF input vector in time domain, $y(k)$ is the output vector in time domain, a_n are weight factors of TF input, b_m are weight factors of TF output and k-n (k-m) means the n-multiple (m-multiple) delay in sampling frequency. Linear parametric models of ARX (autoregressive with external input) or OE (output error) identifying structures were used. The quality of each TF was examined through linear time invariant (LTI) step response [12].

The excitation in the case of the TF means temperature measured close to a heat source and the response stands for caused deflection of the examined direction Z.

$$fit = \left(1 - \frac{\|Y - Y_{HAT}\|}{\|Y - \bar{Y}\|}\right) \cdot 100 \qquad (2)$$

$$\|x\| = \sqrt{x_1^2 + x_2^2 + \cdots + x_n^2} \qquad (3)$$

$$residue = Y - Y_{HAT} \qquad (4)$$

The approximation quality of the simulated behaviour is expressed in eq. (2). This value expresses the percentage of the output variation that is reproduced by the model [12]. The Y value in eq. (2) and eq. (4) means the measured output (thermal deformation), Y_{HAT} is the simulated/predicted model output and $\bar{Y}$ in eq. (2) expresses the arithmetic mean over time of the measured output. The vector norm used in eq. (2) is generally expressed in eq. (3).

The error of approximation is expressed as shown in eq. (4).

All displacements were measured at the stator ($\delta_{Zstat.}$) and TCP (δ_Z) part of Z direction. A difference $\Delta\delta_Z$ (rotor part) used as well in the approximation model is expressed by eq. (5). A closer description of the measured coordinates $\delta_{Zstat.}$, δ_Z and $\Delta\delta_Z$ will be specified in the following calibration and identification part of the paper.

$$\Delta\delta_Z = \delta_Z - \delta_{Z\,stat.} \tag{5}$$

In the view of the fact that time constants of transient processes in the heavy-duty MT cases are rather longer (up to 12 hours in heating and more than 30 hours in cooling phase) than in the case of middle-sized MT [4], the approximation model has to be considered from the calibration time point of view. The approximation of TCP deflection (δ_Z) with the help of a superposition principle [13] follows the above-mentioned requirement and is expressed by:

$$\delta_{Z\,approx} = \underbrace{\left(\Delta T_{spindlemot.} - \Delta T_{reference}\right)\cdot\varepsilon_1}_{\delta_{Z\,stat.}} + \underbrace{\left(K_1\cdot\varepsilon_2 + K_2\cdot\varepsilon_3\right)\cdot\left(\Delta T_{bearings} - \Delta T_{reference}\right)}_{\Delta\delta_Z} \tag{6}$$

where $\delta_{Zapprox.}$ is overall approximation value of thermal deformation at TCP in Z direction and K_1 and K_2 are coefficients indicating the MT configuration ($K_1 = 1$ and $K_2 = 0$ for MT in basic configuration and contrary to previous statement $K_1 = 0$ and $K_2 = 1$ for MT in configuration with a spindle head), ε_1 is TF approximating stator part deflection ($\delta_{Zstat.}$) of MT in basic configuration, ε_2 is TF approximating the difference $\Delta\delta_Z$ of MT in basic configuration and ε_3 is TF approximating the difference $\Delta\delta_Z$ of the spindle head.

This model type allows us to solve the stator and rotor part of the headstock assembly separately with subsequent superposition ($\delta_{Zstat.}$ and $\Delta\delta_Z$ part in eq. (6). The advantage of the model presented in eq. (6) lies in the opportunity to measure the whole MT assembly only in basic configuration (to achieve $\delta_{Zstat.}$ approximation in particular). An interchangeable spindle heads contribution (the $\Delta\delta_Z$ part in eq. (6)) can be measured independently on the MT (e.g. with the help of a test bed). It is necessary to realize two calibration measurements to identify the 3 TFs (ε_1, ε_2 and ε_3) from eq. (6). A principle of a TF identification is described e.g. in [14] with more general details.

3.1. CALIBRATION OF MACHINE TOOL IN BASIC CONFIGURATION AND TF IDENTIFICATIONS

A scheme of the floor type machining centre in basic configuration alongside with

displacement measurement setup is depicted in Fig. 3. Generally, calibration should describe a transient characteristic between two thermodynamic equilibria; one with the MT surroundings and one with all active thermal sinks and sources meant to be approximated.
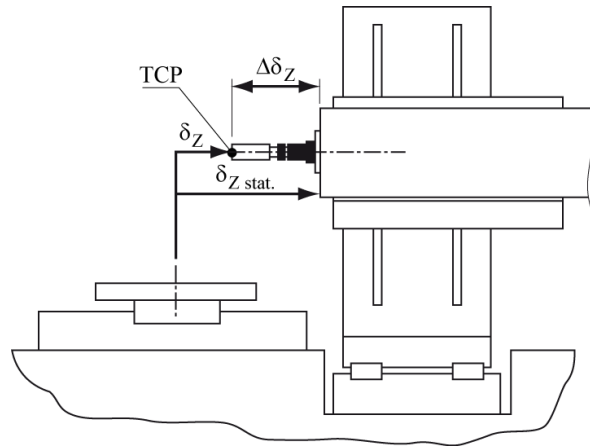

Fig. 3. Schema of a displacement measurement at TCP of a floor type machining centre in basic configuration
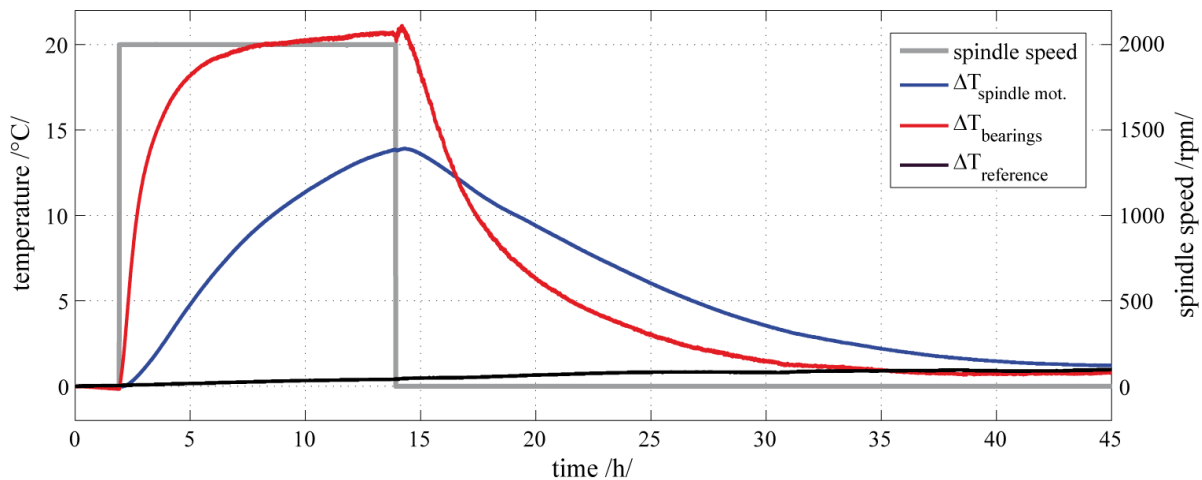

Fig. 4. Measured relative temperatures on MT structure and relevant NC data during constant rpm calibration experiment executed on a floor type machining centre in basic configuration

The calibration experiment consists of spindle rotation at constant rpm and ambient temperature impact. Relevant temperatures (their positions are visible in Fig. 2) in relative coordinates (in other words the TFs excitation is zeroed) collected during both transient characteristics (heating and cooling phase) are shown in Fig. 4. Spindle revolutions are visible in the same figure.

An ambient temperature influence is obvious from the $\Delta T_{\text{reference}}$ behaviour in Fig. 4 and behaviour of δ_Z and $\delta_{Z\text{stat.}}$ in Fig. 5. A temperature difference according to eq. (7) (also used in eq. (6)) is used as a final excitation of TFs to avoid the MT surrounding influence.

$$\Delta T_{excit.} = \Delta T_i - \Delta T_{reference} \tag{7}$$

where $\Delta T_{excit.}$ is final excitation in relative coordinates of identified TFs and ΔT_i means $\Delta T_{\text{spindle mot.}}$ or $\Delta T_{\text{bearings}}$. A favourable excitation of $\delta_{\text{Zstat.}}$ by $T_{\text{spindle mot.}}$ and $\Delta\delta_Z$ by T_{bearings} was determined experimentally.

Measured and calculated displacements (in their relative form related to maximal value from all measured thermal deformations during the calibration measurement) of examined direction Z are shown in Fig. 5.
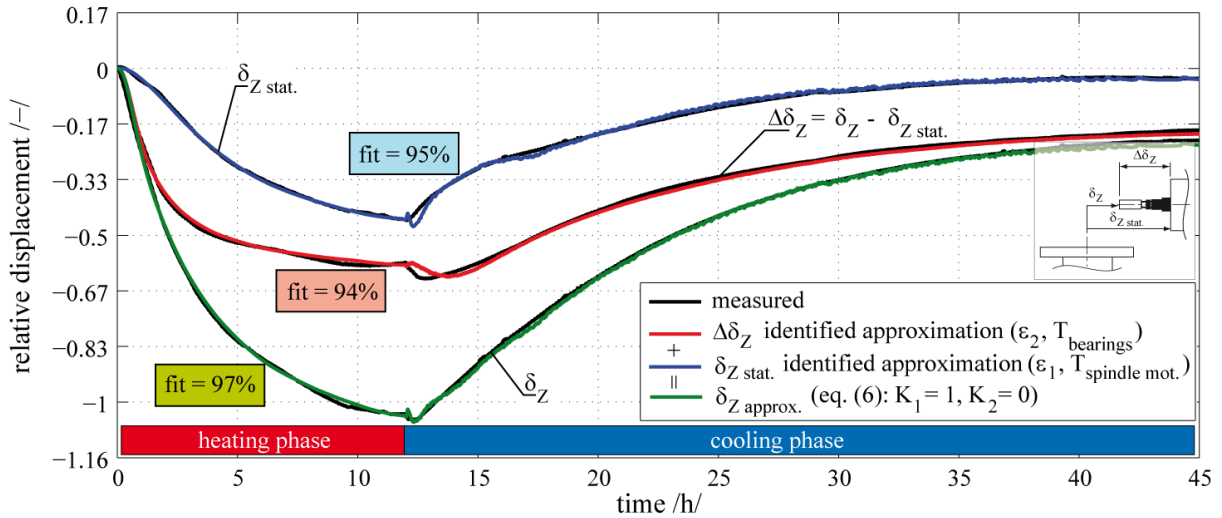
Fig. 5 Measured and simulated thermal displacements of examined direction Z during constant rpm calibration experiment executed on a floor type machining centre in basic configuration

The black curves in Fig. 5 represent measured thermal deflections at TCP (δ_Z), stator part ($\delta_{\text{Zstat.}}$) and their difference ($\Delta\delta_Z$); the blue curve denotes the stator part TF's (ε_1 in eq. (6)) identified response with $\Delta T_{\text{spindle mot.}} - \Delta T_{\text{reference}}$ excitation; the red curve stands for identified approximation (ε_2 in eq. (6)) of difference $\Delta\delta_Z$ (eq. (5)) with $\Delta T_{\text{bearings}} - \Delta T_{\text{reference}}$ excitation; and the green curve is a result of TF model application according to eq. (6) with coefficients $K_1 = 1$ and $K_2 = 0$ (MT in basic configuration) and has rather an informational character in Fig. 5. The approximation quality of individual TFs and the model application is expressed by the *fit* value (eq. (2)).

3.2. CALIBRATION OF MACHINE TOOL WITH SPINDLE HEAD AND TF IDENTIFICATION

A scheme of the floor type machining centre in configuration with the spindle head alongside with displacement measurement set-up is depicted in Fig. 6. The calibration experiment consists of spindle rotation at constant rpm and ambient temperature impact. Relevant temperatures (their positions are visible in Fig. 2) in relative coordinates collected

during the heating phase only are shown in Fig. 7. Spindle revolutions are visible in the same figure.
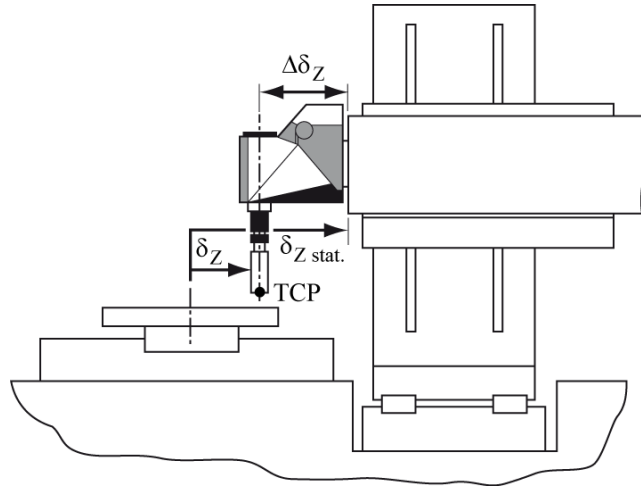

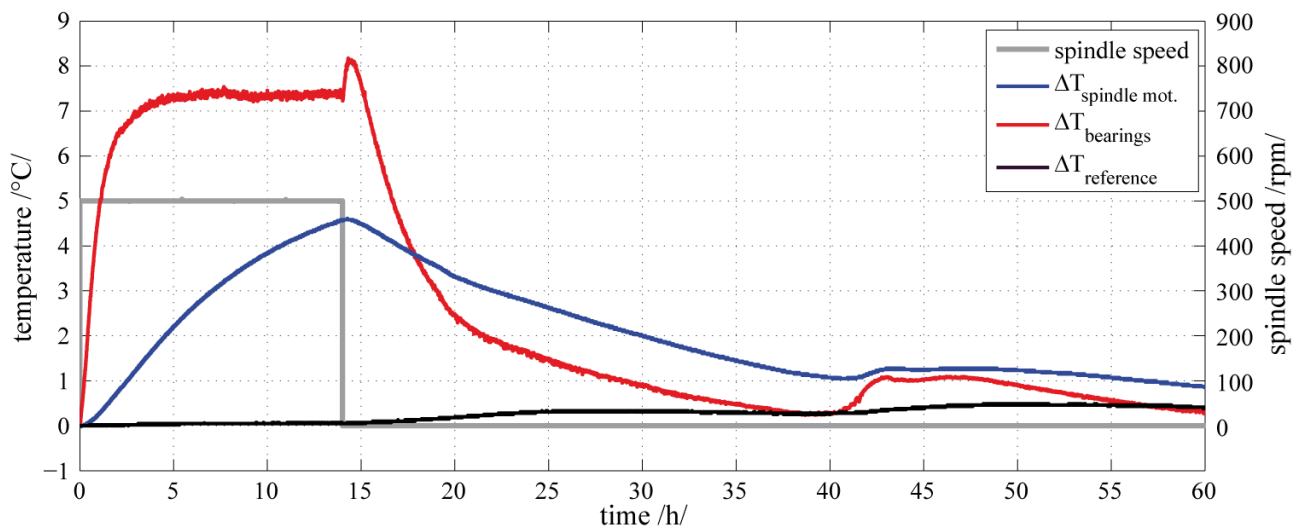Fig. 6. Schema of a displacement measurement at TCP of a floor type machining centre with the spindle head

Fig. 7. Measured relative temperatures on MT structure and relevant NC data during heating phase of constant rpm calibration experiment executed on a floor type machining centre in configuration with the spindle head

Measured and calculated displacements (in their relative form) of the examined direction Z are shown in Fig. 8. Favourable excitations are congruential to the MT in basic configuration case. The approximation of the rotor part (red curve in Fig. 8) expressed by ε_3 in eq. (6) is the only identified TF obtained from the calibration measurement. The gray curve stands for $\varDelta\delta_Z$ approximation by ε_2 identified in the MT in basic configuration case and applied to the discussed configuration with the spindle head. This application has an informational character in Fig. 8 and serves as a confirmation of different thermal behaviour occurring in both MT configurations. The approximation quality of individual TFs is expressed in the figure by the fit value (eq. (2)).
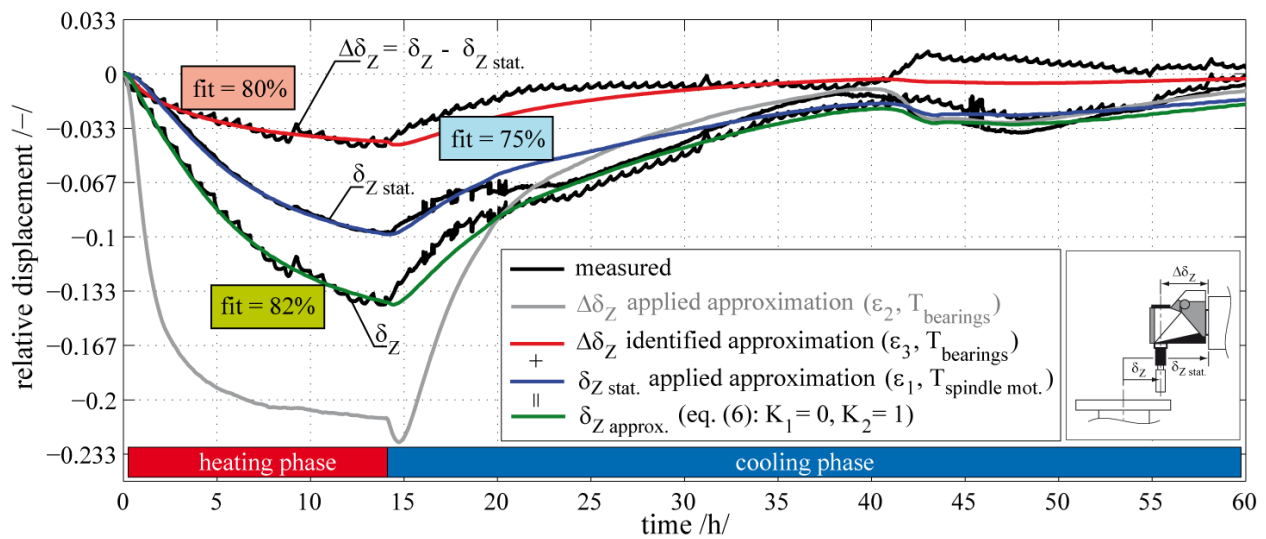
Fig. 8. Measured and simulated thermal displacements of examined direction Z during constant rpm calibration experiment executed on a floor type machining centre in configuration with the spindle head

The assertion that the spindle head has a negligible impact on the rest of the MT structure can be confirmed by comparing Fig. 5 and Fig. 8. Quality approximation was achieved in both cases by one TF identified for stator part ($\delta_{Z\,stat.}$) approximation.

4. VERIFICATION OF THE MODELLING APPROACH

Three TFs were identified from calibration measurements for approximation of thermal sinks and sources impact caused by the activity of spindle rotation and ambient temperature (eq. (6); the principle of the model is also shown in Fig. 9 for the MT in basic configuration and the MT with the spindle head. Only approximation of thermal deflection in the most affected Z direction was considered at one point of the workspace.
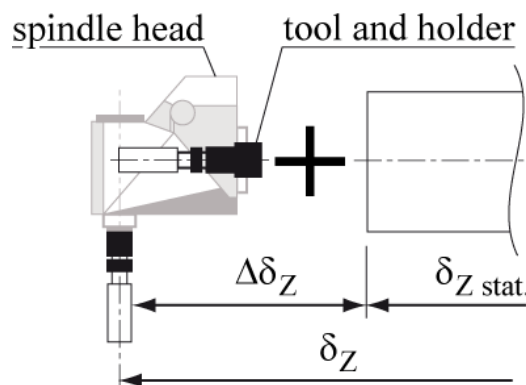

Fig. 9. Schema of TF model using superposition principle

4.1. VERIFICATION OF COMPENSATION MODEL OF MACHINE TOOL IN BASIC CONFIGURATION

A verification experiment consisting of calibrated thermal sinks and sources was designed for clear verification of the compensation model. Varying spindle revolutions are active in the first part of the spectrum (up to 12 hours). An over sixty-hour-long cooling phase follows. Relevant temperatures in relative coordinates collected during the verification test are shown in Fig. 10. The result of the approximation is shown in Fig. 11.
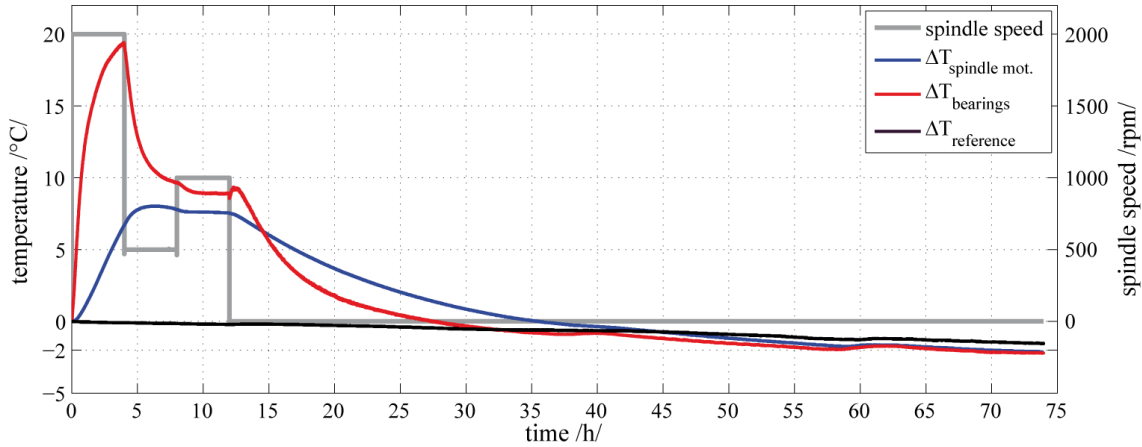

Fig. 10. Measured relative temperatures on MT structure and relevant NC data during verification experiment with spindle speed variation executed on a floor type machining centre in basic configuration
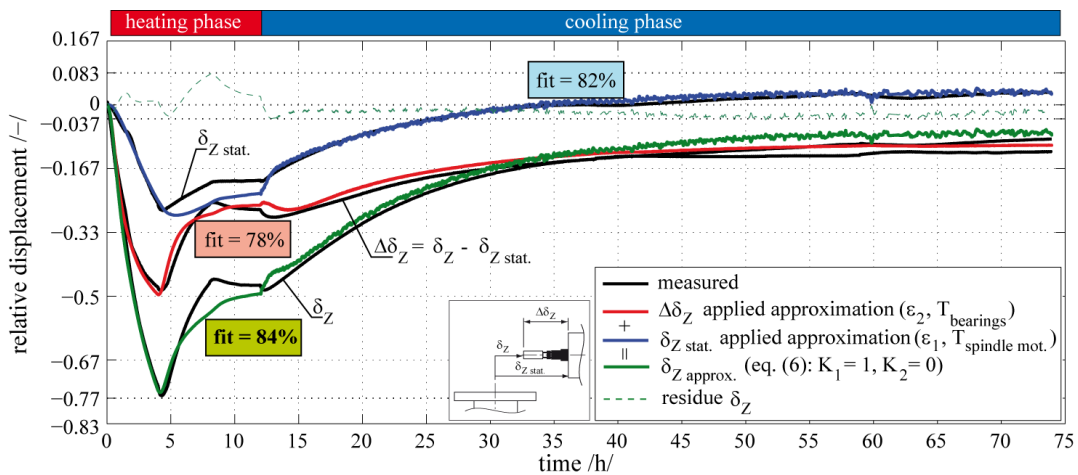

Fig. 11. Measured and simulated thermal displacements of examined direction Z during verification experiment with spindle speed variation executed on a floor type machining centre in basic configuration

The fit value of the TCP thermal deformation simulated by the TF model (eq. (6)) is equal to 84%. In other words, the resultant deformation after the TF model application is more than 6 times smaller in comparison to the uncompensated state. Compensation of clearly visible ambient temperature impact by the TF model is very satisfying as well.

4.1. VERIFICATION OF COMPENSATION MODEL WITH SPINDLE HEAD

A similar verification experiment using the MT in basic configuration was carried out in the MT with the spindle head case. Relevant temperatures in relative coordinates collected during the verification test are shown in Fig. 12. The result of the approximation is shown in Fig. 13.
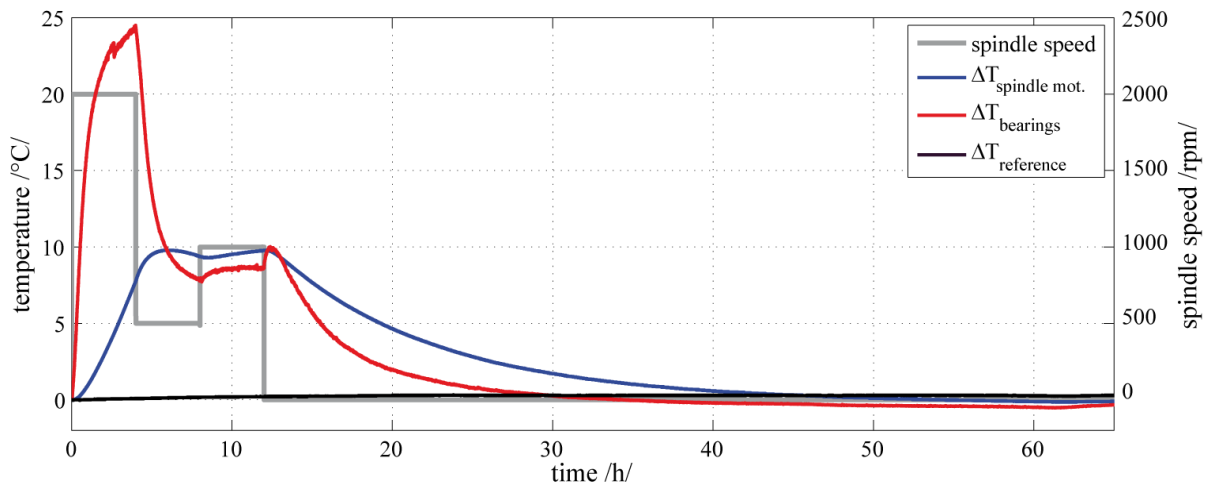

Fig. 12. Measured relative temperatures on MT structure and relevant NC data during verification experiment with spindle speed variation executed on a floor type machining centre in configuration with the spindle head
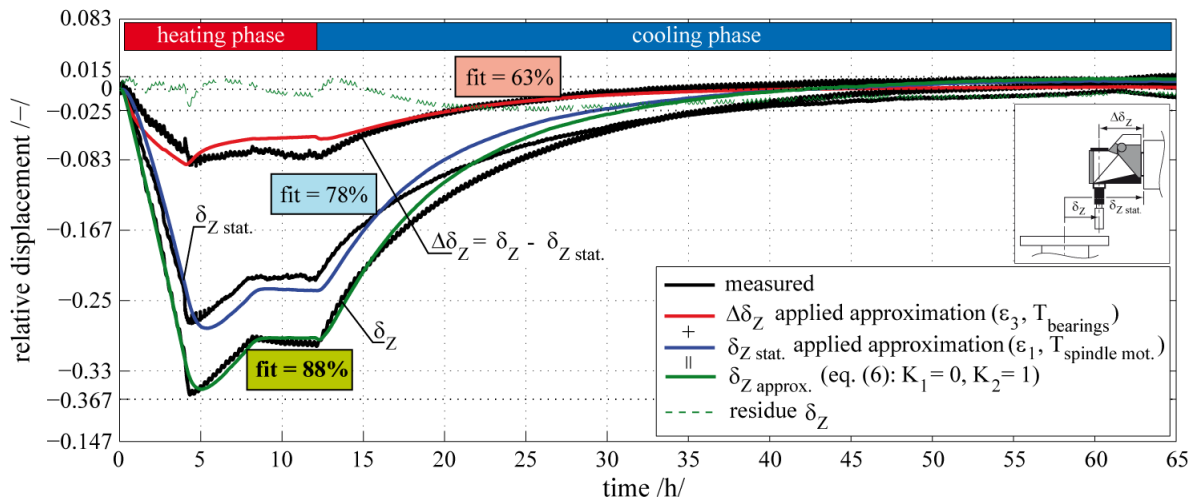

Fig. 13. Measured and simulated thermal displacements of examined direction Z during verification experiment with spindle speed variation executed on floor type machining centre in configuration with the spindle head

The fit value of thermal deformations simulated by the TF model (eq. (6)) is equal to 88%. In other words, the resultant deformation after the TF model application is more than 9 times smaller in comparison to the uncompensated state. Applicability of TF model using the superposition principle according to eq. (6) was confirmed.

5. CONCLUSIONS

The advanced model based on TFs presents a robust approach to modelling of MT thermal behaviour, uses a minimum of additional gauges and can approximate all influences participating in thermal error as one unit.

This paper considerably extends knowledge obtained in previous work [13],[14],[15],[16],[17],[18],[19] by application of a fundamental modelling approach to a heavy-duty MT. Thermal behaviour of the floor type machining centre was approximated by a modelling approach requiring only one calibration measurement on a complete MT assembly. The model verification during varying collective activity of calibrated thermal sinks and sources was presented with highly satisfying results in comparison with the uncompensated state. An additional model comparison from the approximation quality point of view with a standard and current thermomechanical model of the MT based on MLR is shown in Fig. 14 for the MT both in basic configuration and with the spindle head.
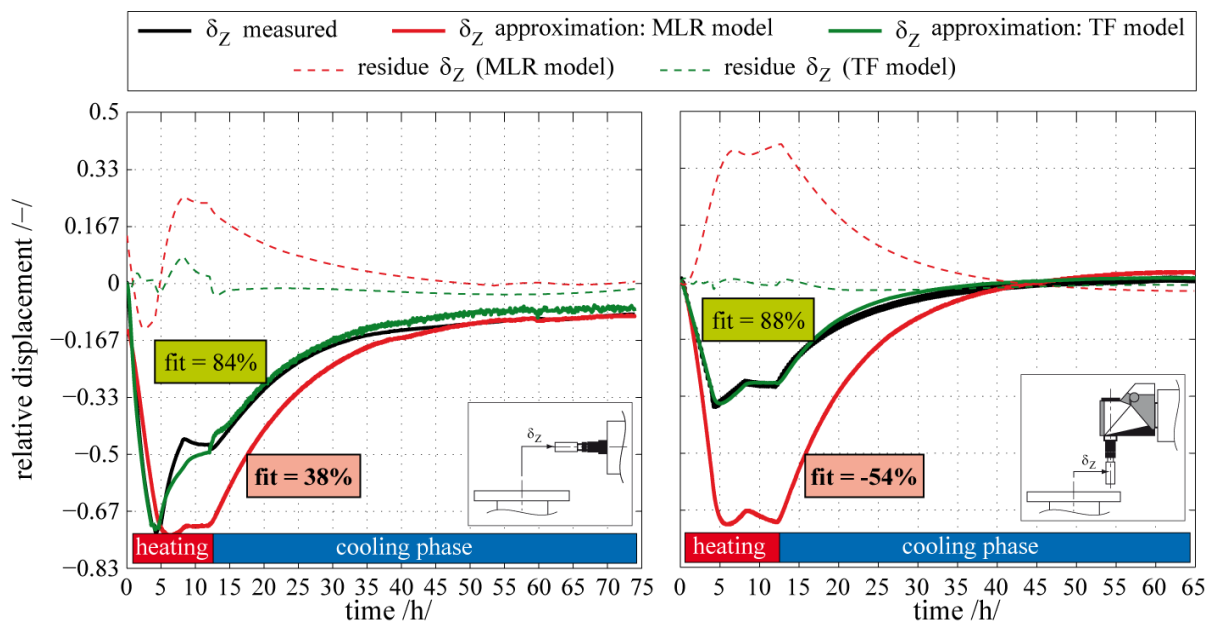

Fig. 14. Approximation quality of standard compensation method (MLR) and TF model comparison during verification experiments executed on a floor type machining centre in basic configuration (left) and with spindle head (right)

The MLR model was calibrated during a similar experiment as shown in Fig. 4. This simple model does not distinguish between the MT configurations, which is reflected in Fig. 14 by lamentable residual thermal error (thin red line) especially after spindle revolution changes.

The immediate future work should concentrate on including more thermal sinks and sources into the MT thermal behaviour description (real cutting process and its impact on a final workpiece, a long term influence of ambient temperature on MT parts, axes movement, etc.), extending the model validity out of the calibrated point in workspace

(volumetric thermal error), testing model portability to the same type of the MT with a different product number, general extending of the portfolio of heavy-duty MTs with advanced thermal error compensation and applying effort to approximation model unification.

ACKNOWLEDGMENTS

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