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ROBUSTNESS AND PORTABILITY OF MACHINE TOOL THERMAL ERROR COMPENSATION MODEL BASED ON CONTROL OF PARTICIPATING THERMAL SOURCES

Thermal errors caused by the influence of internal and external heat sources in machine tool structure can cause more than 50% of total machine tool inaccuracy. Therefore, research on thermal behavior of machine tool structures is crucial for successful manufacturing. This paper provides an insight into the modeling of highly nonlinear machine tool thermal errors using thermal transfer functions (TTF). The method is dynamic (uses machine tool thermal history) and its modeling and calculation speed is suitable for real-time applications. The method does not require interventions into the machine tool structure, uses very few additional gauges and solves separately each influence participating on thermal error. The paper focuses on the development of a robust thermal model sensitive to various machine tool thermal behavior nonlinearities with the help of minimum input information. Model was applied on real machine tool (portal milling centre) and was verified within a complicated electro-spindle revolution spectrum. Moreover, the said compensation model was applied on another machine tool to prove its robustness and portability among machines of the same type set and the results of the TTF model were compared with a model obtained via multiple linear regression (MLR) as a case study.

1. INTRODUCTION

The constant increase in spindle speeds and feed motions of machine tool assemblies entails higher and dynamically changing power losses. As a result, the precision of machine tools and their operations is affected by the generated heat and its accumulation in the machine tool structure (and its environment) and by the heat transmission.

Moreover, machine tools placed in 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

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have a nonlinear and dynamically changing relation with the thermal errors at the tool center point (TCP).

Generally, there are three influences on the working accuracy of a machine tool: static, dynamic and thermo-dependent behavior. Due to scientific achievements in the static and dynamic field of research, the thermal influence on machine tool behavior increases [1].

Thermal effects caused by internal (motors, drives, bearings, ball screws and their nuts, gear box etc.) and external heat sources (effect of the environment, machine operator, radiation etc.) can contribute more than 50% to the overall error [2],[3]. Furthermore, there are continuously increasing demands for machining accuracy in recent years. Therefore this topic is the focus of significant recent research activities [4],[5].

The interest of the manufacturing industry in this topic can also be seen in the latest international standards. In the last two decades a number of international standards [6],[7],[8] with measurement standards and performance parameters to assess the thermal behavior of machine tools under no load and finishing conditions have been developed.

2. STATE OF THE ART

Different approaches exist to minimize thermal errors. In general, it is possible to divide the thermal error issue into three basic groups [3],[9]:

- **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 [10], [11], thermal insulation [12] etc.).
- **Temperature control of machine tool and its environment** (e.g. control of machine tool cooling system [13], electric heater [14] thermal actuator [15], air conditions [16] etc.).
- **Compensation of the thermal errors** - generally, two alternatives for the compensation of thermo-dependent TCP displacement can be classified: **direct compensation** (the resulting displacements are intermittently measured and superposed to the desired position value of the particular axis, the disadvantage of the direct approach is the required interruption of the process in order to measure the displacement) or **indirect compensation** methods (readjustment of the axes positioning by the machine tool’s control based on mathematical models).

Thermal deformation of machine tool structure cannot be sufficiently eliminated at the design stage and/or using temperature control without high additional cost. On the contrary, indirect thermal error compensation is becoming a cost-effective way to improve accuracy of machine tools.

A lot of mathematical models to compensate the thermal errors are developed. The most common model for prediction of thermally induced displacements of machine tools is obtained by multiple linear regressions (MLR) [17],[18]. 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 small, the accuracy and reliability of the estimated thermal deflection are generally poor, because there is information missing from the unmeasured points on the structure [19].

Furthermore, the displacement of the TCP can be calculated by an artificial neural network (ANN) [20], [21], a fuzzy logic [22], [23] or a transfer function model (TF) [24].

The input of the estimated TF can be NC-data like spindle speed, effective power, electric current, torque or feed rate [25], [26] or the temperatures of the machine structure can also be used as an input (thermal transfer function denominated as TTF) [27]. 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 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 modeling of thermally induced displacements of mechanical systems by using TTF requires only few temperature probes in comparison with e.g. ANN, and provides quality comparable to time-consuming methods such as finite element analysis (FEM) [28].

Works treating advanced thermally induced displacements modeling based on TTF, which combines different inputs such as temperature sensors placed on a horizontal milling machine tool structure and rotational spindle speed, are presented in [29], [30]. This study primarily concentrates on the robustness of the modeling approach mentioned above.

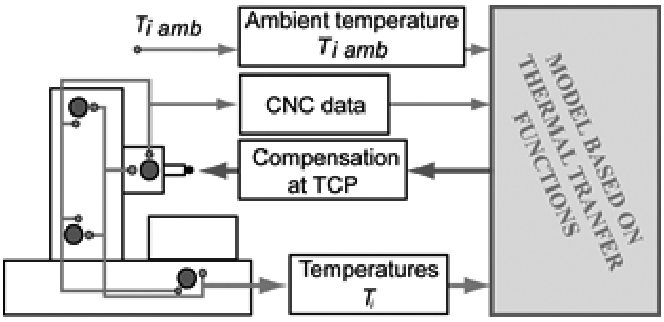

Fig. 1. Scheme of the indirect compensation method based on TTF

The model was applied on a portal milling centre in this case and verified within a complicated electro-spindle speed spectrum under varied conditions. Model portability among machines of the same type set was proved as well and commonly used method utilizing MLR was computed simultaneously to TTF model for comparative motive. The principle of the discussed indirect compensation method is shown in Fig. 1.

3. EXPERIMENT

Data recording, along with the implementation of thermo-elastic models as a control system, were performed with the *National Instruments* diagnostic devices and *LabVIEW*.

Compensations of thermal errors at TCP have been developed and experimentally verified on a portal milling center (Fig. 2).

The maximum revolutions of the spindle were 12000rpm. A procedure for obtaining a compensation algorithm based on TTF combines mathematical modeling with empirical calibration.

3.1. EXPERIMENTAL SETUP

The machine tool was equipped with 70 thermal probes (RTD) for calibration measurements. The number of thermal probes was reduced from the original 70 to 4 probes: T_{30}, T_{58}, T_{62}, and T_{63} (T_{30} taking spindle temperature, T_{58} taking ambient temperature, and T_{62}, T_{63} taking coolant temperatures at the inlet and outlet of the electrospindle cooling circuit) for the prediction of thermal displacement in direction x, y and z based on the TTF compensation algorithm (an additional input of the TTF model is spindle rotational speed).

The remaining temperatures T_1, T_7, T_{12}, T_{13}, T_{15}, T_{26}, T_{29}, T_{44} in association with T_{30} depicted in Fig. 2 were selected as independent variables for MLR models according to the values of correlation coefficients.

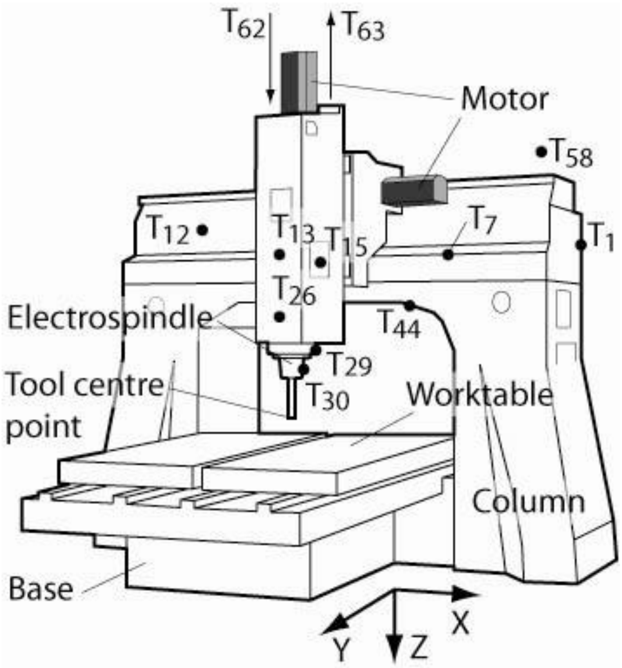

Fig. 2. Resistance thermometers on a portal milling centre

Capacitive sensors are employed for noncontact sensing of displacements at the TCP (in directions x, y and z according to Fig. 2) in nanometre resolution. Thermal displacements in the x and y axes were measured in 2 points to observe also angular displacement (the distance between sensors was 100mm).

Thermal deformations in the x direction are almost negligible compared to the other directions. This fact results from the symmetry of the machine tool structure. Thus the thermal displacements in the y and z directions (according to Fig. 2) were compensated. Compensation in the x direction only depends on changes in ambient temperature (thermal deformations caused by the main source are generally negligible).

3.2. CALIBRATION MEASUREMENTS

Generally, 3 calibration measurements were carried out to obtain 6 TTFs describing the machine tool thermal behaviour with the help of a TTF model. The total time of the calibration measurements was up to 64 hours of deflection description in all three directions. It was necessary to carry out 2 calibration measurements (heating phase at 6000rpm and cooling phase at 6000rpm) for describing the thermal behaviour of the electro-spindle due to its rotation (16 hours). The ETVE (environmental temperature variation error according to [7]) test was used for the calibration measurement of ambient temperature influence (48 hours).

Calibration measurement for MLR model training was performed under variation of electro-spindle speed (electro-spindle speed spectrum). This measurement had a duration of 12 hours.

4. COMPENSATION ALGORITHM BASED ON COMBINATION OF TEMPERATURES AND CNC DATA

All data processing and TTF identification, as well as machine tool (MT) thermal behavior modeling and verification, were performed in *Matlab* and *Matlab Simulink*.

The error of approximation is expressed as shown in Eq. (1). It also represents the fictitious deformation obtained after implementing the model in the control system.

The approximation quality of the simulated behavior is expressed by the *fit* (*%*) value (2) and so-called peak-to-peak residual expression *Δ* (3). The former value expresses the percentage of the output variations that is reproduced by the model [31], and the latter shows the maximal absolute residual deformation along the whole progress of the thermal error.

$$error = Y - Y_{HAT} \tag{1}$$

$$fit = \frac{Y - Y_{HAT}}{Y - \overline{Y}} \ .100 \tag{2}$$

$$\Delta = \max(error) + \min(error) \tag{3}$$

The Y value in Eq. (1) and (2) means the measured output (thermal deformation) , Y_{HAT} is the simulated/predicted model output and $\overline{Y}$ in Eq. (2) expresses the arithmetic mean of the measured output.

4.1. THERMAL TRANSFER FUNCTION MODEL

The described TTF model consists of a variety of TFs controlled by CNC data (electro-spindle revolution *n* in this example).

A discrete 2nd order TF was used to describe the link between the excitation and its response (Eq. (4) and (5)).

$$y\ t\ = \varepsilon.u\ t\ + e(t) \tag{4}$$

$$y\ t\ = \frac{a_1 z^{-1} + a_0 z^0}{b_2 z^{-2} + b_1 z^{-1} + b_0 z^0} u(t) \tag{5}$$

where *u(t)* is the TTF input vector in time domain, *y(t)* the output vector in time domain, ε is TTF in time domain, *e(t)* is disturbance value [31], a_i are weight factors of TTF input and b_i are weight factors of TTF output.

The differential form of the TF in the time domain is introduced in (6):

$$y\ k\ = \frac{u\ k-1\ a_1 + u\ k\ a_0 - y\ k-2\ b_2 - y\ k-1\ b_1}{b_0} \tag{6}$$

where *k-n* means the *n*-multiple delay. Linear parametric models of ARX (autoregressive with external input) or OE (output error) identifying structures were used [31]. The quality of each TTF was examined through linear time invariant (LTI) step response [32].

The excitation in this case means temperature measured close to a heat source and the response stands for caused deflection on TCP.

The main advantage of the model lies in its decomposition into individual elements and blocks describing the above-mentioned nonlinear behavior of MT. All of these elements are solved independently, and it is possible to extend them as necessary in response to the requirements of individual applications.

The described TF model concentrates on cover thermally induced deflections caused by electro-spindle rotation. More specifically, it is necessary to specify two influences besides the main heat source generated in spindle bearings:

- Influence of ambient temperature.
- Forced convection.

Deflection calibration measurement on the stator part of the spindle in addition to TCP (the rotating part of the spindle which is directly exposed to the forced convection impact) assures avoiding the forced convection influence in the cooling phase. Hence, the cooling phase obtained after a constant electro-spindle speed of 6000rpm measured until steady state was used for identification of the main heat source caused by electro-spindle bearings (T_{30} as an excitation). A closer view on the identification result is depicted in Fig. 4 for both phases. The shape of the electro-spindle speed curve was used as an excitation for the identification of both forced convection elements (in heating and cooling phase). The impact of the first influence – ambient temperature – on measured data was negligible.

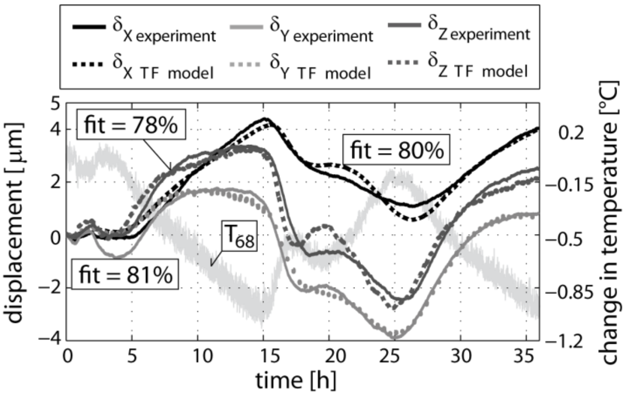

Fig. 3. Calibration measurement and identification of TTFs according to ETVE

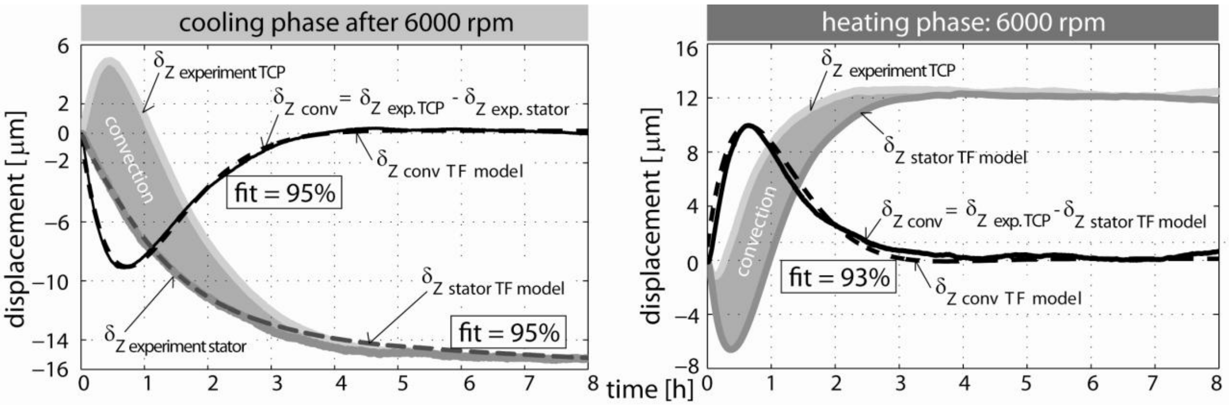

Fig. 4. Identification of influences caused by forced convection in cooling (left) and heating (right) phase

Complete calibration development and verification of the mentioned approach (electro-spindle under 9000 rpm condition) is visible in the following graphs.

The first influence was determined according to ETVE measurement standards [7]. The temperature T_{68} (Fig. 2) was used as an excitation. The result of calibration measurement and TTF identifications is visible in Fig. 3.

The difference between the heating and cooling phase [29] is mainly caused by the presence of the second influence - forced convection (produced by rotating parts of the electro-spindle) [33]. Therefore, the strength of the influence is obtained by simple subtraction of the main source element (caused by spindle bearings) from the measured deformation on TCP.

Approximation of thermal deformation in the *y* direction manages only with a combination of the main source (spindle bearings) and the influence of ambient temperature. Impacts of the remaining elements (forced convection in heating and cooling phase) were ascertained as insignificant.

The model depends on a decision block, which is represented in the model by current electro-spindle revolutions. A simple switch element chooses the appropriate TTFs to approximate thermal errors, depending on the states of the machine tool (e.g. a heating or cooling phase, switch from one rev to another etc.).

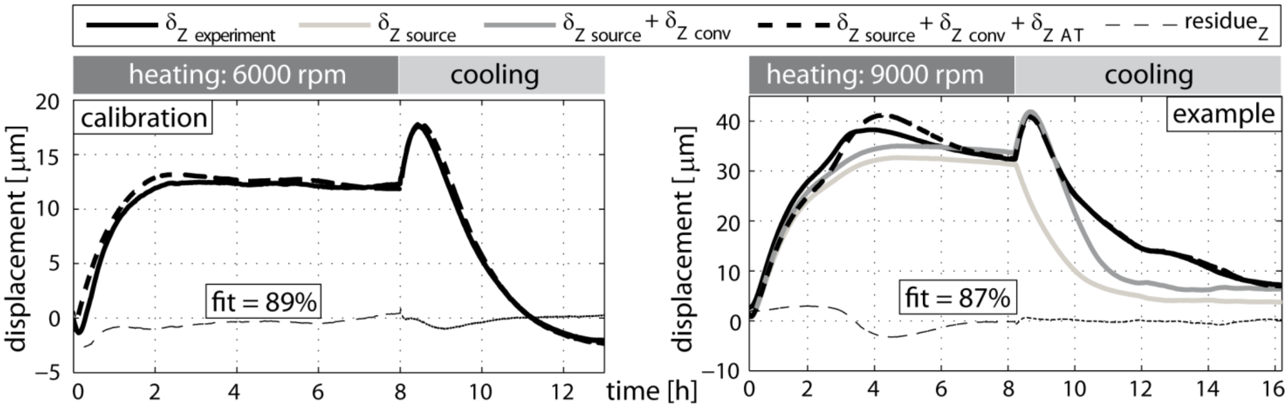

Fig. 5. Calibration measurement and approximation by TTF model (left) and verification with detailed model description (right) for *z* direction

The model is verified on variation of electro-spindle speed. A compensation result for the *z* direction is depicted in Fig.6. From the peak-to-peak point of view the reduction from the original 50 to 12μm is reached.

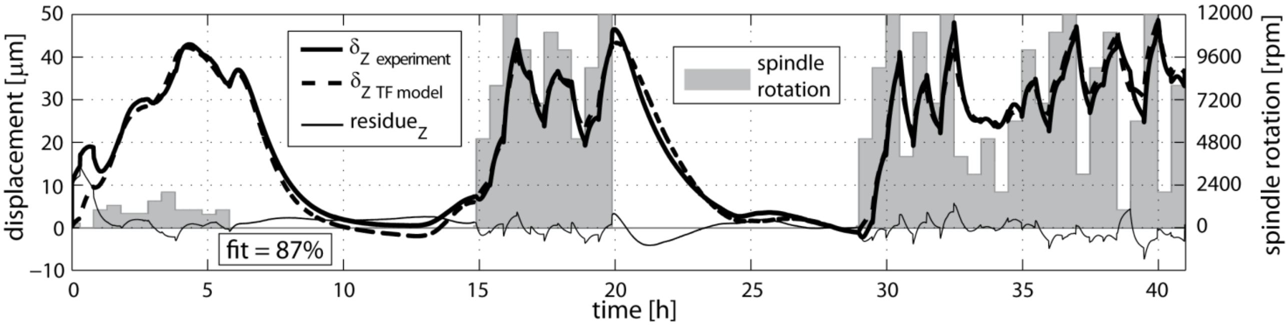

Fig. 6. Compensation result of TTF model during spindle revolution spectrum in *z* direction

Results in the *y* direction show insignificant deformations in comparison with the thermal error in the *z* axis. A reduction of displacement from 20 to 8μm is achieved.

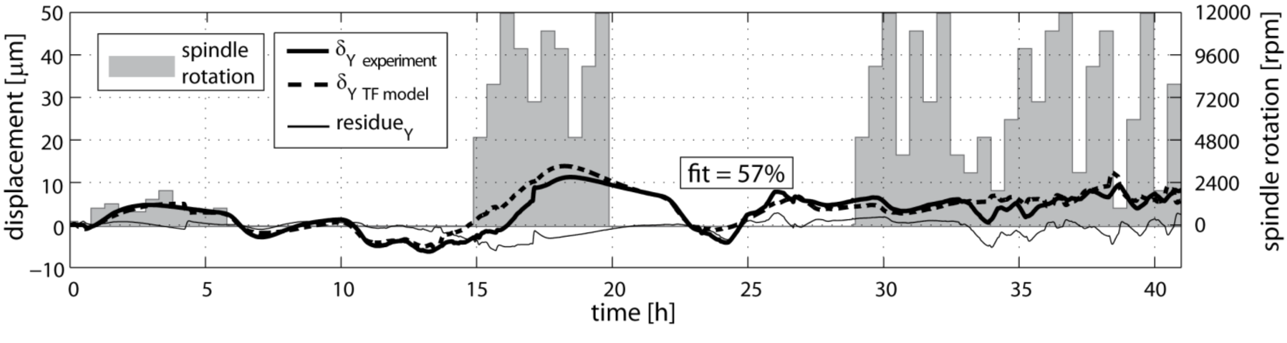

Fig. 7. Compensation result of TTF model during spindle revolution spectrum in *y* direction

4.2. MULTIPLE LINEAR REGRESSION MODEL

The principle of MLR method lies in the solution of an overdeterminated equation system. The equation system in a matrix notation can be expressed as follows:

$$Y.\beta = \delta \tag{7}$$

$$\beta = \ Y^T\,Y\ ^{-1}Y^T\delta \tag{8}$$

where Y is the matrix of temperatures (chosen on the basis of correlation analysis), β is the vector of weight factors and δ is the vector of deformations measured on TCP in the relevant direction. The desired coefficients of vector β are determined according to Eq. (8).

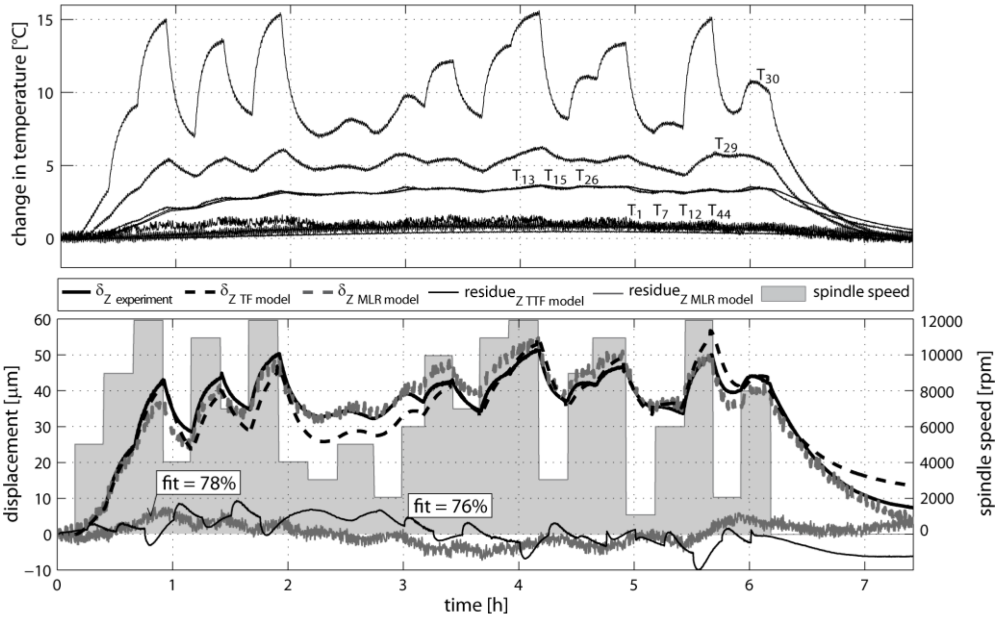

Fig. 8. Compensation result of MLR and TTF models during calibration measurement of MLR method in *z* direction

The results of the MLR model calibration in the *z* direction is depicted in the following graph. An approximation quality of the TTF model is also visible.

In the top graph in Fig.8 is outlined the temperature development over MT structure (probe places - Fig.2). Depicted temperatures are necessary to fill the MLR model - Eq.(7).

5. ROBUSTNESS OF TTF MODEL

The robustness of the TTF model will be proved on an additional same-shape spindle speed spectrum as visible in Fig. 8. However, significant changes in conditions contrary to the ones in calibration measurement are observable.

Next, attention will be paid to the cover of thermal errors in the *z* direction according to their transparency and relatively minor thermal error contributions in other axes.

5.1. TEST WITH A CHANGE IN TEMPERATURE GRADIENT

Failure of the static MLR model during a change of gradient in ambient temperature (top graph in Fig. 9) is noticeable in the bottom graph in Fig. 9. Dynamic approach represented by the TTF model is stable. The difference in compensation results of the MLR calibration measurement (Fig. 8) and the spectrum with temperature gradient change lies in 1% range for the TTF model.

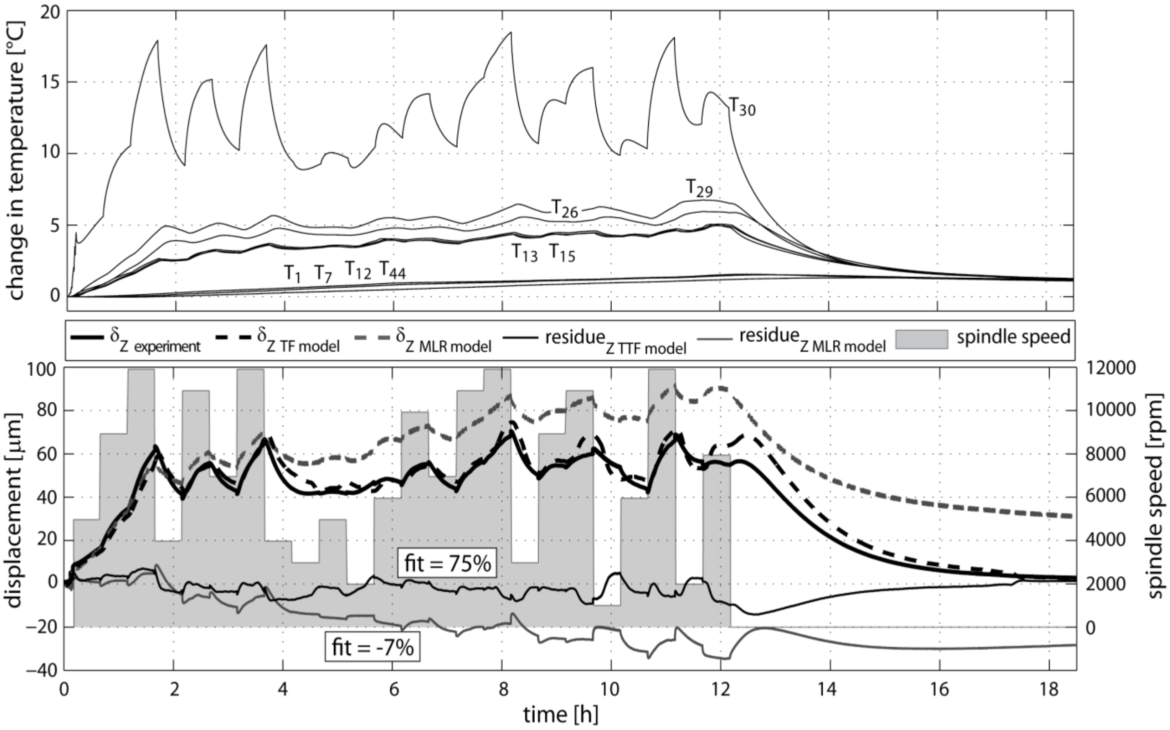

Fig. 9. Compensation results of TTF and MLR models during spindle revolution spectrum with a change in temperature gradient

5.2. TEST ON ANOTHER MACHINE TOOL

The following test (similar electro-spindle speed spectrum to the one in Fig. 8) was performed on another MT of the same type. All components and structure stayed unaltered but the initial stretch in individual parts created by the assembling process is dissimilar. The application results of both models are depicted in Fig.10. The outcome of the widely-used MLR model is depressing again. The TTF model contrarily remains in the 1% divergence.

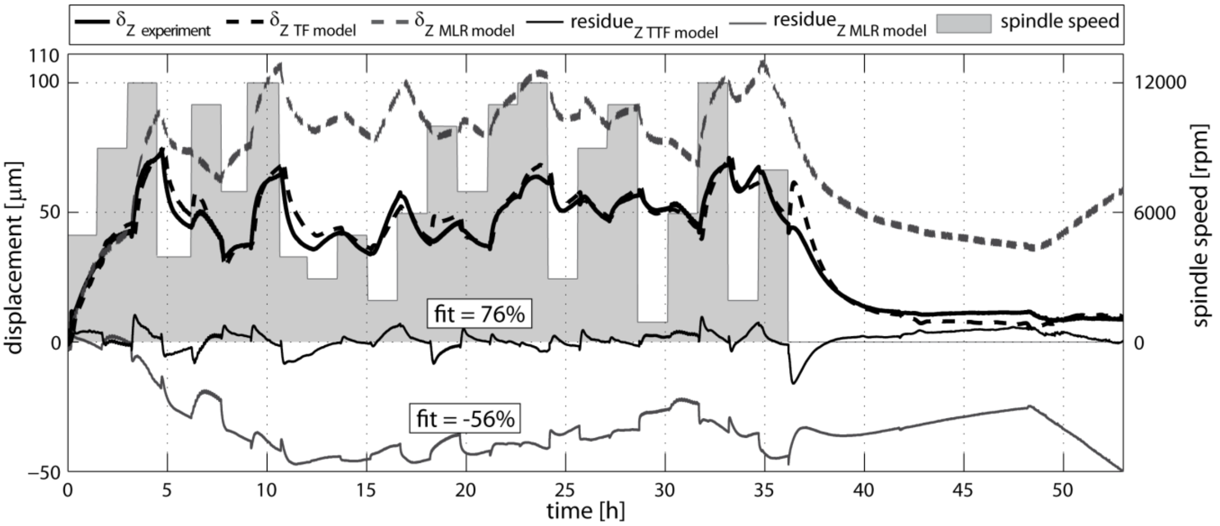

Fig. 10. Portability test of TTF and MLR models among one type of MT

6. CONCLUSIONS

Models based on TTFs present a robust approach to modelling of MT thermal behaviour, use a minimum of additional gauges (in comparison with the commonly used method of multiple linear regression (MLR) analysis [18]) and solve each influence participating in thermal error separately. The model was implemented into the MT control system. Its improvement was up to 87 % during a two-days-long varied working cycle (Fig. 6) in comparison with the uncompensated state. These models are open to extension of other independent thermal error elements such as heat sources generated by movements in the machine drive axis, coolant impact etc. Model portability among one type of MT has been proved. The summary of results achieved by both TTF and MLR models is presented in Table 1. The outcomes of the TTF model under hard changing conditions (in contrast to calibration measurement) alternate in 1% range.

Table 1. Comparison of thermo-elastic models

Thermo-elastic model	**MLR calibration**		**Change in temp. gradient**		**Portability test**	
	Δ [μm]	**fit** [%]	**Δ** [μm]	**fit** [%]	**Δ** [μm]	**fit** [%]
Without compensation	51	-	65	-	74	-
TTF	19	**76**	17	**75**	20	**76**
MLR	15	78	42	-7	46	-56

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