COMPENSATION OF MACHINE TOOL THERMAL ERRORS BASED ON TRANSFER FUNCTIONS

O. Horejs, M. Mares, P. Kohut, P. Barta, J. Hornych
Research Center of Manufacturing Technology
at Czech Technical University in Prague, Czech Republic

e-mail: j.vesely@rcmt.cvut.cz

This paper reports on a new method for compensation of machine tool thermal errors that is based on system of thermal transfer functions. Due to their relative simplicity they enable real-time calculations which make them suitable for compensation algorithms of thermal displacements at tool centre point. The applicability and robustness of the thermal transfer function compensation model have been experimentally verified on a real machine tool. Tested compensation algorithms proved its ability to significantly reduce thermal errors. The thermal error minimization of more than 85 % of the standard compensation technique based on linear regression model was achieved in particular machine tool coordinate direction.

Keywords
Thermal errors, Compensation, Ultra precision, Accuracy, Transfer function

1. Introduction

Thermal errors at the tool centre point (TCP) have affected the accuracy of production machines for a long time. They are dominant sources of inaccuracy [Bryan 1990] and are often the most difficult to reduce nowadays. Many solutions exist for the machine tool builder to reduce thermal errors that can be applied at the design stage including symmetric machine tool structures, liquid circulation cooling systems or low thermal expansion coefficient materials. Nevertheless a design effort together with a cooling system (without its precise control) can not absolutely eliminate thermal errors but only help to reduce them.

Generally direct and indirect compensation methods can be classified. In case of direct compensation, the resulting displacements are intermittently measured and superposed to the desired position value of the particular axis. The substantial advantage of direct compensation strategy consists of the fact that the deviations which have to be compensated are directly available. Nevertheless a sufficient sampling rate has to be chosen which leads to an intermission of the process and consequently to a lower operating efficiency [Brecher 2004].

Different indirect compensation algorithms are used to eliminate thermal errors [Ramesh 2000], but their efficiency corresponds to the quality of the thermo-elastic machine tool model and an ability to compensate thermal errors. Moreover a majority of developed sophisticated techniques often require complicated testing regimes to train the models and/or these methods are suitable only for narrow range of machine tool duty cycles. Commonly used linear regression (or multiple regression) model which is built in majority of machine control systems is insufficient because of the problem above-mentioned.

2. Compensation method

The frequency transfer function describes the link between the output (response) and the input (excitation) of a dynamic system in the frequency domain. If the system is linear the transfer function (TF) is constant. Various physical problems can be described by TF. However its application on thermo-mechanical system is relatively new phenomenon [Fraser 1998a].

2.1 Thermal transfer function

A thermal transfer function (thermal 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, because the data are forced to conform to the same principles as the real process. At the same time the results are obtained by two orders of magnitude faster [Fraser 1998b].

These parameters make the thermal TF very suitable for real-time modelling and diagnostics of varied thermo-mechanical systems. This topic is rarely discussed in a technical literature; therefore authors firstly created terminology used for thermal TF which is described in Tab. 1.

Type of transfer function	Nomenclature time/freq. domain	Excitation (input)	Response (output)
Temperature TF (TTF)	γ/Γ	Heat source	Temperature
Deformational TF (DTF)	δ/Δ	Heat source	Deformation
Temp.-deformational TF (TDTF)	ε/E	Temperature	Deformation
Inverse forms of TF (ITTF, IDTF, ITDTF)			

Table 1. *Terminology of thermal TFs*

The thermal TF can be employed for wide spectrum of application including diagnostics, determination of boundary conditions for a thermo-elastic FEA or a compensation of thermal errors at TCP, e.g. an inverse temperature transfer function (ITTF) is suitable for real-time heat source identification [Horejš 2009] etc.

2.2 Principle of the compensation techniques

Thermal errors of a machine tool are result of a very complex thermo-mechanical process. In order to create high quality real-time thermal error model of a machine tool using transfer functions, these functions must contain dynamic parameters resulting from the current thermo-elastic state of a machine tool. The real-time self tuning of TF parameters will lead to a precise real-time estimation of current thermal errors. When these thermal errors are compensated, long-term thermal stability of a machine tool can be achieved.

Compensation of thermal errors at TCP have been developed and experimentally verified on different real machine tools using two different compensation strategies. First method is based on control of the cooling systems which has to cause deformation right opposite to instantaneous thermal errors. This method is thoroughly described in [Bárta 2007].

This paper is focused on a second developed compensation technique using indirect software compensation. Principle of the method is shown in Fig. 1.

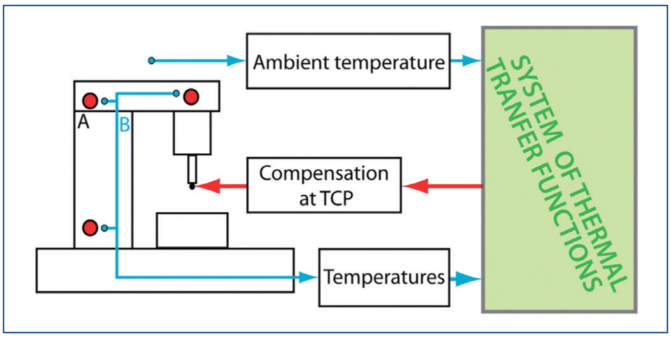

Figure 1. *Principle of the compensation technique*

Herein input parameters to the compensation algorithm are temperatures from sensors (schematically marked as B in Fig.1, symbols A represent heat sources) placed on machine tool structure and a shop floor temperature.

Generally additional input parameters can be used such as internal data of the feed drives and the main spindle (e.g. the rotational speeds values were used in [Brecher 2004]), heat transfer coefficients measured real-time on the machine tool structure etc. Real-time thermal error model based on system of thermal TFs is obtained by procedure which is depicted in Fig. 2.

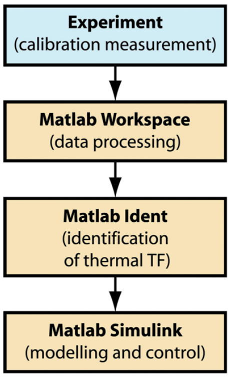

Figure 2. *Procedure of a data processing and assembling of real-time model*

First of all it is necessary to perform calibration experiments on the machine tool. Afterwards, the data processing is carried out in software Matlab and Simulink. Consequently several thermal TFs are identified using Matlab's System Identification Toolbox. Type of machine tool structure, machine tool components used and heat sources/sinks considered in the compensation algorithm determine the final number of thermal TFs required. A more detailed description of this topic is presented in [Hornych 2009]. The main heat source in machine tool structures (and also the largest cause of thermal distortions at the TCP) is usually a main spindle. Presently developed thermal error model includes the influence of the main spindle rotation and variation of the ambient temperature. Modelling and control is realized in software Simulink®. Model calculates the displacements in each particular coordinate direction *x*, *y* and *z* in real-time. The calculation is performed for the variation of the shop floor temperature (ETVE test in ISO 230–3 – Test code for machine tools – Part 3: Determination of thermal effects) and for the rotation of the spindle based on an empirically determined thermal error model. All single displacements are afterwards superposed to the overall displacement values. Thus real-time corrections for each machine tool coordinate axis are determined. Calculated corrections are implemented into the machine control system using programmable logic controller (PLC) as shown in Fig. 3.

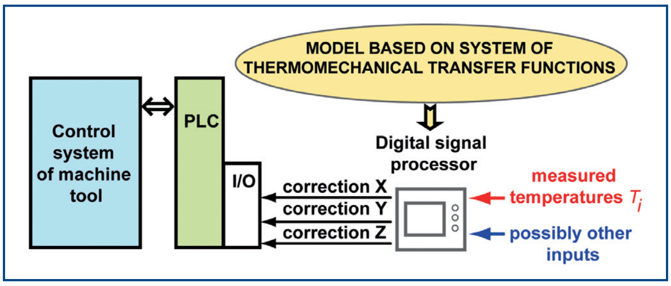

Figure 3. *Implementation of the compensation into the control system*

3. Experiment

In order to calibrate thermal TFs, experiments were performed on horizontal milling centre. This horizontal milling centre was equipped with Siemens® machine control system (Siemens 840 DSL). The thermally induced deformations of this machine are normally compensated by an empirically determined linear (or multiple) regression model. The main advantage of the linear regression model is that this compensation algorithm is usually part of the common machine control system (e.g. Siemens®, Heidenhain® etc.). In general the linear regression model is based on dependency between temperatures measured somewhere on the machine tool structure and displacement at TCP. There are two temperature sensors permanently located on the structure of the machine tool. The first resistance thermometer $T_{spindle}$ is placed inside of the main spindle between its bearings. The second sensor T_{base} is located on the base of the machine centre. The linear regression model of this machine tool can be expressed as

$$\begin{aligned} y &= k_y \cdot \Delta T = k_y \cdot (T_{spindle} - T_{base}) \\ z &= k_z \cdot \Delta T = k_z \cdot (T_{spindle} - T_{base}) \end{aligned} \qquad (1)$$

where *y*, *z* are thermal displacements at TCP in machine tool coordinate axis *y* (vertical) and *z* (horizontal, along the spindle axis), $k_y = 1.5.10^{-6}$ m.K^{-1} and $k_z = 0.7.10^{-5}$ m.K^{-1} are constants obtained by regression analysis from previous experiments.

3.1 Experimental setup

The experiment was carried out for three constant rotational speeds (3200 rpm, 4800 rpm and 6400 rpm) of the main spindle (maximal allowed rotational speed of the spindle is 8000 rpm). Then the environmental temperature variation error test was performed (ETVE test above mentioned). Finally measurement with changeable power of the main spindle (changeable rotational speed) was conducted. Spindle power was changed approximately in hour interval during the heating phase of the machine centre and also during the cooling phase. Four different values of spindle power (resp. rotational speeds) were set during the test as shown in Fig. 4 (this experiment is denominated as SPECTRUM test in the paper). There were 23 resistance thermometers used for continuous acquisition during all experiments (class A, accuracy ±0.15 °C, range: 30°C – 350 °C). Three resistance thermometers were located at the spindle surface (T_1, T_2 and T_6) as shown in Fig. 5.

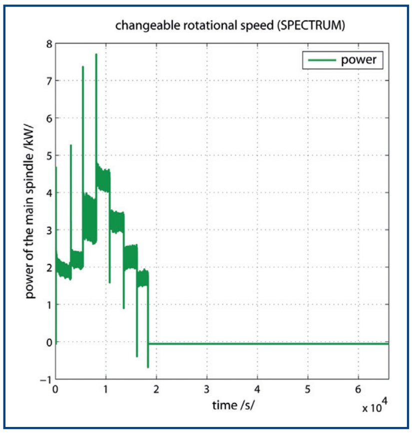

Figure 4. *Change of the spindle power (SPECTRUM test)*

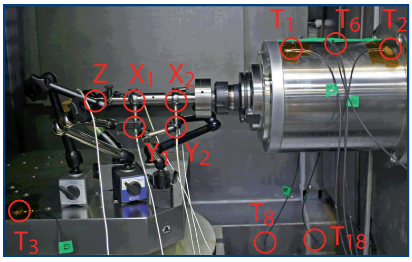

Figure 5. *Temperature sensors and noncontact measurement of the displacements*

Other temperature sensors were placed on the frame (see Fig. 6); the work table (T_3) and the ram.

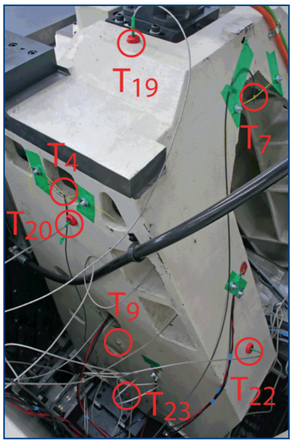

Figure 6. *Resistance temperature detectors (RTD) placed on the machine tool frame*

Few surrounding temperatures (air temperature) close to the machine tool were observed by additional RTD sensors (T_4, T_7, T_8, T_{15} and T_{18} see Fig. 5 and Fig. 6). Capacitive sensors are employed for noncontact sensing of the displacements at the TCP in micrometer resolution as shown in Fig. 5. Displacements in the x and y axes were measured in 2 points to observe angle displacement (distance between sensors were 100 mm). Moreover two temperatures $T_{spindle}$ and T_{base} and the power of the main spindle were observed during all experiments.

3.2 Experimental results

Figure 7 shows an example of measured thermo-elastic displacements in the *x, y* and *z* directions in the case of constant rotational speed of 6400 rpm. Figure 8 shows an example of measured temperatures in the case of test with a changeable rotational speed of the main spindle (SPECTRUM test).

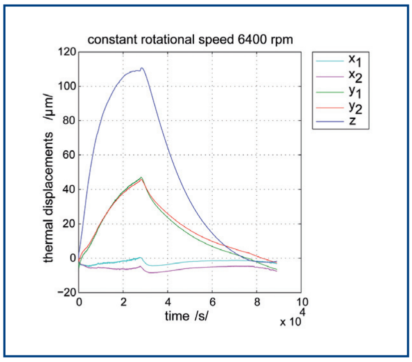

Figure 7. *Thermo-elastic displacements in the x, y and z*

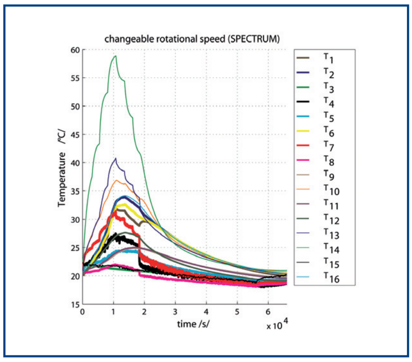

Figure 8. *Temperatures over time during the SPECTRUM test*

Time behaviour of the temperatures which are employed in standard compensation algorithm using linear regression model (see Eq. (1)) are depicted in Fig. 9.

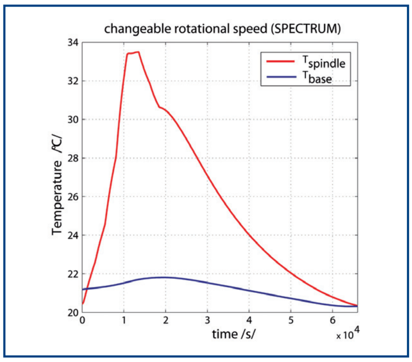

Figure 9. *Temperatures time behaviour ($T_{spindle}$ and T_{base})*

4. Simulation

4.1 Identification of thermal TF

As the machine centre has a thermally and mechanically symmetrical structure in *yz* plane, the thermal error in the *x* directions is negligible. This fact is confirmed by measured data (see thermal error in the *x* direction in Fig. 7). Thus only thermal displacements at the TCP in the direction *y* and *z* are compensated (thermal displacements in *x* direction are not discussed in the following text).

Thermal behaviour at the TCP differs during the heating phase and cooling phase. Therefore two different TDTFs (temperature–deformational TF see Tab.1) have to be identified for each direction (*y* and *z*). Moreover the TDTF which describes influence of the ambient temperature has to be determined. Hence, thermal error model consists of 5 thermal TFs.

Temperatures with the fast reaction and dominant dependency between the input and the output were chosen as input temperatures to the identification process. Finally only 3 temperatures are used as the input to the compensation algorithm ($T_{spindle}$, temperature from sensor placed on the ram T_{10} and shop floor temperature T_{15}).

Experiment with constant rotational speed of 6400 rpm is used for the calibration of TDTFs (see Fig. 7). Figure 10 shows an example of TDTF identification for *z* direction (heating phase). The upper graph shows the input *u (t)* and the output *y (t)* of the time-domain data imported to the System identification toolbox of the software Matlab®.

The bottom figure represents fit between the model and measured deformation (fit value of 97.17 %). The System identification toolbox enables to use different estimating models as ARX model or OE model etc. (see [Ljung 2007] in detail). The type of used model is depicted in the bottom figure as well. The identified TDTF is expressed as

$$E_{z\_heat} = \frac{K_1 + K_2 s + K_3 s^2}{T_1 + T_2 s + T_{D1} s^2} \tag{2}$$

with parameters of transfer function K_1 = 0.0162 m.K^{-1}, K_2 = 10.74 m.s.K^{-1}, K_3 = 5.368 m.s^2.K^{-1}, T_1 = 0.002098, T_2 = 2.379 s, T_{D1} = 1 s^2.

Other TDTFs are second-order TF according to Eq. (2) only with different value of the parameters. TDTF which describes a variation of the ambient temperature is forth-order TF defined as

$$E_{ETVE} = \frac{K_{15} + K_{16} s + K_{17} s^2 + K_{18} s^3 + K_{19} s^4}{T_{11} + T_{12} s + T_{13} s^2 + T_{14} s^3 + T_{D6} s^4} \tag{3}$$

where K_{15} = 4.028.10^{-10} m.K^{-1}, K_{16} = 1.491.10^{-7} m.s.K^{-1}, K_{17} = 0.0002884 m.s^2.K^{-1}, K_{18} = 0.0002421 m.s^3.K^{-1}, K_{19} = 4.895.10^{-5} m.s^4.K^{-1}, K_{11} = 4.02.10^{-10}, K_{12} = 1.181.10^{-6} s, K_{13} = 0.001166 s^2, K_{14} = 0.01072 s^3 and T_{D6} = 1 s^4 are parameters of transfer function.

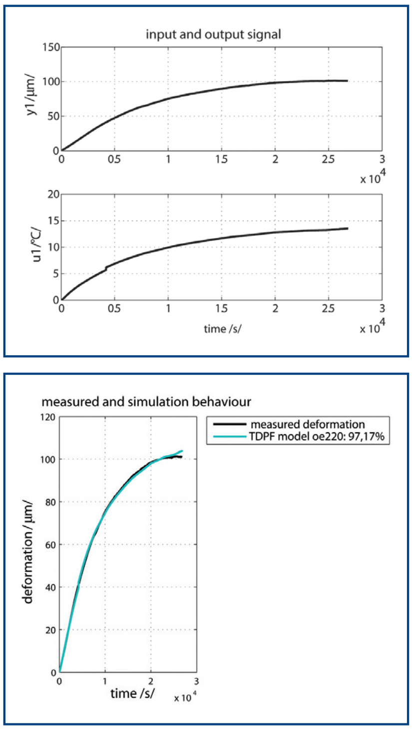

Figure 10. *Temperatures time behaviour ($T_{spindle}$ and T_{base})*

4.2 Simulation results

Comparison of the existing compensation (linear regression model) and compensation using thermal TF model in the *y* and *z* direction is depicted in Fig. 11. The both graphs correspond to the SPECTRUM test with changeable spindle power (see Fig. 4) of the main spindle during the test. The results of the thermal TF model at TCP (blue curves) are in good agreement with measured displacements in the *y* and *z* coordinate directions (black curves in Fig. 11). The green curves represent common compensation algorithm – the linear model calculated based on temperature difference Δ*T* according to Eq. (1).

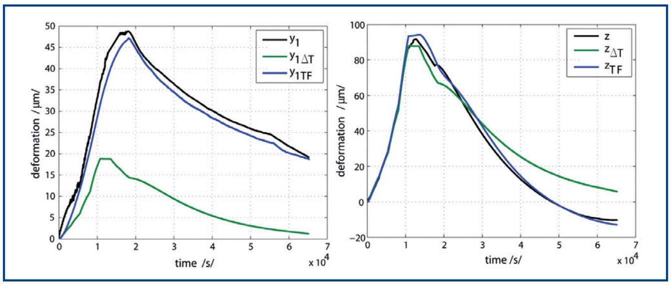

Figure 11. *Comparison of the compensation (y and z direction)*

Approximation errors of both compensation algorithms are shown in Fig. 12.

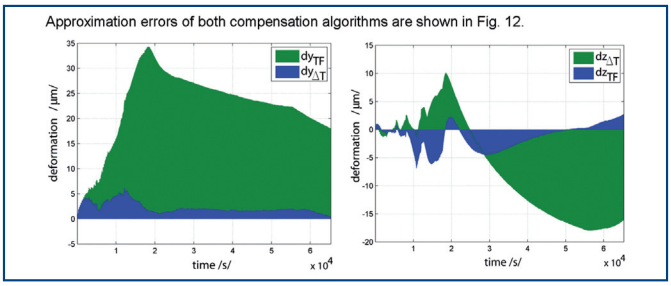

Figure 12. *Approximation errors of the compensation algorithms (y and z direction)*

5. Conclusions

The applicability and robustness of the thermal TF model have been experimentally verified on the real machine tool using indirect software compensation.

At present, linear regression model for compensation of the thermal errors is frequently implemented in common control systems of machine tools. However this type of compensation is often insufficient and limited.

This standard compensation method was compared with software compensation algorithm based on thermal TF. The thermal error minimization of more than 85 % of the standard compensation technique based on linear regression model was achieved (in the *y* coordinate direction). Thus the tested compensation algorithms proved its ability to significantly reduce thermal errors. A thermal TF contains the nature of the heat transfer principles. Thus the calibration of the empirical parameters is simple. The important merit of the developed compensation method is that the thermal error model is in addition more reliable with untested inputs as was shown by compensation during the test with changeable power of the main spindle (SPECTRUM test). However additional experiments have to be carried out in future to test impacts of other important heat sources/sinks in machine tool structure (e.g. feed drive, cutting process).

Acknowledgements

This research has been supported by the Czech Ministry of Education grant No. 1M6840770003.

References

[Barta 2007] Barta, P., *et al*. Thermal transfer function based control method of a machine tool cooling system. *Proceedings of the Topical Meeting: Thermal Effects in Precision Systems*, Maastricht, December, 2007. Euspen, pp 16–18.

[Brecher 2004] Brecher, C. and Hirsch, P. Compensation of Thermo-elastic Machine Tool Deformation Based on Control internal Data. *Annals of the CIRP*, Vol. 53, No.1.

[Bryan 1990] Bryan, J. International Status of Thermal Error Research. *Annals of the CIRP*, Vol. 39, No.2, pp 645–656.

[Fraser 1998a] Fraser, S., *et al*. Modelling, Identification and Control of Thermal Deformation of Machine Tool Structures, Part 1: Concept of Generalized Modelling. *Journal of Manufacturing Science and Engineering*, Vol. 120, pp 623–631.

[Fraser 1998b] Fraser, S., *et al*. Modelling, Identification and Control of Thermal Deformation of Machine Tool Structures, Part 2: Generalized Transfer Functions. *Journal of Manufacturing Science and Engineering*, Vol. 120, pp 632–639.

[Horejs 2009] Horejs, O., *et al*. Determination of Thermo-mechanical State of a Cooled Ball. *Conference Proceedings of the 9th International conference of the EUSPEN*, San Sebastian, 2–5 June, 2009. Euspen, Vol.1, pp 216–219, ISBN 978–0-9553082–6–0

[Hornych 2009] Hornych, J., *et al*. Issues in Identification of the Thermal Transfer Functions of Machine Tools. *Proceedings of the 9th International conference of the EUSPEN*, San Sebastian, 2–5 June, 2009. Euspen, Vol.1, pp 451–454, ISBN 978–0-9553082–6–0

[Ljung 2007] Ljung, L., System Identification Toolbox: User's guide. 7th ed. The Mathworks.

[Ramesh 2000] Ramesh, R. *et al*. Error Compensation in Machine Tools – a Review. Part II: Thermal errors. *International Journal of Machine Tools and Manufacture*, Vol.40, pp 1257–1284.

Contacts

Dr. Otakar Horejs
CTU in Prague, RCMT – Research Center of Manufacturing Technology
Horska 3, Prague, 128 00, Czech Repubic
tel.: +420 221 990 953, e-mail: o.horejs@rcmt.cvut.cz