Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia CIRP 4 (2012) 67 – 72

www.elsevier.com/locate/procedia

3rd CIRP Conference on Process Machine Interactions (3rd PMI)

Advanced Modelling of Thermally Induced Displacements and Its Implementation into Standard CNC Controller of Horizontal Milling Center

Otakar Horejš[a]*, Martin Mareš[a], Lukáš Novotný[a]

[a]*CTU, Faculty of Mechanical Engineering, RCMT, Prague, Horská 3, 128 00, Czech Republic*.

* Corresponding author. Tel.: +420-221-990-953; fax: +420-221-990-999 .*E-mail address*: O.Horejs@rcmt.cvut.cz.

Abstract

This paper is a continuation of scientific work on advanced modelling of thermally induced displacements based on thermal transfer functions (TTF). A mathematical model using TTF was implemented into a standard CNC controller of horizontal milling center to compensate for thermal errors in real time. The inputs of the compensation algorithm are spindle rotational speed and the temperatures of the machine structure. It was achieved a reduction of thermal errors of more than 75% of the initial value in various working cycles. Moreover, the results of the TTF model were compared with 2 models obtained via MLR as a case study.

Keywords: Precision machining; Machine tool ; Thermal error; Compensation; Transfer function; Accuracy

1. Introduction

The heat generated by moving axes and machining processes create thermal gradient inside the machine tool structure, resulting in the thermal elongation and bending of machine tool elements, which substantially deteriorate the machine tool accuracy.

Thermal effects can contribute more than 50 % to the overall error [1-2]. Furthermore, there are continuously increasing demands for machining accuracy in recent years. Thermal errors currently become more significant in their contribution to the total error due to scientific achievements in the static and dynamic field of research [3].

Moreover, the thermal errors are strongly dependent on the continuously changing operating conditions of a machine and its surrounding environment (especially in ordinary shop floors without additional air conditioning). Therefore this topic is the focus of significant recent research activities [4-5].

Different approaches exist to minimize thermal errors. . In general, it is possible to divide the thermal error issue into three basic groups [2], [6]: **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 [7-8], thermal insulation [9] etc.), **temperature control of machine tool and its environments** (e.g. control of machine tool cooling system [10], electric heater [11] thermal actuator [12], air conditions [13] etc.), and **compensation of the thermal errors** - generally, two alternatives for the compensation of thermo-dependent tool center point (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

 doi:10.1016/j.procir.2012.10.013

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 compensation is one of the widely employed techniques to reduce the thermal errors due to its cost-effectiveness and ease of implementation.

Indirect compensation strategies are based on measured auxiliary variables. Here in most cases temperature values of representative points of the machine structure are used for calculation of the resulting displacements by an empirically determined mathematical model. The most common model for prediction of thermally induced displacements is obtained by multiple linear regressions (MLR) [14-16]. However, 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 [17].

Furthermore, the displacement at the TCP can be calculated by an artificial neural network (ANN) [18-21], a fuzzy logic [22-23] or a transfer function model (TF).

The input of the estimated TF can be NC-data like spindle speed, effective power, electric current, torque or feed rate [24-25] or the temperatures of the machine structure can also be used as an input (thermal transfer function denominated as TTF) [26].

This paper is a continuation of scientific work on advanced modelling of thermally induced displacements based on thermal transfer functions (TTF). TTF 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 [16].

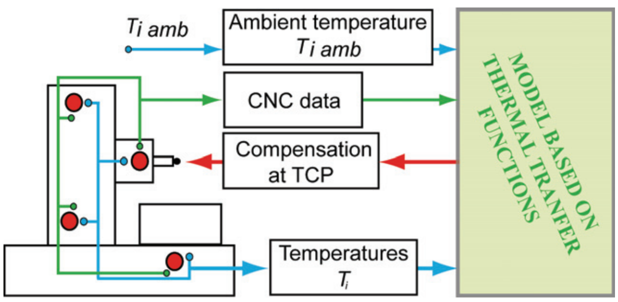

Fig. 1. Scheme of the indirect compensation method based on TTF

A mathematical model using TTF was implemented into a standard CNC controller of horizontal milling center to compensate for thermal errors in real time. The inputs of the compensation algorithm are spindle rotational speed and the temperatures of the machine structure. Principle of the indirect compensation method is shown in Fig. 1.

It was achieved a reduction of thermal errors of more than 75% of the initial value in various working cycles. Moreover, the results of the TTF model were compared with 2 models obtained via MLR as a case study.

2. Experiment

Compensations of thermal errors at TCP have been developed and experimentally verified on a 4-axis horizontal milling center (Fig. 2).

The maximum revolutions of the spindle were 15000 rpm. A procedure for obtaining a compensation algorithm based on TTF combines mathematical modelling with empirical calibration.

2.1. Experimental set-up

The machine tool was equipped with 21 thermal probes (RTD) for calibration measurements. The number of thermal probes was reduced from the original 21 to 4 probes: T_1, T_2, T_3, and T_4 (T_1 taking spindle temperature, and T_2 taking ambient temperature, and T_3, T_4 coolant temperatures at the inlet and outlet of the electro spindle cooling circuit) for the prediction of thermal displacement in direction z based on the TTF compensation algorithm (an additional input of the TTF model is spindle rotational speed n).

The remaining temperatures T_5 to T_{12} depicted in Fig. 2 were selected as independent variables for MLR models according to the values of correlation coefficients.

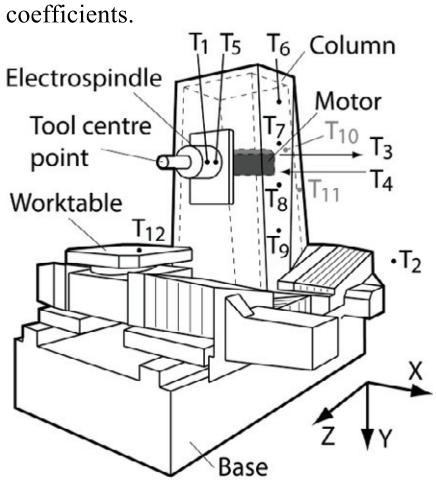

Fig. 2. Resistance thermometers on a 4-axis horizontal milling center

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

Thermal deformations in the x direction are 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 (see Fig. 2) were compensated.

2.2. . Calibration measurements

Generally, 8 calibration measurements were carried out to obtain 8 TTFs describing the machine tool thermal error over 7 days. It was necessary to carry out 6 calibration measurements (heating phase at 3200, 8000, 15000 rpm and cooling phase at 3200, 8000, 15000 rpm) for describing the thermal behavior of electro spindle due to its rotation.

The calibration measurement of coolant influence was performed as follows: the cooler maintained the coolant temperature 3 °C below the ambient temperature. The electro spindle was kept in the drive control ON mode. The supply of liquid into the cooling circuit was closed. In the meantime, the cooler cooled the liquid to 10 °C below the ambient temperature. Afterwards, the coolant supply into the electro-spindle was restored. The information about deformation response at the TCP to the coolant temperature jump was obtained.

The ETVE (environmental temperature variation error according to [27]) test was used for the calibration measurement of ambient temperature influence.

3. Compensation of a 4-axis horizontal milling center

All data processing and TTF identification, as well as machine tool thermal behavior modeling and verification, were performed in *Matlab* and *Matlab Simulink*. Data recording and implementation of the machine tool thermal model into the control system were performed with National Instruments diagnostic devices and *LabVIEW*.

3.1. Compensation approach

A discrete 2nd order TTF was used to describe the link between the excitation and its response,

$$y(t)=\varepsilon\cdot u(t)+e(t) \tag{1}$$

$$y(t)=\frac{a_1z^{-1}+a_0z^{0}}{b_2z^{-2}+b_1z^{-1}+b_0z^{0}}u(t) \tag{2}$$

where $u(t)$ is TTF input vector in time domain, $y(t)$ output vector in time domain, ε is TTF in time domain, $e(t)$ is disturbance value [27], a_i are weight factors of TTF input and b_i are weight factors of TTF output.
The differential form of the TTF is introduced as

$$y(k)=\frac{u(k-1)a_1+u(k)a_0+y(k-2)b_2+(k-1)b_1}{b_0} \tag{3}$$

Linear parametric models of ARX (autoregressive with external input) or OE (output error) structures were used to identify TDTFs in Matlab [27]. The quality of each TTF was examined through linear time invariant (LTI) step response.

In order to minimize number of calibration experiments and to ensure accuracy and robustness of compensation algorithm, superposition of two TTFs were applied using appropriate weight ratios in the following general form

$$y(t)=\varepsilon'\cdot u(t)\cdot\alpha+\varepsilon\cdot u(t)\cdot\beta \tag{4}$$

where α_i is TTF weight factor of previous spindle speed step and β_i is TTF weight factor of current spindle speed step. Genetic algorithms were used to obtain the weight coefficients α_i and β_i [*29*].

The main advantage of the model lies in its decomposition into individual elements and blocks describing the above-mentioned nonlinearities. 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 model depends on a decision block, which is represented in the model by current spindle revolutions. A simple switch element chooses the appropriate TTFs or their superposition 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, and so on).

Developed compensation algorithm using TTF is described in detail in [*30*].

In order to minimize number of calibration experiments and to ensure accuracy and robustness of compensation algorithm, superposition of two TTF were applied using appropriate weight ratios in the following general form.

3.2. Implementation of a compensation algorithm into the machine tool control system

A mathematical model based on TTF was implemented into a standard CNC controller of an horizontal milling center to compensate for thermal errors in real time as shown in Fig. 3.

Calculated displacements are superposed as an offset to the desired position values.

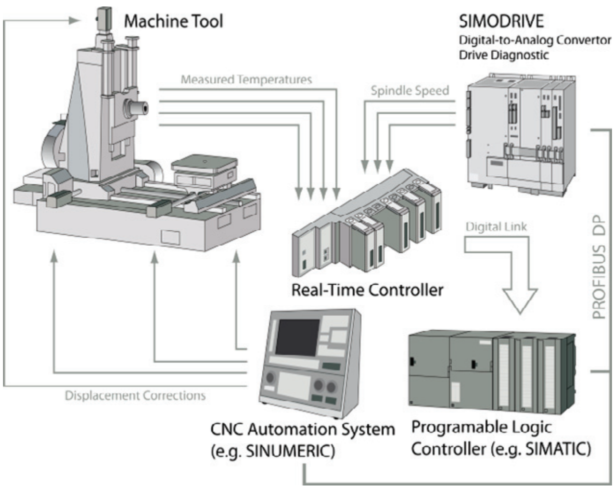

Fig. 3. Implementation of thermally induced displacements compensation algorithm into the machine tool control system

4. Compensation results and comparison with MLR models

4.1. Compensation results

The results of thermal displacements in the z directions will be discussed hereafter.

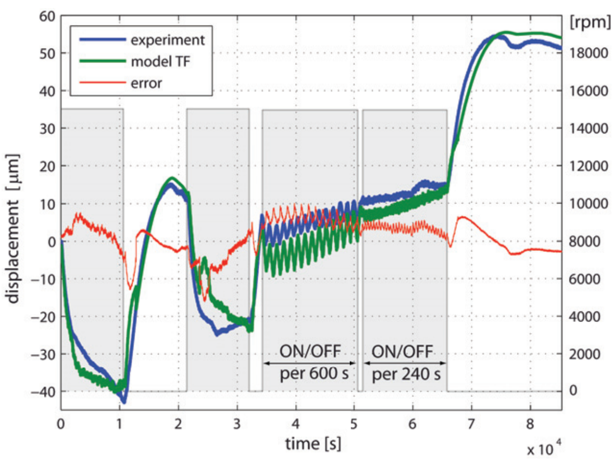

Fig. 4. Comparison of the TTF model and MLR model (REG_4) – residual errors in z direction (both compensation algorithms are based on 4 temperature probes)

The compensation method was verified on varied working cycle over almost 3 days (70 h). The verification spectrum includes several loads (different speeds of the main spindle) and decay phases. The maximum revolutions of the spindle *n* (15000 rpm) took turns with no revolution at regular intervals of 600 s (approximately 4.5 h), then subsequently 240 s (approximately 4 h) during the last part of the verification spectrum as shown in Fig. 4.

An example of the predicted thermally induced TCP displacements in the *z* direction using TTF model is depicted in Fig.4. The results of the compensation algorithm (green curve) are in good agreement with measured displacements (blue curve in Fig. 4) in the *z* coordinate directions. The residual error (red curve in Fig. 4) is plotted as the difference between the measured and the simulated displacement. The second axis of ordinates presents the rotational speed of the main spindle.

In case of verification spectrum, the uncompensated displacement is located between -42 and 55 μm (Fig. 4). The compensation reduces it to a range between -14 and +10 μm. There are only a few regions where the simulated displacement is noticeable different from the measured displacement. A similar result has been achieved in *y* direction.

The method achieved a reduction of thermal errors of more than 75% of the initial value for varied working cycle over almost 3 days (70 h). Thus, the verification spectrum shows clearly that the compensation method using a TTF model is a robust method to optimize thermally induced displacements at the TCP of machine tool.

4.2. Comparison with MLR models

Several MLR models were tested for a comparison with results of the TTF model. Finally, 2 MLR models were chosen for comparison with the TTF model.

A first MLR model (denominated as REG_4) using the same number of temperatures (T_1, T_2, T_3, T_4) as TTF model, and a second MLR model (denominated as REG_9) with 9 temperatures as independent variables (T_1, T_5, T_6, T_7, T_8, T_9, T_{10}, T_{11}, T_{12}). Model REG_9 was the most accurate and reliable of all tested MLR models.

A comparison of the TTF model and MLR model (REG_4) is shown in Fig. 5 and with MLR model (REG_9) in Fig. 6.

The blue curve represent measurement data, the red curve corresponds to the residual error of TTF model and residual error of MLR model is plotted as yellow curve.

In case of Fig. 6, the predicted thermally induced TCP displacements in the *z* direction using TTF model is plotted as green curve and results of MLR model is plotted as brown curve.

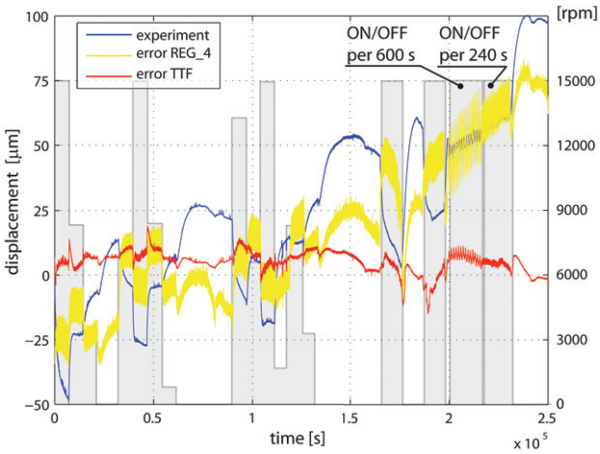

Fig. 5. Comparison of the TTF model and MLR model (REG_4) – residual errors in z direction (both compensation algorithms are based on 4 temperature probes)

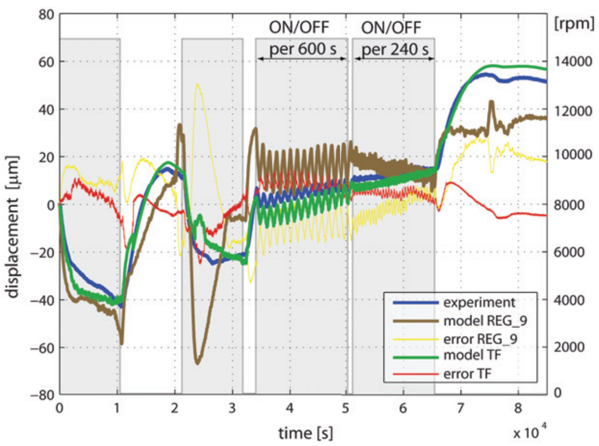

Fig. 6. Thermally induced displacements in z direction predicted by the MLR model based on 9 temperatures and TTF model (varied operating conditions)

The accuracy and reliability of the estimated thermally induced displacements at the TCP using MLR models are poor, as was expected. The accuracy of the MLR model increases with an increasing number of temperature probes (inputs). Nevertheless, even the accuracy of the MLR model with 9 temperatures as independent variables (model REG_9) is incomparable with TTF model using only 4 temperature probes.

5. Conclusions

In this paper an approach to fast and robust modeling of thermally induced displacements at the TCP of machine tool thermal behavior was presented without the noticeable need for intervention in its structure and with a minimum of additional gauges.

The model uses different transfer functions, based on actual rotational spindle speed. With four temperature measurements, the thermal displacements of up to 100 μm of a horizontal milling center can be estimated within 10 μm.

It was shown experimentally that the model based on TTF was successful in estimating relative (thermally induced) displacements at the TCP. The method achieved a reduction of thermal errors of more than 75% of the initial value for varied working cycle over almost 3 days (70 h).

Moreover, obtained compensation results were then compared to 2 MLR models, showing a much better accuracy and reliability of the TTF model.

Acknowledgements

The results have been obtained with the support of the 1M0507 Czech Ministry of Education, Youth and Sports grant "Research Center of Manufacturing Technology."

References

[1] Bryan, J., 1990. International Status of Thermal Error Research, Annals of the CIRP, Vol. 39/2, pp 645-656.

[2] Weck, M. et al., 1995. Reduction and Compensation of Thermal Errors in Machine Tools, Annals of the CIRP, Vol. 44, No. 2, pp 589-598. ISSN 00078506

[3] Brecher, C. et al., 2006. Messtechnische Untersuchung von Prozess und Maschine, Beurteilung und Abnahme von Werkzeugmaschinen (ab 1960), in "*Weck M (ed) 100 Jahre Produktionstechnik*". Springer, Berlin, pp 437-448.

[4] Jedrzejewski, J. et al., 2008. Precise Model of HSC Machining Centre for Aerospace Parts Milling, Journal of Mechanical Engineering, Vol. 8, No. 3, pp 29-41.

[5] Mayer, J. et al., 2012 (in press). Thermal issues in machine tools, Annals of the CIRP, Vol. 61, No. 2.

[6] Ramesh, R. et al., 2000 Error compensation in machine tools - a review, Part II: thermal errors, International Journal of Machine Tools & Manufacturing, Vol. 40, pp 1257-1284.

[7] Meo, F. et al., 2008. Advanced hybrid mechatronic materials for ultra precise and high performance machining system design, in *"Innovative production machines and systems"*, D.T. Pham, E.E. Eldukhri and A.J. Soroka (eds), MEC. Cardiff University, UK.

[8] Uhlmann, E. et al., 2008. Compensation of Thermal Deformations at Machine Tools using Adaptronic CRP-Structures, in "*Proceedings of 41st CIRP Conference on Manufacturing Systems: Manufacturing Systems and Techniques for the New Front"*, pp 183-186.

[9] Jedrzejewski, J., 1988. Effect of Thermal Contact Resistance on Thermal Behaviour of the Spindle, Int. J. Mach. Tools Manufacturing. Vol. 28, No. 4, pp. 409-416.

[10] Bárta, P. et al., 2007. Thermal transfer function based control of a machine tool cooling system, in *"Proceedings of the topical meeting: Thermal Effects in Precision System"*. Maastricht, Netherlands, pp 18-19.

[11] Mareš, M. et al., 2011. Compensation of Machine Tool Angular Thermal Errors using Controlled Internal Heat Sources, Journal of Machine Engineering, Vol. 11, No. 4, pp 78-90.

[12] Mitsuishi, M. et al., 2001. Development of an Intelligent High-Speed Machining Centre, Annals of the CIRP, Vol. 50, No. 1, pp 275-280.

[13] Zhao, Y. et al., 2010. Optimization and Temperature Mapping of an Ultra-High Thermal Stability Environmental Enclosure, Precision Engineering, Vol. 34, pp 164-170.

[14] Lee, D. S. et al., 2003. ICA Based Thermal Source Extraction and Thermal Distortion Compensation Method for a Machine Tool, International Journal of Machine Tools and Manufacture, Volume 43, pp 589-597. ISSN 08906955.

[15] Postlethwaite, S. R., 1998. The Use of Thermal Imaging, Temperature and Distortion Models for Machine Tool Thermal Error Correction, Proceedings of the Institution of Mechanical Engineers, Vol. 212, pp 671-679. ISSN 09544070.

[16] Du, Z.C. et al., 2002. Modelling approach of regression orthogonal experiment design for the thermal error compensation of a CNC turning center, J. Mater. Process Technol., Vol. 129, pp 619-623.

[17] Fraser, S., et al., 1998. Modelling, Identification and Control of Thermal Deformation of Machine Tool Structures, Part 1: Concept of Generalized Modelling, J. Manuf. Sci. Eng., Vol. 120, pp 623-631.

[18] Kang, Y.et al., 2007. Modification of a neural network utilizing hybrid filters for the compensation of thermal deformation in machine tools. Int. J. Mach. Tools Manuf., Vol. 47, pp 376-387.

[19] Mize, C. D. et al., 2000. Neural network thermal error compensation of a machining center, Precision Engineering, Vol. 24, pp 338-34. ISSN 01416359.

[20] Srinivasa, N. et al., 1996. Automated measurement and compensation of thermally induced error maps in machine tools. Precision Engineering, Vol. 19, pp. 112-132. ISSN 01416359.

[21] Mitsuishi, M. et al. 1994. Active thermal deformation compensation based on internal monitoring and a neural network, in “Advancement of intelligent production”, pp 215-220.

[22] Lee, J. H. et al., 2001. Thermal error modeling of a horizontal machining center using fuzzy logic strategy, J Manuf. Process, Vol. 3, pp 120-127.

[23] Wang, K. C., et al., 2006. Thermal error modeling of a machining center using grey system theory and adaptive network-based fuzzy inference system, Int. J. Ser. C. Mech. Syst. Mach Elem Manuf., Vol. 49, pp 1179–1187

[24] Moriwaki, T. et al., 1998. Analysis of Thermal Deformation of an Ultra Precision Air Spindle System, in *“CIRP Annals”*, Vol. 47, pp 283-286. ISSN 00078506.

[25] Brecher, C. et al., 2004. Compensation of Thermo-elastic Machine Tool Deformation Based on Control internal Data, in *“CIRP Annals”*, Vol. 53, pp. 299-304. ISSN 00078506.

[26] Horejš, O. et al., 2010. Compensation of Machine Tool Thermal Errors Based on Transfer Functions, in *“MM Science Journal”,* pp. 162-165. ISSN 18031269.

[27] ISO 230-3, 2007. Test Code for Machine Tools – Part 3: Determination of Thermal Effects, Genf, Switzerland.

[28] Ljung, L., 2007. System Identification Toolbox® 7 User’s guide, The Mathworks®,.

[29] Houck, CH. R. et al., 1999. A genetic algorithm for function optimization: A Matlab implementation, North Carolina State University.

[30] Mareš, M. et al., 2011. Control and Detailed Modeling of Machine Tool Highly Nonlinear Thermal Behavior Based on Thermal Transfer Functions. World Academy of Science, Engineering and Technology, Vol. 59, pp. 2735-2740, ISSN 2010-376X.