Control-Internal Compensation Algorithm for thermally induced volumetric Tool-Center-Point Deviations

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Abstract

Compensation of the thermo-elastic behavior of machine tools is one key factor for precision machining. Environmental and internal influences lead to inhomogeneous temperature distributions within the machine structure and result in position dependent Tool-Center-Point (TCP) deviations. Therefore, a volumetric investigation of the working area is indispensable.

This paper discusses an internal compensation algorithm for thermally induced volumetric deviations of machine tools. The volumetric thermo-elastic behavior of the machine tool is described by the physical-mathematical relationship between input power and the resulting error motions based on time delay elements. The compensation algorithm is parameterized by thermo-elastic displacement experiments using a tracking interferometer to measure the volumetric deviations.

1 Introduction

Nowadays, the thermo-elastic behavior of machine tools still is not entirely mastered. Over 70% of the final workpiece error can be traced back to thermal effects [1, 2].

Several internal and external heat sources lead to an unstable temperature distribution within the machine structure. This results in volumetric Tool-Center-Point (TCP) deviations [3], especially for unsymmetrical machine tool designs. The standard measurement equipment according to ISO 230-3 is therefore not a preferable choice to capture those volumetric deviations. Hence, a volumetric measurement as well as a volumetric compensation approach is necessary.

In this paper an indirect compensation approach for volumetric TCP deviations due to loads on the linear machine axes is discussed. A volumetric measuring method based on tracking interferometers is used to capture the thermally induced deviations.

2 Measurement of volumetric deviations

In the last decades a lot of research has been done in the field of the compensation of thermally induced machining errors. Most of these approaches have the used measurement technique on common. In the majority of the research projects only one TCP position or a small batch of them is measured using a measuring rod and angle according to ISO 230-3. Only a few papers cover at least a section of the working area [4, 5, 6, 7, 8].

As stated before, thermally induced axis-related TCP deviations highly depend on the TCP position and therefore require a volumetric measurement. This measurement is done by tracking interferometers capturing 17 of the 21 geometrical errors according to ISO 230-1 in a short time period of approximately 8 minutes during each measuring cycle [9] (Fig. 1). A modified evaluation method based on [8] is used. More details regarding the measurement and evaluation procedure can be found in [9].

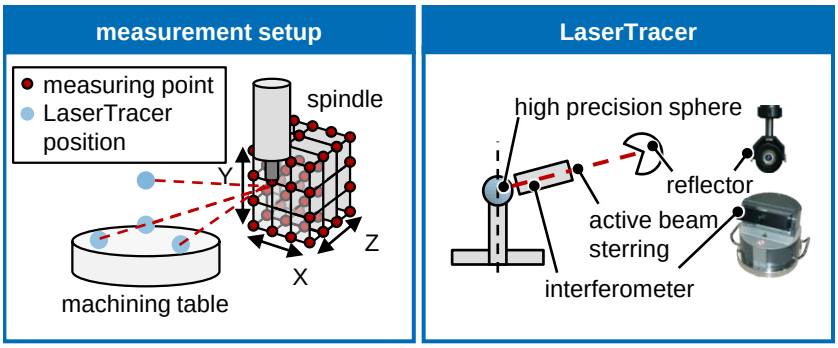

Figure 1: Measurement setup, ref. to [9]

The investigation of a small-sized vertical and medium-sized horizontal three axis milling machine reveals that not all error motions have to be taken into account for these machine structures. In both cases, straightness as well as a part of the rotational error motions have no significant influence on thermally induced deviations due to axis loads. The most relevant errors are the positional error motions, the regarding Abbe-Errors as well as the squareness errors. The former error motions can be neglected for compensation [9].

3 Compensation Approach

In the last decades different indirect approaches based on internal data such as dissipation losses or actual speed of the axes [4, 11, 12, 13] temperature [5, 8] as well as elongation [14] have been conducted.

In this paper an indirect approach based on control internal data, which was used for the compensation of spindle related errors in the past [13] and has been advanced to calculate volumetric thermo-elastic deviations induced by linear machine axes, is presented (Fig. 2).

The compensation algorithm uses transfer functions to calculate the deviation of the TCP out of the load-representative physical auxiliary variables. The modeling is carried out using first order time delay elements:

$$T \cdot \dot{y}(t) + y(t) = K \cdot u(t) \text{ where}$$

$y(t)$: output variable (displacement)
$u(t)$: input variable (engine output)
K: amplification factor
T: time constant

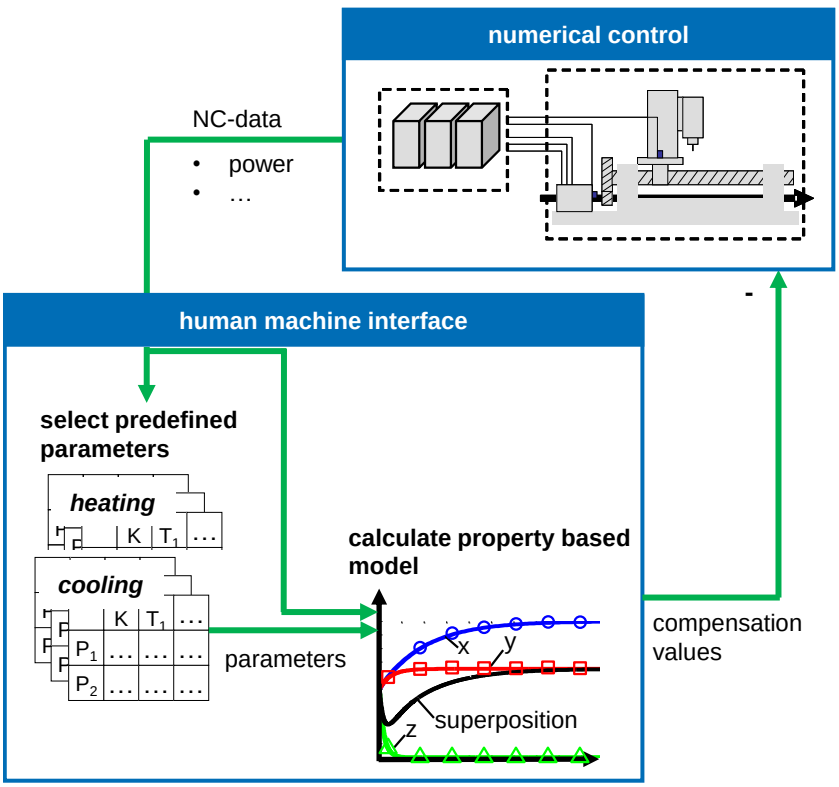

Figure 2: Compensation approach

In contrast to modeling individual space coordinates, the modeling of the volumetric state of machine tools needs an efficient volumetric description methodology. Here, thermal drifts of the error motions according to ISO 230-1 are used by the compensation approach for a volumetric description. This offers an easy implementation into the machine control as well as the ability to enable smooth travel paths.

The thermo-elastic behavior of the machine tool is captured during displacement experiments of each individual axis. The load is applied by constant air cuts. Future work will deal with the load-dependent behavior. Therefore a stressing unit for linear axes is developed and currently put into service [15].

First, the displacement experiments are conducted for each individual axis for at least two different loads (traverse speeds) (Fig. 3). Then, the thermal course of the error motions is modeled individually for each axis by the proposed first order time delay elements. The heat up and cool down phase has to be regarded separately due to the different time constants. Finally, the behavior of the individual axes is superposed to calculate the overall error. It could already be shown that a superposition is applicable [9]. The parameterized machine model is validated for a different load and motion sequence. In this context, different loads on the individual axes are calculated by a rule of three on basis of two experiments per axis with a low (10 m/min) and a high (30 m/min) speed. The axis engine output given by the numerical control is used as the input of the transfer functions.

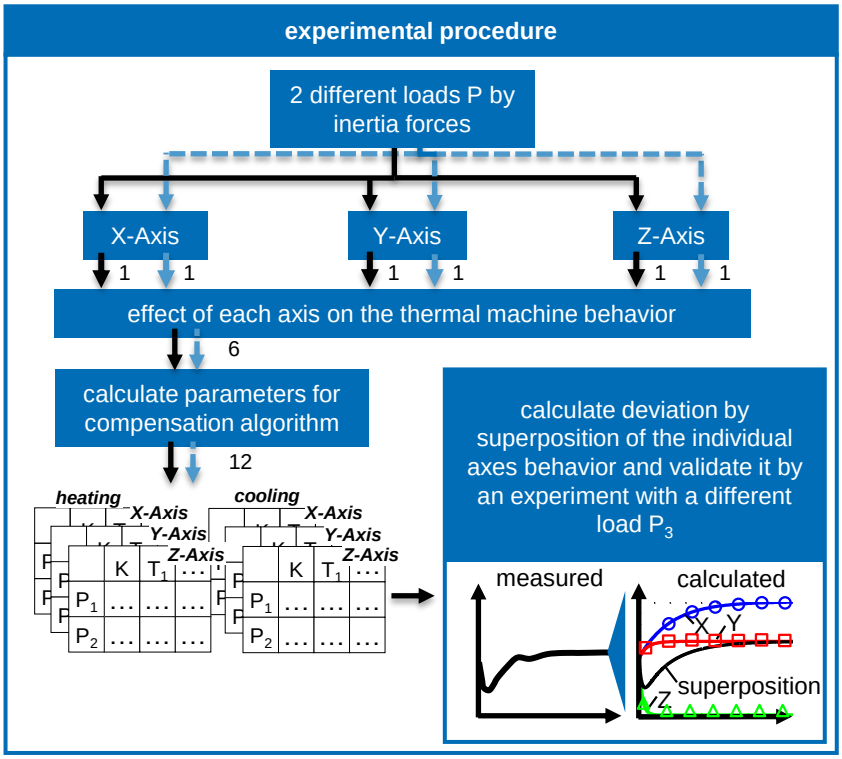

Figure 3: Experimental procedure

4 Modeling

A first approach for individual point measurements reduces the linear axis related thermo-elastic error to less than 5 µm, which means an improvement of 60% [15]. Furthermore, the experiments reveal the limits of the used compensation algorithm which can be estimated to a residual error of 5 µm.

As stated before, the modeling can be reduced to the positional error motions EXX, EYY and EZZ, the corresponding Abbe-Error motions EBX, EAY, EBZ, as well as the three squareness errors A0Z, B0Z, C0X. Further experiments reveal that the error motions of the individual axes are only influenced by the corresponding axis itself [9]. Due to the limitations of the used indirect measuring method, the error motion EBZ cannot be measured. The resulting error is calculated as a portion of the other 17 error motions.

For each of these error motions an individual time delay element is fitted for each axis position (Fig. 4).

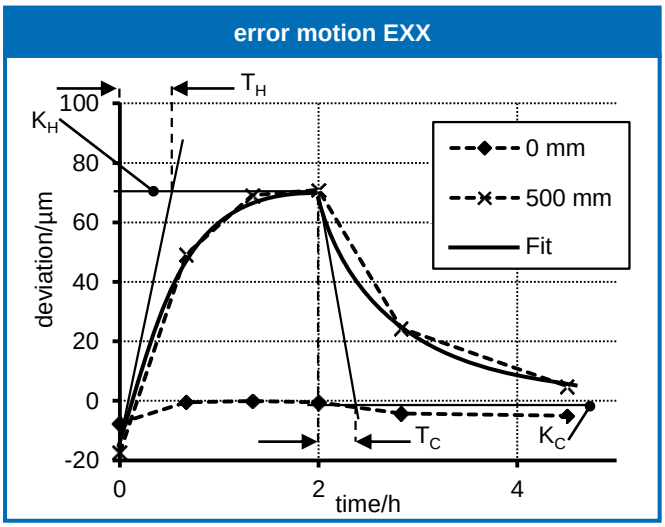

Figure 4: Modeling example for error motion EXX for 0 mm and 500 mm

An example for modeling the error motion EBX during a load of the x-axis at 30 m/min is given in Fig. 5. The residual error as the maximum difference between measured and fitted values is approximately 4 µm with a standard deviation below half a micron and an average mean residual error of zero (Fig. 5, bottom left).

For the given machine a linear approximation of the error motion EBX according to the position on the x-axis is a good choice (Fig. 5, bottom right). The same could be shown for the investigated medium-sized horizontal milling machine [9]. Due to the definition of the error motion EBX to be set zero at the start position of the x-axis, only one first order time delay element is necessary. As a result, the residuals during heat up are nearly the same, while those during

cool down are bigger (Fig. 5, bottom right). This could be explained by the nonlinearity of the undirected heat flows during cool down. The linear assumption fits for the other error motions, too (not shown here).

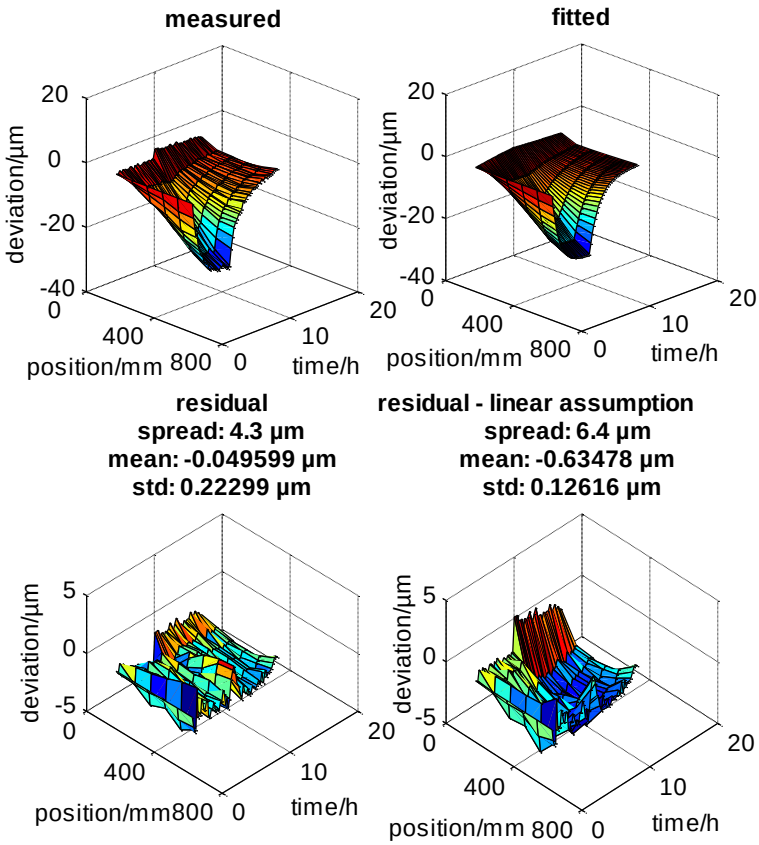

Figure 5: Description of error motion EBX due to x-axis load by first order time delay elements

The first order time delay elements are calculated for each of the previously mentioned significant error motions using the linear assumption. Modeling the influence of the axis load is done by two experiments per axis as stated before (10 m/min and 30 m/min).

The results of the calculated error motion EBX using a rule of three for the medium axis load (20 m/min) is illustrated in Fig. 6. Both, the amplification factor as well as the time constant are calculated in a proper way. As a result, the residual error is less than 5 micron. Huge residual errors only appear during the cool down phase, where a huge rate of change exists. Further experiments regarding the other error motions reveal similar responses.

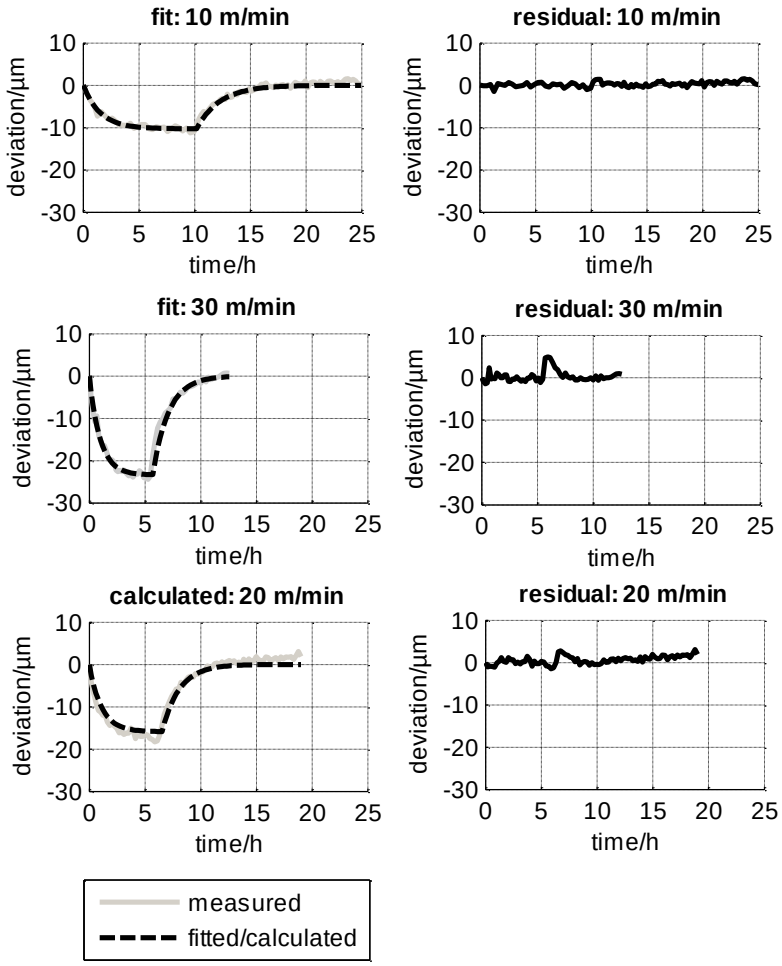

Figure 6: Validation results of calculated error motion EBX for a different axis load

The same calculations for squareness error A0Z are shown in Fig. 7. Here, the spread of the measured squareness error is bigger. This results in a challenging fitting process and finally higher residuals. The spread of the residual of the fitted as well as calculated squareness error is approximately 15 µm. However, the thermal drift of the squareness error could be removed and the final error is reduced by over 70%. To ensure consistent compensation results, the measurement process has to be modified to guarantee a higher measurement quality of the squareness errors.

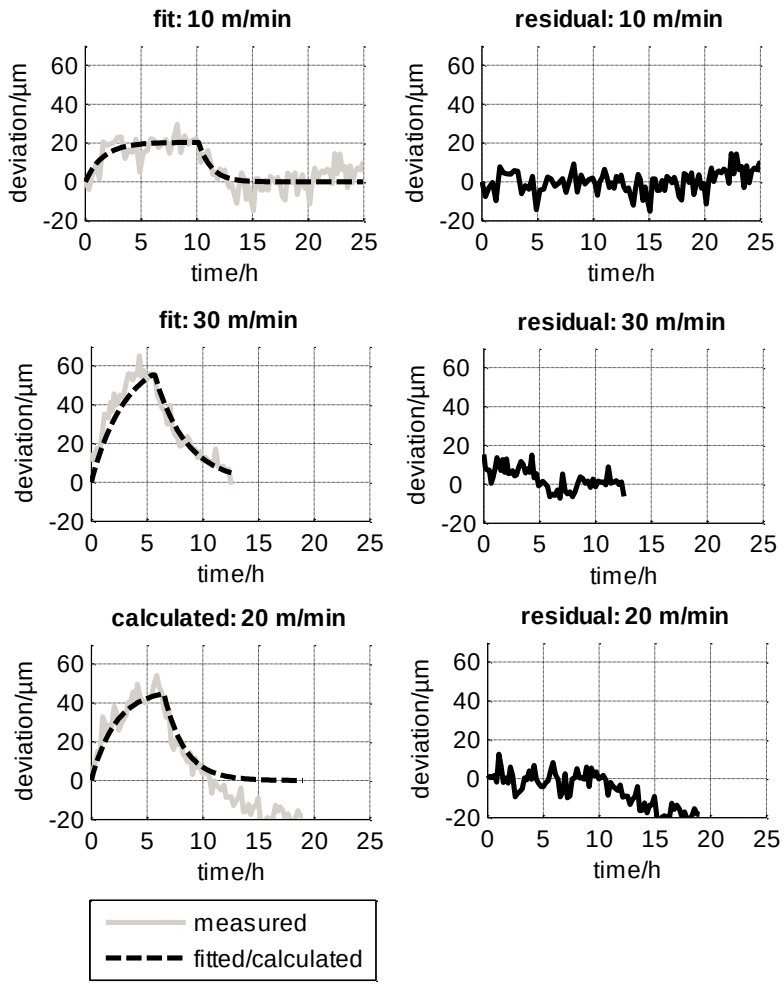

Figure 7: Challenges due to volumetric measurement uncertainties, squareness error A0Z as an example

5 Summary

The used volumetric measurement methodology offers a great insight into the thermo-elastic behavior of machine tools. In this way measured error motions according to ISO 230-1 offer an efficient way to compensate volumetric thermo-elastic errors. In this context, experiments reveal that only some error motions have to be taken into account for compensation of thermo-elastic deviations due to axis loads. For these, the proposed compensation model offers a great potential by removing the thermal error drifts. Nevertheless, the measurement uncertainty is partly too high for a good compensation quality.

6 Further Work

The presented challenges of the compensation approach define further work. The thermo-elastic behavior of machine tools has to be investigated in more detail. Especially measurement uncertainties of the volumetric deviations lead to modeling errors. To overcome this, the current activities deal with an improvement of the evaluation methodology enabling it to describe thermo-elastic deviations. The currently used static machine model will be advanced to a dynamic model, enabled to describe the drift of the thermo-elastic machine tool errors.

Additionally, the development of the compensation model requires a more detailed view on the volumetric behavior of machine tools. Here, the load-dependent thermo-elastic behavior will be investigated using the designed stressing unit.

6 Acknowledgments

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7 References

[1] Bryan J et al 1990 *International status of thermal error research* CIRP Ann Manuf Technol vol 39(2) pp 645–56

[2] Mayr J et al 2012 *Thermal issues in machine tools* CIRP Ann Manuf Technol vol 61(2) pp 771–91

[3] Brecher C, Wennemer M and Fey M 2014 *Temperaturstabile Werkzeugmaschinen—Messverfahren zur volumetrischen Korrektur thermoelastischer Verlagerungen* wt Werkstatttechnik online vol 114(7) pp 490–95

[4] Gebhardt M 2014 *Thermal Behaviour and Compensation of Rotary Axes in 5-Axis Machine Tools* ETH Zürich (Zürich Switzerland)

[5] Gomez-Acedo E et al 2013 *Methodology for the design of a thermal distortion compensation for large machine tools based in state-space representation with kalman filter* International Journal of Machine Tools & Manufacture vol 78 pp 100-8

[6] Florussen GHJ 2002 *Accuracy analysis of multi-axis machines by 3D length measurements* Eindhoven University of Technology (Eindhoven Netherlands)

[7] Delbressine FLM, Florussen GHJ, Schijvenaars LA and Schellekens PHJ 2006 *Modeling thermomechanical behaviour of multi-axis machine tools* Precision engineering vol 30(1) pp 47–53

[8] Denkena B and Scharschmidt K-H 2007 Thermal Compensation Method for Machine Tools *Proceedings of the Topical Meeting: Thermal Effects in Precision Systems euspen* (Maastricht Netherlands) pp 19-21

[9] Brecher C, Fey M and Wennemer M 2014 *Volumetric thermo-elastic machine tool behavior* Production Engineering DOI 10.1007/s11740-014-0584-5

[10] Schwenke H et al 2005 *Error mapping of CMMs and machine tools by a single tracking interferometer* CIRP Ann Manuf Technol vol 54(1) pp 475–78

[11] Mares M et al 2013 *Robustness and Portability of Machine Tool Thermal Error Compensation Model based on Control of participating Thermal Sources* Journal of Machine Engineering vol 13(1) pp 24-36

[12] Horejs O et al 2013 Complex Verification of Thermal Error Compensation Model of a Portal Milling Centre *International Conference on Advanced Manufacturing Engineering and Technologies* pp 233-41

[13] Wissmann A 2014 *Steuerungsinterne Korrektur thermisch bedingter Strukturverformungen von Bearbeitungszentren* RWTH Aachen (Aachen Germany)

[14] Brecher C, Klatte M, Wenzel C and Flore J 2013 In-Process Measurement of Machine Structure Deformation and Compensation of Resulting Workpiece Inaccuracies *Laser Metrology and Performance X: Proceedings of the 10th International Conference on Laser Metrology Maschine Tool, CMM & Robotic Performance Lambdamap* (Milton Keynes USA) pp 111–21

[15] Wennemer M, Brecher C and Fey M 2014 Correction model of load-dependent structural deformations based on transfer functions *Thermo-energetic Design of Machine Tools* (Heidelberg Germany) pp 175–84