Special Interest Group Meeting on Thermal Issues
Laboratory for Machine Tools and Production Engineering (WZL) of
RWTH Aachen, Germany, February 2020
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# Enhancement of vertical turning lathe accuracy by minimising thermal errors depending on rotary table activity and workpiece clamping diameter

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**Abstract**

Thermally induced errors are dominant sources of inaccuracy and are often the most difficult types of errors to reduce today. Software compensation of thermally induced displacements at the TCP is a widely employed technique to reduce these errors due to its cost-effectiveness and minimal demands for additional gauges. Compensation models for machine tool thermal errors were successfully applied on various kinds of machine tool structure and implemented directly into their control systems. The aim of this research is to evaluate an enhancement of vertical turning lathe accuracy by minimising of thermal errors. Thermal errors caused by rotary table speed are nonlinear and a dependency on the workpiece clamping diameter has to be taken into account. Calibration of a reliable compensation model is a real challenge resulting in demands of a dependable verification approach. Techniques using international standard testing and manufacturing of testing workpiece were considered in the research for verifying a practical applicability of the compensation model.

Thermal error, Accuracy, Compensation, Finishing cutting conditions

## 1. Introduction

The heat generated by moving axes and machining processes creates thermal gradients, resulting in the thermal elongation and bending of machine tool (MT) elements, which substantially deteriorate MT accuracy. Thermal errors cannot be sufficiently reduced by design concepts and/or by temperature control without significant additional costs. On the contrary, indirect (software) compensation of thermal errors at the tool centre point (TCP) is one of the most widely employed reduction techniques due to its cost-effectiveness and ease of application.

Ordinarily, approximation models are based on measured auxiliary variables [1] (temperatures, spindle speed, etc.) used to calculate the resulting thermally induced displacements at the TCP. Many strategies were investigated to establish the models, e.g. multiple linear regressions (MLR) [2], artificial neural networks [3], transfer functions (TF) [4], etc. (for more detail see also [5]).

Although real-time software compensation approaches for thermal errors exist, these compensation approaches have a number of serious drawbacks. In the work [6] a promising approach to thermal error minimisation of spindle unit is introduced but the model was verified within calibration conditions resulting in a small value added compared to MLR simple modelling approaches; an interesting application of thermal error reduction is presented in [7] providing a solution only for thermo-mechanically steady states of tested device; a sophisticated apparatus used for MT surrounding impact simulation is topic of research [8] considering a limited conditions of real MT working cycles though.

An approach to thermal error modelling of a rotary table activity of a vertical turning lathe is proposed in this research. The compensation model based on TFs was directly implemented into MT control system and internal information (temperatures measured close to heat sources) were used as model inputs. A nonlinear MT thermal behaviour during turning operations was observed and workpiece clamping diameter had to be considered as additional model input parameter. The approach practical verification according to international standards ISO 230-3 [9] (using displacement probes) and using testing workpiece manufactured within finishing cutting conditions were considered to prove compensation model industrial applicability. A comparison of the applied compensation method outcomes with original (uncompensated) state of the machine is presented.

## 2. Modelling of thermo-mechanical behaviour

The chosen compensation strategy is based on TFs; a dynamic method with a physical basis. The difference form (suitable for programing languages e.g. Python) of the TF in the time domain is introduced in eq. (1),

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

where $u$ is the TF input vector, $y$ is the output vector, $k$-$n$ ($k$-$m$) signifies 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 to set TF calibration coefficients $a_n$ and $b_m$ [10].

### 2.1. Experimental set-up

All of the experiments were performed on a vertical turning lathe with a maximal clamping diameter of 3,000 mm and maximal rotary table speed of 200 rpm. The MT is composed as multifunctional and is capable of two full-bodied technologies: turning and milling. The milling operations are not considered in the article.

Eddy current sensors (PR6423) firmly clasped in a thermal stable frame are employed for noncontact sensing of displacements between the TCP position and the rotary table (regular position of a workpiece). Other information (rotary table bearing temperature $T_{\mathrm{bearings}}$, column temperature $T_{\mathrm{column}}$ and rotary table speed) are taken directly from the MT control system. Thermal stable frame assembled from carbon fibre bars was fixed in headstock tool holder as depicted in Figure 1. The frame is divided into two arms of the same length 1,500 mm. Both arms carry connectors for noncontact displacement sensors. Displacement sensors measured thermal displacement of the rotary table in three positions (0, 1,500 and 3,000 mm) defined by measuring artefacts. Sensors in 3,000 mm position are doubled (one for each end of the frame arm) to ensure the symmetricity of the rotary table thermal errors.

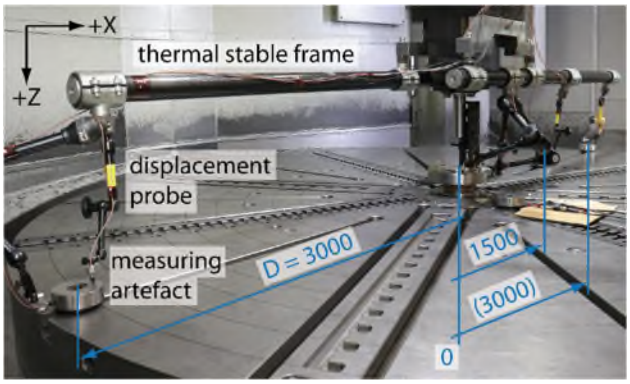


**Figure 1.** Experimental set-up for calibration measurement

All of the results and conclusions are closely associated with the following experiment conditions: load-free (without a cutting process in calibration part of experiments); testing in one MT axis configuration (with a reference to Positionally-dependant errors given only by thermal stable frame use); deformations in *Z* direction only were taken into account (without any reference to table diameter changes); the compensation model is implemented directly into MT control system and the MT multifunctionality is not considered so far.

### *2.2. Calibration*

The calibration measurement consist of transient behaviour between two thermodynamic equilibria (MT in approximate balance with its surroundings and MT steady state during heat source activity).

Calibration measurement of rotary table thermal behaviour is divided into two cyclically repeated parts. The first part "loading" means 10 min of table rotation on constant rpm. The second part "measuring" means 10 s of measuring thermal deformations in *Z* direction between thermal stable frame and artefacts (see Figure 1). Rotary table thermal behaviour calibration and TF modelling result is shown in Figure 2.

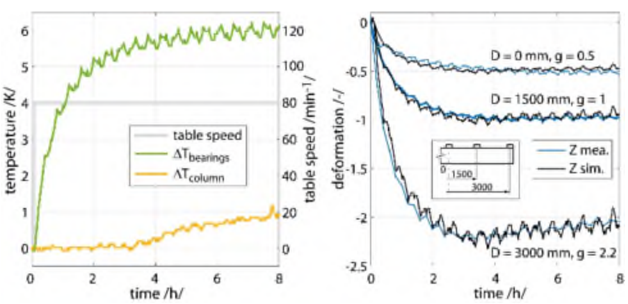


**Figure 2.** Calibration and modelling of rotary table thermal behaviour

The graph on the left in Figure 2 shows the input into the thermo-mechanical system and the graph on the right shows the measured and simulated outputs. Only heating phase is taken into account. The diameter of 1,500 mm is considered in modelling process (bold blue curve right in Figure 2). Other clamping diameters are solved as magnitude of the calibration curve with good resolution. The approximation of thermal deformations between headstock and rotary table is expressed by eq. (2),

$$z_{sim.} = [(\Delta T_{bearings} - \Delta T_{column}) \cdot \varepsilon_1] \cdot g, \qquad (2)$$

where $\Delta T_{bearings}$ is the table bearing temperature difference, $\varepsilon_1$ represents the transfer function approximating thermal errors due to table rotation (for TF calibration coefficients see Table 1) and $g$ represents the gain factor dependant on workpiece clamping diameter (see right part in Figure 2). Temperature behaviour $\Delta T_{column}$ is the base temperature difference reflecting to changes in ambient temperature. The influence of the ambient temperature on thermal error is not fully considered due to its modelling difficulties [8] and is scheduled as future work.

**Table 1** Coefficients of identified transfer functions

| ***TF*** | ***coefficients*** | | | |
|---|---|---|---|---|
| $\varepsilon_1$ | $a_0$ | $a_1$ | $a_2$ | $a_3$ |
| | -82.41672 | 82.41479 | 0 | 0 |
| | $b_0$ | $b_1$ | $b_2$ | $b_3$ |
| | 1 | -0.64533 | 0.10375 | -0.45835 |

### *2.3. Verification*

Following experiment has been designed to verify the validity of the compensation model. The verification test consists of rpm spectra with no record of cooling phase.

Figure 3 shows thermo-mechanical system temperature input during verification test and also depicts ambient temperature and table speed behaviours.

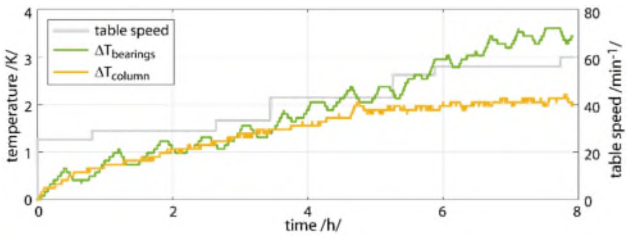


**Figure 3.** Verification test set-up, conditions and model input behaviours

Figure 4 shows outputs from the thermo-mechanical system as measured (left part in the figure) and simulated (the right part) thermal error during table rotation impact verification test.

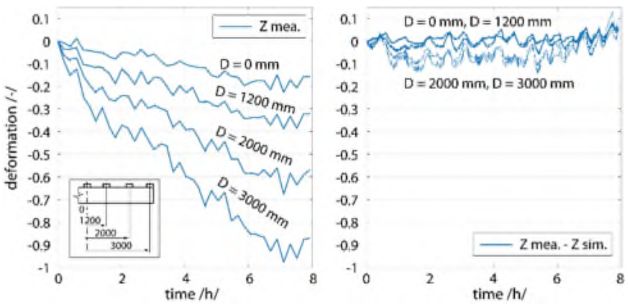


**Figure 4.** Measured (right; uncompensated state) and simulated (left; after applied compensation) thermal errors during verification test

The conditions of verification test differed from calibration measurement in positions of the artefacts (0, 1,200, 2,000, 3,000 mm). The compensation model was applied offline on measured uncompensated data and MT state after compensation was computed by difference of measured and simulated behaviours. The results in different artefact positions (1,200 and 2,000 mm) were obtained by multiple of linear interpolation of gain factor *g* in the compensation model.

Compared to the uncompensated state, the improvement of the thermo-mechanical state during the rotary table activity was 65% in 0 and 1,200 mm diameters and 84% in 2,000 and 3.000 mm diameters.

The verified compensation model was converted to Step7 code as machine controller Siemens allows for direct implementation. The compensation is executed in a frequency of one per second via an offsets setup on linear axis *Z*.

### 3. Testing workpiece manufacturing

Another verification test is further introduced due to authentication of a practical applicability of the compensation model: during a real finishing machining; out of the model's calibration range.

The testing workpiece is presented in Figure 5. The workpiece consists of four circular areas 1 (8), 2 (7), 3 (6) and 4 (5) meant for manufacturing and measuring in *Z* direction respectively. The workpiece clamping diameter was 1,200 mm and model gain factor to $g = 0.76$ had to be adjusted. The workpiece was placed on accurately polished underlies (for potential measurement on CMM machine) and fixed to the rotary table by clamps.

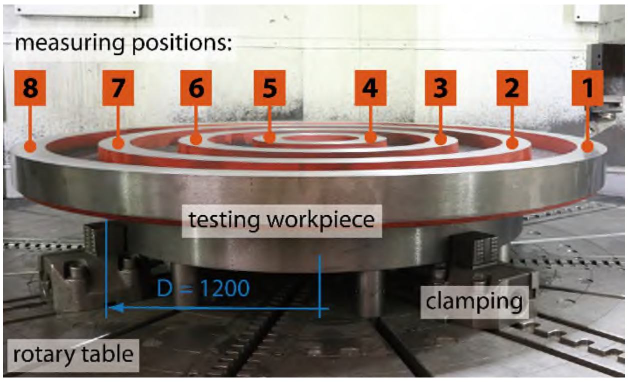


**Figure 5.** Testing workpiece

The manufacturing process of the testing workpiece during verification test within finishing cutting conditions is depicted left in Figure 6. Measuring principle of manufactured areas is shown right in the same figure.

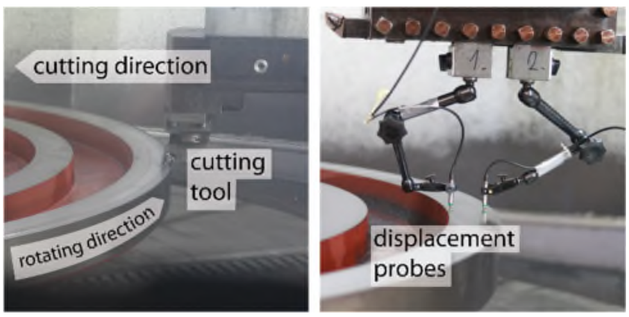


**Figure 6.** Testing workpiece manufacturing (left) and measuring (right)

The testing workpiece manufacturing process was carried out as fallow. First circular area 1 (8) was manufactured by prescribed finishing cutting conditions (Table 2). Then steady cutting tool waited 1.5 hour between areas 1 (8) and 2 (7). Rotary table was active on constant rpm. Second area 2 (7) was manufactured after the pause and so on until the tool reached the middle of the workpiece and experiment was ended.

Two contact displacement probes were mounted on headstock tool holder to measure the workpiece deformations after MT cooled down. The two points were measured in all measuring positions (1 to 8). Table was repositioned five times (in 45°) and all positions measured for statistical data; evaluation uncertainty of Type A.

**Table 2** Cutting parameters

| **table speed** [rpm] | **depth of cut** [mm] | **feed rate** [m·min$^{-1}$] | **pitch** [mm·rpm$^{-1}$] |
|---|---|---|---|
| variing (see Fig. 7) | 0.2 | 120 | 0.15 |

Two experiments were carried out (with and without thermal error compensation active in MT control system) to evaluate MT accuracy enhancement. The measured model input behaviours and table speed during both tests with cutting process are depicted in Figure 7.

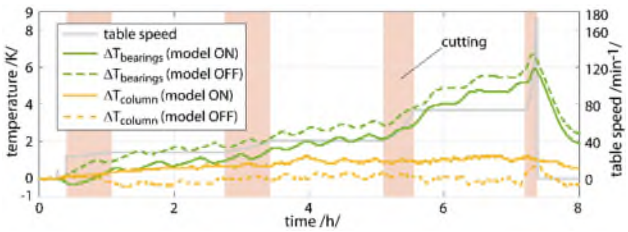


**Figure 7.** Cutting test set-up, conditions and model input behaviours

From measurements the arithmetical mean of thermal deformations was calculated in all measuring positions. The measured deformations in *Z* direction with active compensation are depicted left in Figure 8. Deformations without compensation are shown right in Figure 8. Since the experiment set-ups are similar both MT thermo-mechanical states are possible to easily compare.

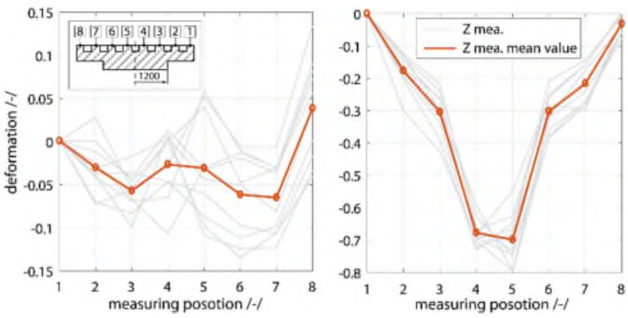


**Figure 8.** Measured deformations with compensation (left) and without compensation (right) during the finishing cutting tests.

The improvement of the thermo-mechanical state is estimated 7-fold (87%) in the *Z* direction compared to the uncompensated state. Additionally the testing workpiece thermal errors were measured by a precision level and on CMM machine with similar results.

### 4. Conclusions

The main objective of the scientific investigation presented in this extended abstract is enhancement of MT accuracy by minimising thermal errors and evaluation of practical applicability of implemented (directly in MT control system) compensation model within finishing cutting conditions. The role of main thermal source, elimination of its influence on MT typical operations, workpiece clamping diameter consideration and minimal increase of the MT costs all represent basic requirements placed on specific compensation methods and TFs seem to be a suitable apparatus.

The tested machine was a vertical turning lathe. Calibration experiments were carried out under specific conditions: no cutting process was involved and were performed along the one MT axes configurations. The developed compensation model approximates undesirable thermal errors caused by the rotary table activity. Compensation was taken into account for linear deformations in *Z* direction and along the whole table diameter (measured with the help of thermal stable frame). The approximation quality of the model based on TFs was compared to uncompensated MT state within finishing cutting conditions with result of 87% of MT thermo-mechanical behaviour improvement.

The follow-up research will focus on MT thermo-mechanical behaviour regarding its multi-functionality (milling operations) and model transferability to other machines of the same construction but different size.

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