Proceedings of the 13th **euspen** International Conference – Berlin – May 2013

Physical and phenomenological simulation models for the thermal compensation of rotary axes of machine tools

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Abstract

Up to now, research of the thermo-mechanical deformations was focused on the environment, the spindle, the bed and the linear axes of machine tools. The thermal behavior of rotary and swiveling axes was not studied in the same detail, but they are getting more important due to the increasing requirements for 5-axis machine tools. This paper deals with the comparison of a physical and a phenomenological simulation model for a model-based compensation of thermal errors of rotary axes.

1 Introduction

Thermo-mechanical deformations caused by internal or external heat sources are still responsible for up to 75% of all geometric errors on machine tools. Because of this significance, there are many approaches with the goal to reduce these errors [1]. Regarding the thermo-mechanical flow (Figure 1), this can be achieved in two ways.

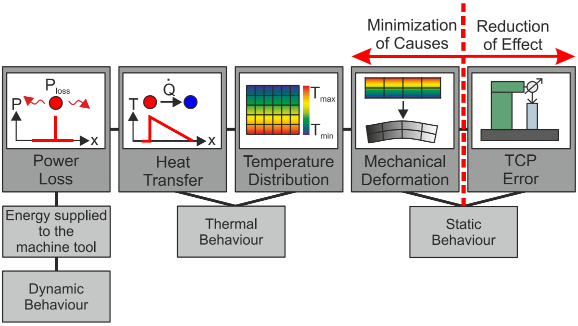

Figure 1: Thermo-mechanical flow diagram

On one hand, the *causes* can be minimized. This can be carried-out by reducing power losses or by altering heat transfer in the machine tool. The temperature distribution can also be homogenized or the resulting mechanical deformation can be decreased by a more thermo-symmetrical design or a smart material mix. On the other hand, the *effect* (the thermo-mechanically caused TCP error) can be reduced by a compensation strategy. Therefore, a kind of error modeling is necessary, which implicates proper know-how about the thermal characteristics of the relevant axis.

2 Thermal characterization of rotary axes

As mentioned in [2] and [3], an ideal measuring device for the thermal characterization of rotary axes is the R-Test device (Figure 2, left side). When it is carried out as "R-Test discrete" (Figure 2, right side), all significant errors of the rotary axis or of functional surfaces can be evaluated by measuring 5 discrete points at 0, 90, 180, 270 and 360°.

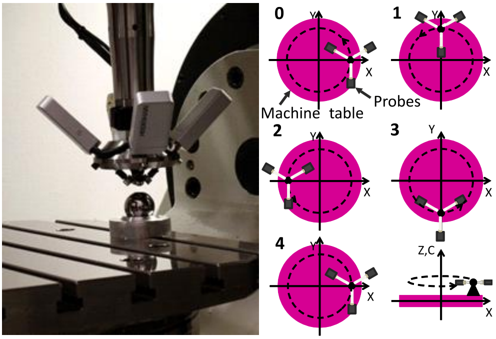

Figure 2: "R-Test discrete" setup and measuring cycle [2]

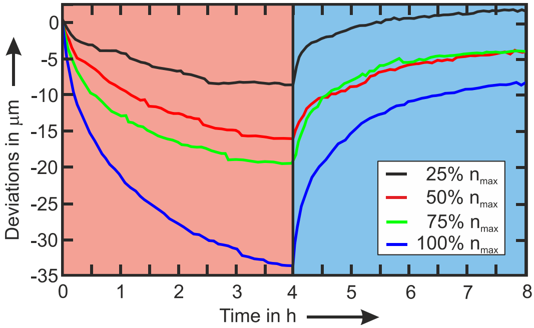

Figure 3: Axial growth of machine table *(Z0T)* for different rotational speeds, n_{max} = maximum rotational speed.

As an example for a significant location error caused by a rotary axis, Figure 3 shows the axial table growth (*Z0T*) of a C-axis machine table over 8 h (warm-up 4h, cool down 4 h). The relationship between the thermal caused deviation and the thermal load is represented by 4 different rotational speeds.

3 Modeling and simulation

There are several approaches for thermal modeling which allow the compensation of thermo-mechanical errors like FEM models, neural networks, phenomenological models or simplified physical models using the transient heat conduction. In this paper, a phenomenological model and a simplified physical model are compared and tested. Advantages and Disadvantages of these two simulation approaches compared to FEM modeling are described in Table 1.

Table 1: Comparison between different model-approaches

	Advantages	**Disadvantages**
Simplified physical model (heat transfer)	- Physical model (extrapolation: unknown conditions) - Small modeling effort - Few measurements required	- Modeling: - Number of elements - Geometry of elements - Manual modeling - Alignment of model and measurements (Model-matching, e.g. density, heat transfer coefficient, ...)
Phenomenological modeling	- No physical model necessary - Only measurements necessary - Low Uncertainties, good quality of model	- Many measurements necessary (takes time) - Uncertainty in unknown conditions
FEM	- Physical model (extrapolation: unknown conditions) - If model is available from phase of design: small modeling effort	- Complex model (Implementation in NC very difficult) - Alignment of model and measurements (Model-matching, e.g. density, heat transfer coefficient, ...)

To compare both approaches, an axis movement sequence according to Figure 4 was measured and simulated (with the physical and the phenomenological model) for a vertical rotary axis with a direct drive system.

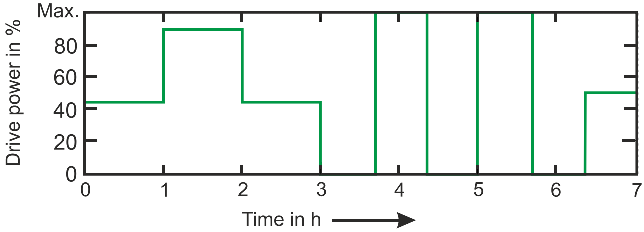

Figure 4: Test sequence with varying thermal load for verification of error models

3.1 Phenomenological model

The structure of the phenomenological model presented in this paper can be seen in Figure 5. It is based on three R-Test measurements at different thermal loads (at 33%, 66% and 100% of the maximum power) for parameter identification. Each measurement returns location and positioning errors in the form of first-order lag elements as a response to the thermal load induced into the system. As model parameters, proportionality constants and time constants of the three measurements are used. A simple linear interpolation between these three sampling points provides compensation parameters for all other conditions. To consider the environmental temperature variation, an environmental temperature variation error test (ETVE test) was carried out over one week and implemented into the model.

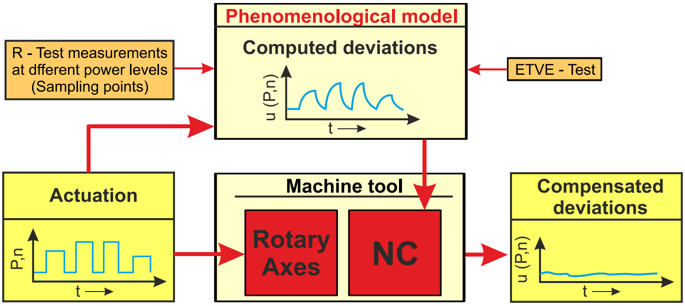

Figure 5: Structure of phenomenological simulation model

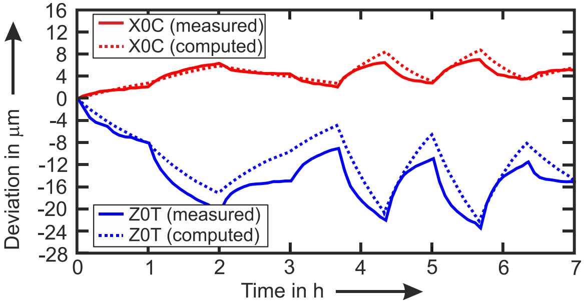

Figure 6: Comparison between measurement and phenomenological simulation

Figure 6 shows the measured and computed results of two location errors for the introduced test sequence: *X0C* (C-Axis movement in X-direction) and *Z0T* (axial growth of machine table). For a reasonable verification, the test sequence was carried out at different thermal loads as the measurements used for model set-up.

3.2 Physical model

The physical model presented in this paper is based on a discretization of the machine structure in a few significant elements (Figure 7). Each of these elements represents a part of the structure and its physical properties as mass, heat capacity, convection, heat conduction or cooling power. The temperature in each element is assumed as homogenous and based on the temperature distribution over all elements the deformation can be computed. The main parameter is the current power input of the drives of the rotary axes, which is read from the NC online via a C++ code.

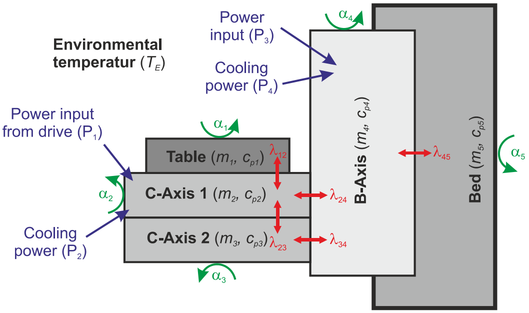

Figure 7: Discretization of a tilting rotary table unit by 5 significant elements

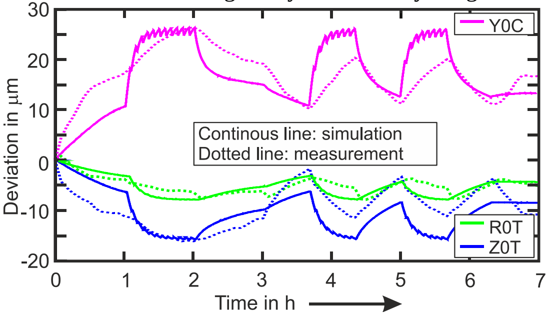

Figure 8: Measurements and a first simulation approach with physical model

In Figure 8, first simulation results with physical model are compared to measurements (the underlying thermal load is according to Figure 4). The figure shows, that the basic characteristic of the location errors can be simulated very well, but the magnitude and the transition between different proportional constant and delay times has to be improved. A possible solution could be to use the physical model together with a parameter identification. Using measured data, it would be possible to identify parameters or reduce the uncertainty of estimations.

4 Compensation

The results of a first compensation of the location errors *X0C* and *Z0T* are shown in Figure 9. The compensation is based on the phenomenological model presented above. In this first approach, the compensation data was implemented via the NC code. With the compensation, the thermo-mechanical deviation could be successfully reduced by up to 75%.

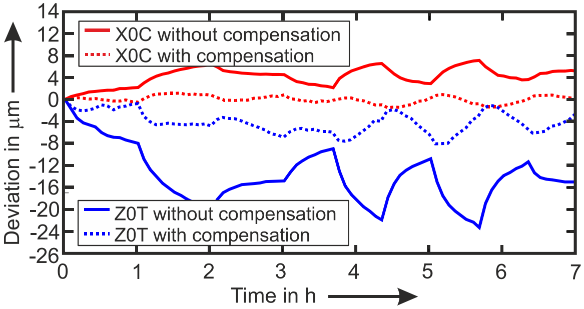

Figure 9: Measurements with and without compensation (based on phenomenological model)

5 Conclusion & Outlook

Two approaches for thermal modeling of location and position errors of rotary axes of machine tools were compared. The implementation of a first phenomenological approach showed a reduction of two different thermal location errors up to 75%. As a next step, the physical model shall be tested and implemented into a NC. As an extension, a parameter identification is planned. Therefore, the model shall be adaptable easily to different machine tools or environmental conditions.

References:

[1] Mayr J. et al. (2012) Thermal issues in machine tools. Annals of the CIRP, 61/2:771-791

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