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Efficient thermo-mechanical model of a precision 5-axis machine tool

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Abstract
Thermally induced deviations of machine tools result in geometric errors of manufactured parts. Thermo-mechanical models are a great asset in order to predict the thermal response of machine tools and understand the thermal design. This paper presents a thermo-mechanical model of a 5-axis precision machine tool, focusing on the thermal response during the rotation of the C-axis. In order to reduce the computational effort, this work uses a surrogate model by means of projection-based Model Order Reduction (MOR). The model setup, reduction, and analysis are performed in MORe, an simulation package designed for the development of efficient model of machine tools. The response of the thermo-mechanical model is compared to the measured thermo-mechanical deviations during the rotation of the C-axis. The validated thermo-mechanical model enables analysis of the thermal design of the machine tool, in frequency and in time domain.

Thermo-mechanical model; model order reduction (MOR); machine tool

1. Introduction

The review paper of Mayr et al. [1] pointed out that the thermal error sources are one of the main contributors to geometric errors in manufactured parts. Recent advances in modelling techniques facilitate the understanding of the thermal behavior of machine tools. Physical models, based on the finite element (FE) discretization of the heat transfer and elasticity equations, serve as virtual prototypes to test different design alternatives. However, the thermo-mechanical FE-models are computationally expensive due to the geometrical complexity of the machine tools. This limits the applicability when a large number of model runs or real time capabilities are required. Therefore, developing efficient modeling approaches is necessary to ensure the usability of physical models. Surrogate models are computationally efficient models reproducing the response of a high-fidelity model. Projection-based surrogate model or Model Order Reduction (MOR) is based on the projection of the original model in a lower dimensional subspace. The main advantage of MOR is that it retains the system structure while it allows tracing the system dynamics, as explained by Benner et al. [2].

2. MORe: an efficient simulation framework

MORe [3] is a software package developed at inspire AG for the simulation of the static, dynamic, and thermo-mechanical behavior of machine tools. The simulation platform offers tools to analyze efficiently the behavior of machine tools and optimize their design.

The simulation platform provides an efficient workflow to develop physical models of machine tools. Figure 1 illustrates the tool chain for the creation of a model of a machine tool assembly. A commercial FE software, Ansys, performs the FE discretization of each of the components of the assembly. As shown in Figure 1, MORe imports the geometrical information and system matrices delivered by the FE commercial software. After importing the required information, the model setup, analyses and postprocessing of the simulation results is performed in the software MORe.

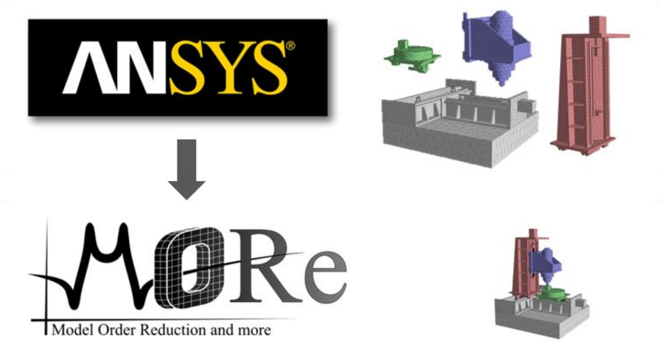

Figure 1. Tool chain of MORe: an efficient simulation framework

The model setup requires the definition of the different boundary conditions, e.g. moving or stationary thermo-mechanical contacts between the different components or convective boundary conditions. These boundary conditions are interfaces of the system, i.e. independents inputs considered for the reduction. After the complete definition of the model interfaces, the system equations are reduced by means of projection-based MOR. The Krylov Modal Subspace (KMS) approach is used for the creation of the projection basis. The work of Spescha [4] and Hernández-Becerro [5] provides a more detailed description of the reduction methods. The reduced models enables the efficient evaluation of the thermo-mechanical behavior of machine tools.

MORe offers dedicated analysis tools designed to investigate the design of machine tools. The thermo-mechanical transfer function in frequency domain evaluates the thermal response of the machine tool at characteristic frequencies, such as the 24 hours periodicity of the environmental temperature associated to the day-night cycle. The thermal transient response provides the thermo-mechanical response of the system under internal and external thermal influences. A full-featured postprocessor with cutting-edge visualization tools supports the evaluation of the simulation results.

3. Thermo-mechanical model of a 5-axis machine

This paper investigates of the thermo-mechanical behavior of the machine tool of Figure 2. The investigated machine tool is a 5-axis milling machine with a rotary table, a swiveling axis, and a vertical spindle. The kinematic configuration according to ISO 10791-1:2015 adapted for vertical spindles is:

$$V\ [w\ C2'\ B'\ b\ [Y1\ Y2]\ X\ [Z1\ Z2]\ (C1)\ t]$$

The dimensions of the working space is 730x510x510 mm for the investigated machine tool. The rotary table has a diameter of 500 mm. The C-axis of this machine tool provides the possibility to perform turning operations, enabling a maximal rotational speed of 1200 rpm. The rotation of the C-axis results in thermally induced deviations that directly affect the accuracy of the machine tool. This section presents an efficient thermo-mechanical model of the rotation of the C-axis. The thermal error model is performed in software environment MORe, introduced in Section 2.

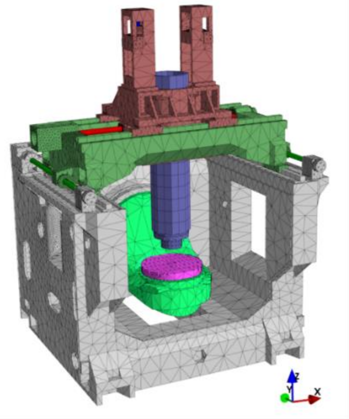

Figure 2. Model of the Mori Seiki NMV 5000 DCG in MORe

3.1. Setup of the thermo-mechanical model

In order to create the thermo-mechanical model, a commercial FE software performs the FE-discretization of the geometry of each of the components of the machine tool assembly. According to the workflow presented in Figure 1, the data is then imported into MORe where the thermal contacts, mechanical contacts, and other boundary conditions are defined. Among the thermal contacts at the different machine elements, the thermal contact conductivity (TCC) of the bearing of the C-axis plays a relevant role to describe the response of the machine tool to the investigated load case. For the estimation of the TCC of the bearing, the empirical correlations proposed by Wiedermann [6] are used. These formulas are based on the geometry of the bearing (e.g. diameter of the rolling elements) and rotational speed. The description of the thermal behavior requires the estimation of the convective boundary conditions. Pavliček et al. [7] presented a meta-model for the evaluation of the HTC inside the enclosure of the machine tool of Figure 2. The meta-models, validated with full CFD models, provide an estimation of the convective heat transfer inside the working space during the rotation of the C-axis.

The thermal response to the rotation of the C-axis originates heat losses at the machine elements. In order to quantify these heat losses, thermo-energetic models are a useful tool. Thermo-energetic models predict the different energy flows between the different components, providing an accurate estimation of the thermal boundary conditions. Züst [8] developed a simulation platform, EMod, to quantify the different energy flows in machine tools. Mohammadi et al. [9] used this simulation platform to create a thermo-energetic model of the investigated machine tool.

Figure 3 shows the different energy flows occurring during the rotation of the C-axis. The electrical power (P_{axis}) of the axis unit is supplied to the amplifiers. The amplifiers receive AC signal and rectify it in order to deliver a pulse width modulated (PWM) signal to the torque motor (P_{motor}). A power measurement system provides the power supplied to the axis unit during the rotation of the C-axis. A part of the power supplied to the amplifier is transformed into thermal energy ($Q_{amplifier}$). The amplifiers are structurally disconnected from the structural parts and the heat is removed from the EC by the ventilation system. Thus, the thermo-mechanical model of the C-axis does not consider the heat dissipated by the amplifiers. At a constant rotationally speed, i.e. after the acceleration of the axis, the energy supplied to the motor (P_{motor}) is converted into heat losses at the stator (Q_{stator}) and bearings ($Q_{bearing}$). Provided the characteristics of the torque motor and bearings the thermal losses at these elements can be quantified, as suggested by Züst [8].

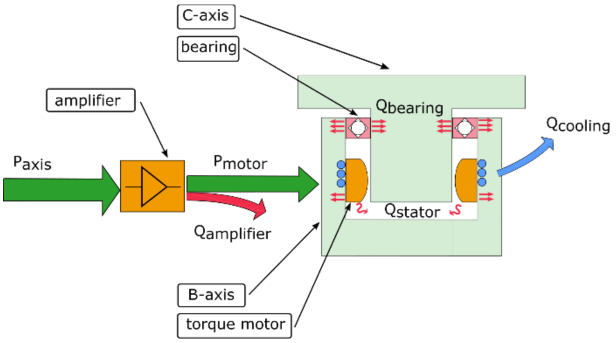

Figure 3. Energy flow in the rotary table unit of the NMV 5000 DCG

The cooling system is responsible for evacuating part of the heat dissipated in the machine elements, as depicted in Figure 3. External pumps supply pressurized fluid to the cooling channels arranged around the torque motor. An external unit controls the inlet cooling temperature to a reference temperature provided by a sensor located in the machine tool bed. Measuring the difference of the inlet and outlet temperature as well as the volumetric flow provide an estimation of the heat removed by the cooling system.

After the definition of the inputs of each of the parts of the machine tool assembly, a surrogate model by means of MOR is created. MORe provides a set of reduction methods based on the Krylov Modal Subspace (KMS) [4] method for the efficient simulation of machine tools. The projection basis captures the steady state part of the response including a basis of the Krylov subspace with an expansion point at a low frequency, i.e. 10^{-8} rad/s. Furthermore, the projection basis includes the eigenmodes of the system in order to reproduce the transient response. The a priori error estimator of the KMS ensures that the relative error between the reduced and original system remains below 0.05 for a frequency up to 0.01 rad/s. The MOR transforms the original thermal system of 508,462 dofs to a reduced system of 392 dofs. In order to evaluate the mechanical response, a reduced thermo-coupled system needs to be also created. For the thermo-mechanical coupled system, an expansion point at 30 rad/s is chosen in order to capture the static mechanical response. The original mechanical model of 1,525,386 is reduced to 1,164. The reduced models enable the efficient simulation of the thermo-mechanical behavior of the investigated machine tool, facilitating the validation process.

3.2. Validation of the thermo-mechanical model

After completing the model setup and quantifying the boundary conditions, the comparison of the simulated and measured thermally induced deviations provides a validation of the thermo-mechanical model.

Weikert [10] developed the an indirect volumetric measurement technique, the R-Test, for geometric calibration of 5-axis machine tools. The R-Test evaluates the linear deviations between a sensor nest located on the spindle and the precision sphere located on the table. Measuring the relative deviation at four different indentations of the rotary table provides the thermally induced position and orientation of the C-axis. Blaser et al. [11] adapted R-Test measurement by including an on-machine measurement system. Instead of a sensor nest with displacement sensors, the measurement setup uses a 2.5D touch trigger probe. The main advantage of this measurement setup is that it facilitates its integration for online compensation strategies. This work uses this measurement system for the validation of the thermo-mechanical model.

In order to characterize the thermal behavior of the rotary table, the C-axis rotates at 1200 rpm over 3 hours. During the rotation of the C-axis, the inlet and outlet temperature is measured, as depicted in Figure 4. The difference between the inlet and the outlet temperature remains 0.8°C over the measurement time. This difference of temperature provides the the heat removed by the cooling system, which is an input of the thermo-energetic model. The chiller of the cooling fluid causes the fluctuations of the absolute values of the cooling temperature, as illustrated in Figure 4.

In order to define the boundary conditions, the fluctuations of the temperature of the air needs to be considered. For the validation of the thermo-mechanical model, the C-axis is rotated over 3 hours, which is a short time in order to observe significant fluctuations of the environmental temperature in the workshop outside the machine tool enclosure. Therefore, the temperature of the air outside the machine tool housing is assumed constant during the rotation of the C-axis. However, this is not valid for the air inside the machine tool enclosure, rising over 3.3 °C during the measurement time. The temperature increase stabilizes after 150 min of the rotation of the C-axis. Figure 4 shows the temperature rise inside the machine room (MR), which is an input for the thermo-mechanical model.

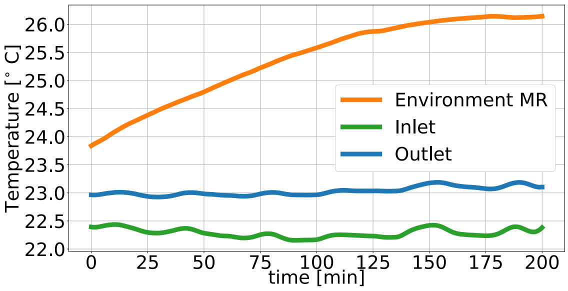

Figure 4. Measured temperatures during the rotation of the C-axis at 1200 rpm over 3 h. MR: machine room

In order to validate the model, the simulated thermal response is compared with the measured deviations. The investigated thermal load is the rotation of the C-axis at 1200 rpm over 3 h. The measurement system evaluates the thermally induced linear deviations every 6 min during the rotation of the C-axis. Figure 5 shows the comparison between the simulated and measured thermal behavior of the investigated machine tool. Due to the symmetry of the design of the machine tool, the machine tool does not show any deviations in X-direction. The dominant thermally induced deviations are in Y- and Z-direction. The model succeeds in representing the absolute values as well as the transient trends of the thermal deviations. Figure 5 shows that the thermo-mechanical model reproduces the thermal response of the investigated machine tool during the rotation of the C-axis. The main discrepancies between model and simulation are in Z-direction during the first hour. These discrepancies can be attributed to the lack of detail in modeling the thermal behavior of the measurement system.

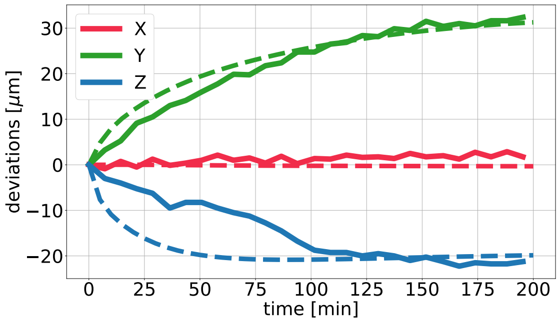

Figure 5. Comparison between measured and simulated thermal deviations due to the rotation of the C-axis at 1200 rpm over 3 h

3.3. Investigation of thermal design of the machine tool

After validating the thermo-mechanical model of the machine tool, the thermal design of the machine tool to internal heat sources can be further investigated. Mayr et al. [12] proposed the analysis of the thermal response of machine tools in frequency domain. The transfer function describes the effect of the variation of the thermal inputs on the outputs of the system for a given frequency range. For the thermal load under consideration, the input of the transfer function is the energy provided to the motor, P_{motor}, which transforms into heat dissipated at the bearings and stator. The outputs of the transfer function are the deviations between the TCP and the workpiece in X-, Y-, and Z-direction. The transfer function, shown in Figure 6, describes the thermal behavior in a frequency range between 10^{-6} and 0.01 rad/s. The thermal transfer illustrates that internal heat losses affect predominately the deviations in Y-direction, as observed also in the transient response of Figure 5. Furthermore, the transient function of Figure 6 provides the time constants of the response of the system. The model predicts that the time constant associated to the deviations in Y-direction is larger than the time constant of the response in Z-direction. The information about the different time constants of the response of the machine tool in different directions is of great interest when designing thermal error compensation strategies.

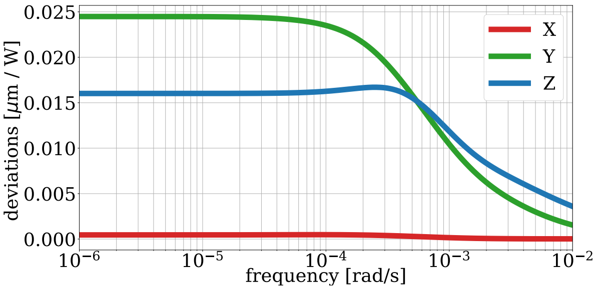

Figure 6. FRF response of the machine tool of Figure 2. Input: heat losses at the machine elements. Output: TCP deviations relative to the workpiece for the X-, Y- and, Z-direction.

A combination of the internal heat losses and the increase of the temperature inside the MR determines the thermal response of the machine tool during the rotation of the C-axis. The thermo-mechanical model enables the separation of these two the influences. Figure 7 shows the deformation of the machine tool, displaying the structural parts of the Z-, B-, and C-axis. The left part of Figure 7 illustrates the effect of the internal heat losses, i.e. losses at the stator and bearings, while the right side shows the deformation due to the increase of the air temperature inside the enclosure. On one hand, the internal heat sources affect predominantly the workpiece-sided axes, leading to deformations in Y- and Z-direction. On the other hand, the variation of the MR air temperature affects the workpiece-sided axes as well as the part of the Z-axis inside the working space. Therefore, the tool-sided axes are accountable for part of the thermally induced deviations. If the TCP deviations are measured relative to the inertial system, i.e. not considering the workpiece as a reference, the thermal deviations in Z-direction are -2.4 µm. This corresponds to 12% of the relative deviation between TCP and workpiece. For other direction, the contribution to the total thermal deviations of the tool-sided axes is negligible. The fact that part of the thermal deviations are originated in the tool-sided axes have a great significance during the design of the thermal error compensation strategies. The workpiece-sided deviations in Z-direction measured at B = 0° result in deviations both in Z- and X-directions for other positions of the B-axis different from 0°. However, the tool-sided deviations in Z-direction are unaffected by the position of the B-axis. Therefore, the possibility to quantify and separate between the tool- and workpiece-sided deviations benefits directly the quality of the thermal error compensation.

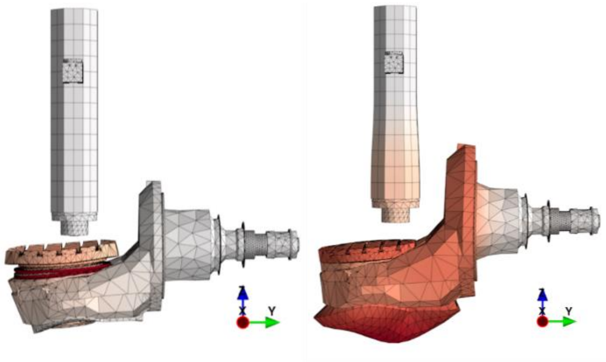

Figure 7. Structural deformation of the machine tool. Only the Z-, B-, and C-axis are shown. Right: thermal response to the internal heat sources. Left: thermal response to the increase in the temperature of the MR

4. Conclusions and outlook

This paper investigates the thermal response of a precision 5-axis machine tool during the rotation of the C-axis. The heat losses determine the thermal response of the machine tool. Therefore, the model requires considering the different energy flows during the rotation of the C-axis. In order to ensure an efficient simulation, this work creates a surrogate model by means of MOR. The simulation platform MORe enables an efficient workflow for the setup of the thermo-mechanical model. The software package MORe integrates reduction approaches to approximate the thermo-mechanical behavior of the original system. This paper compares the predicted and the measured thermally induced deviations, concluding that the developed thermo-mechanical model can represent the thermal response of the machine tool during the rotation of the C-axis. The validated model serves as a virtual prototype to investigate the thermal design of the machine tool and assess the validity of the thermal error compensation strategies. Future work will concentrate on the investigation of the thermal response of the machine tool to other load cases as well as improving current thermal error compensation models.

5. Acknowledgments

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