METHODS FOR DETERMINING THERMAL ERRORS IN MACHINE TOOLS BY THERMO-ELASTIC SIMULATION IN CONNECTION WITH THERMAL MEASUREMENT IN A CLIMATE CHAMBER

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Thermo-elastic deformation of the machine tool due to thermal expansion of machine components presents one of the biggest challenges in maintaining accuracy and product quality. The operation of the machine inevitably leads to waste heat due to friction losses of bearings and guides and electrical losses of motors and control cabinets. These internal heat sources lead to inhomogeneous and changing temperature fields, which also interact with the ambient temperature. An interaction with the environment takes place via natural or forced convection and radiation. During the design phase, these thermal effects are determined using thermal (typically FEM) simulations. For existing machines, thermal measurements are possible but require careful planning and execution. Thermo-elastic FEM simulations coupled with thermal measurements in a climate chamber with controlled ambient and foundation temperature, lead to an optimal understanding and management of thermal errors in machine tools. In this paper, the process of thermo-elastic FEM in connection with measurement principles in a climate chamber will be presented. The five-axis milling machine tool DMU 80 evo is used to demonstrate and validate the results of the thermo-elastic FEM with measurement data.

KEYWORDS

Thermo-elastic simulation, thermal measurement, machine tool precision, thermal error, error compensation, FEM modelling

1 INTRODUCTION

Thermal effects on machine tools lead to geometric inaccuracies on workpieces and are the most difficult error types to control [Mayr 2018]. The reason for this lies in the complex interaction of different physical effects with different time response behaviours. Additionally, machine-dynamic effects such as vibrations and natural frequencies play a role, too [Kidani 2020]. Since the latter have a very short time interval and occur immediately, a compensation of these effects during operation is possible immediately. With the help of mechatronic models and simulations, the dynamic behaviour can be determined almost exactly with a high temporal resolution. With thermal effects, however, things are much more complicated, since cause and effect occur with a time delay due to thermal inertia and large time constants. An example is a changing ambient temperature that slowly affects a machine tool over several hours. This delay depends on many parameters, to name a few: machine size, enclosure, material, humidity. Another example is the local heat generation as a result of power loss due to friction (e.g. screw drives, guide rails, bearings) or electro-mechanical losses (motor spindle, electric motors), which lead to thermal expansion. By tilting or deforming the component, the effect at a point further away from the source, such as a tool tip, can be very large. A well-known example is the skew of the spindle unit. In order to correctly measure this effect in a time-resolved manner, a temperature sensor would have to be positioned directly at the heat source, which is not possible in practice in many cases. The temperature sensors are usually positioned at a distance from the heat source and therefore react with a time delay. This presents a great challenge for sensor-based error compensation methods. An improvement can be achieved by methods of optimal sensor placement [Herzog 2018] or through the use of time delay elements [Wissmann 2011]. Another possibility would be to use virtual thermal twins to predict the thermal errors and compensate them with the right values at the right time. This model-based approach uses numerical computer simulations to model the physical behaviour of the machine tool as accurately as possible under different conditions. Since only a limited number of simulations can be performed economically in order to determine the reference load cases, an additional data interpolation method is required to integrate the error compensation into the machine control. Algorithms are needed, that can interpolate the values for unknown load cases on the basis of existing simulation data. Multiple regression analysis (MRA) models such a characteristic diagrams or artificial neural networks (ANN) are suitable for this task. The high demand on a simulation model, that is as exact as possible is essential, since wrong simulation results can even increase the error.

Chapter 2 starts with an overview of the relevant internal heat sources and heat sinks and the effects of ambient conditions on the thermal machine tool behaviour. Chapter 3 describes how thermo-elastic FE models are created, how a thermal machine measurement is set up and performed and shows some results. Chapter 4 gives a brief overview of the measurements performed on the DMU 80 evo. Finally, a summary of the work and an outlook on future research topics conclude the paper in chapter 5.

2 SYSTEMATIZATION OF THERMAL INFLUENCES

A subdivision of the thermal effects in a machine tool is extremely important for an overall understanding of the problem. In order for a simulation model to calculate as accurately as possible, all boundary conditions must be recorded and reproduced correctly. A categorization of the relevant thermal influences is presented in the following subchapters.

2.1 *Internal heat sources*

Internal heat sources are mainly machine components and objects close to the machine, which generate heat and lead to an increase in temperature. This occurs on moving components through friction, electrical losses due to electrical resistances in electric motors and switch cabinets.

The following machine components generate waste heat and can be considered as internal heat sources (see fig. 1):

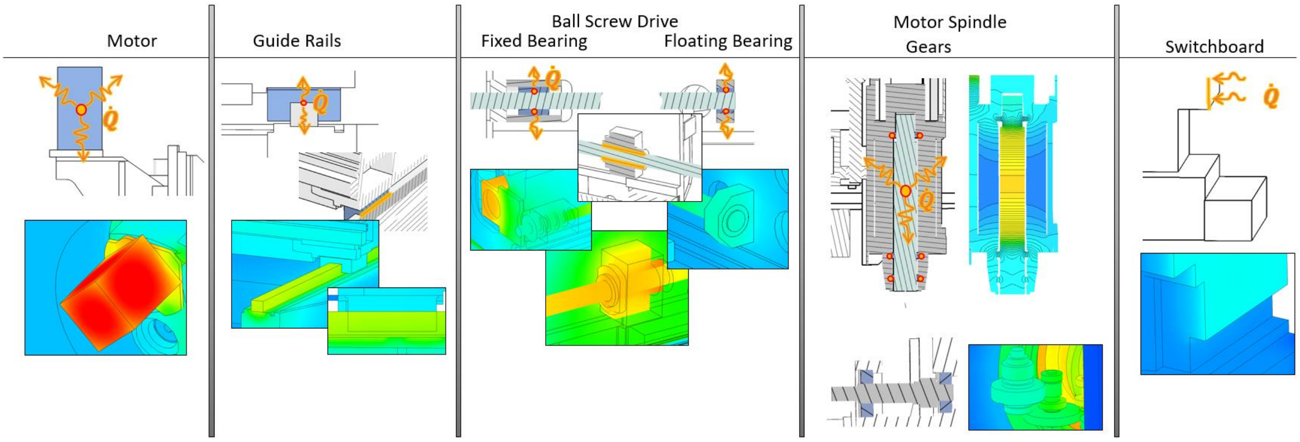

Figure 1. Overview of internal heat sources in a machine tool

a. Friction Losses:
   - Guide rails and carriages
   - Ball screw drives
   - Main bearings for rotary tables, swivel units
   - Ball bearings, motor spindle bearings, gears
b. Electrical Losses:
   - Motor spindle
   - Motors
   - Switchboard
c. Other heat sources
   - Pumps
   - Hydraulic and Pneumatic units
   - Auxiliary units

The heat flow is introduced into the machine structure mostly via the component contact (conduction) and leads to a temperature field that is inhomogeneous and transient. The transient temperature field development depends purely on the material, component geometry and component size. The thermal diffusivity is used as a parameter for the material behaviour, which results from the thermal parameters of thermal conductivity, density and heat capacity.

Part / Assembly	Materials	Duration until steady state
Ball bearings	Steel	10 - 30 min
Motor spindle	Mainly steel, cast iron	1 - 2 h
Cast iron frame	Cast iron	Several hours
Concrete frame	Concrete	3 - 7 days

Table 1. Thermal time behaviour of different machine components

A high thermal conductivity causes a component to reach a steady state more quickly and leads to smaller time constants. In contrast, a high thermal capacity causes a thermally inert behaviour. Such components react only slowly to external temperature changes and are able to store a lot of thermal energy. Examples of this are large machine beds made of concrete or mineral casting [Hermansky 2022].

2.2 *Internal heat sinks*

Heat sinks can produce the opposite effect to heat sources by dissipating heat through a negative heat flow. Examples are integrated cooling structures, fluid cooling circuits or Peltier elements. While the latter are not commonly used in machine tools, component cooling with fluids is state of the art. The aim of component cooling is to not only reduce mechanical wear but also to dissipate heat from heat-generating components in a targeted manner in order to increase machine accuracy. This is to prevent the heat from flowing into machine structures unobstructed and deforming the machine. Some ultra-precision machine tools with complex cooling concepts can almost completely prevent a heat influx. Their technical effort and costs, however, are quite significant. A residual error therefore always remains, which must thus be estimated and compensated.

Examples of internal heat sinks are:

- Spindle cooling of the stator
- Cooling bars or cooling pipes on guide rails
- Cooled roller bearings
- Cooled motors
- Cooled table unit
- Integrated cooling circuits in machine frames

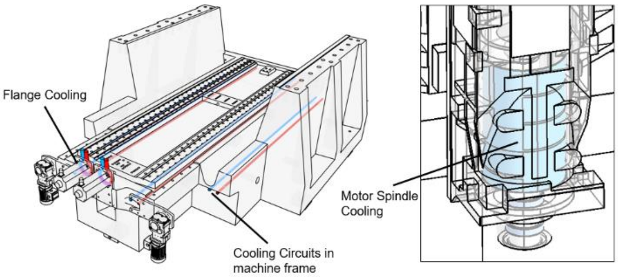

Figure 2. Examples for integrated cooling structures

2.3 *Ambient influences*

The ambient temperature is a very important influence on the machine behaviour, as it interacts with all machine parts that are in contact with the ambient air or are not insulated. These are usually the entire machine and particularly the workspace. The ambient influences are the most difficult to model and compensate, because they are unpredictable and subject to stochastic variation, unless the environment is subject to controlled air conditioning. On larger machines, the ambient influence clearly outweighs the internal sources and leads to much larger thermal errors, sometimes several hundred µm. In large machines, the air layering also plays a decisive role. In the case of environmental influences, heat is exchanged via radiation and free and/or forced convection. The decisive factor here is the surface (area, normal vector and material).

In free convection, an air flow is created as a result of a difference in density of the air due to different temperatures. In warm air, the streamlines are directed opposite to gravity. In closed rooms (e.g. in the workspace or in the housing of machine tools) circulation occurs, because warm air rises on a vertical wall.

In forced convection, on the other hand, there is an additional overlap with an artificially generated flow, whose flow velocity can exceed that of natural convection by several times. This makes the direction of flow independent of gravity, so that gravity can be neglected in flow simulations. It is irrelevant whether the reference system is moving with a velocity in the air or is being flowed towards. Examples for the first case are moving machine axes (linear axis movement) or rotating machine parts. For the second case, an example could be an opened factory door near a machine tool in winter. The amount of heat transferred depends essentially on the temperature difference between fluid and solid, the surface and the heat transfer coefficient (HTC).

$$\dot{Q} = A \cdot \alpha \cdot (T_W - \bar{T}_F) \qquad (1)$$

The heat transfer coefficient as the most important parameter depends on the flow velocity and the two local coordinates of the surface.

$$\alpha_{x,y} = \mathrm{f}(\boldsymbol{v}, x, y) \qquad (2)$$

For practical calculations, the area-averaged value is used in most cases. This can be determined directly using empirical formulas for simple geometries (cuboids, cylinders, spheres). For more complex structures (e.g. machine frames, tables), analytical solutions become very imprecise. Since this characteristic value must be known for an FEM simulation, only a numerical determination using a flow simulation (CFD) or an experience based estimation are possible. In the latter case, the error rate is relatively high.

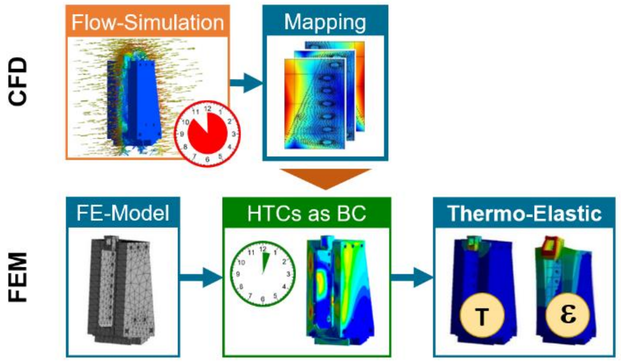

Figure 3. Decoupling approach for quickly supplying heat transfer coefficients from CFD to thermal FEM simulations [Kumar 2021]

One possibility for modelling these effects in the thermal FEM is to divide the machine surface into several sections with a distinction between vertical, horizontal and inclined surfaces. The average heat transfer coefficient for these surfaces can be determined by means of a flow simulation or simply by empirical calculations. In practice, it has been shown, that this approach can already lead to sufficiently good results in many applications [Zwingenberger 2014].

An even more accurate method would be to assign a local heat transfer coefficient to each mesh node of the surface. However, this requires a coupling with a thermo-fluidic model (fig. 3), whereby the modelling effort increases considerably. In commercial FEM software, this requires specially written scripts. A more efficient and even online-capable method for supplying these HTCs for different ambient loads is via the decoupling of thermal and fluidic simulation using characteristic diagrams. A number of CFD simulations for different ambient loads are run and used to train the characteristic diagrams, which can then interpolate the precomputed values for the current ambient load required within the transient thermal FEM simulation [Glänzel 2016].

A direct measurement of the HTCs is not possible. It can only be derived from the indirect measurement of other physical quantities (mainly temperature) [Dontchev 2007]. The following table can serve as a guide for the heat transfer coefficient.

Heat Transfer Coefficient [W/(m² K)]	Examples
2 - 20	Free convection in calm air
10 - 250	Forced convection with air flow
50 - 2,000	Convection of a body in water
500 - 10,000	Heat transfer in an impingement flow (water)
5,000 - 100,000	Heat transfer during phase change (condensation, evaporation)

Table 1. Typical range for heat transfer coefficients

2.4 Cooling lubricants

The cooling lubricant has three important main tasks:

- Fast and targeted removal of process heat from the workpiece and the tool,
- Reduction of friction on the cutting surface and minimization of tool wear,
- Chip removal and flushing in the workspace.

The first task is achieved by a fast heat transfer between the impinging coolant jet and the hot surface. It is very important that the coolant is fed locally into the cutting zone, as the largest heat flows occur in the chip formation zone. Ideally, the cooling lubricant is supplied via the tool tip through integrated channels at specific points (internal coolant supply). In addition, the cooling lubricant can be supplied through nozzles mounted beside the spindle (external coolant supply), which are directed at the cutting zone. In practice, both versions are often combined. Additional nozzles may be available in the workspace for chip removal and workspace flushing.

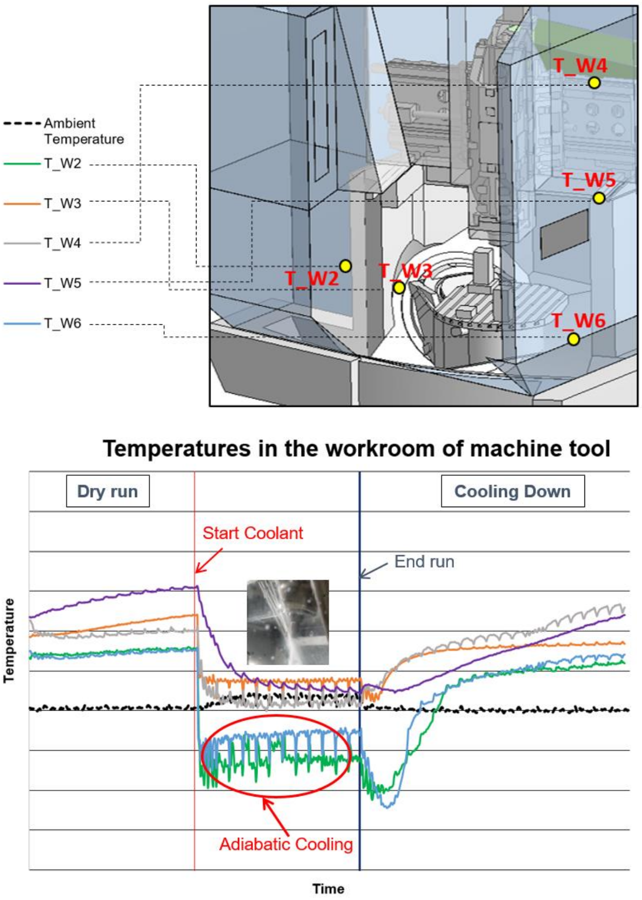

Figure 4. Cooling effects of cutting fluid in a machine tool workspace

The cooling lubricant is always an emulsion with water, to which other substances are added. This serves primarily for corrosion protection and better lubricating properties.

During wet machining, a separate microclimate is created in the workspace, which is clearly different from the environment. The supply of cooling lubricant leads to a supersaturation of the air with water and finally to mist formation. In addition to forced convection, there are also phase transition effects such as evaporation or condensation. Modelling in the workspace during wet machining is very complex and thus still under research.

Figure 4 shows a sample measurement on the DMU 80 evo. The first phase of the experiment ("dry run") is air-cutting with all five axes moving cyclically at 75% of the maximum speed. After this phase, the coolant is activated (flood cooling). A sharp drop in the temperatures in the workspace can be observed in this phase. Notable is also the adiabatic cooling occurring on the housing walls, which results in temperatures below the ambient temperature. Since the coolant is tempered to match the ambient temperature, there are normally no temperatures below this value. In the third phase, the machine goes into stand-by and the temperatures slowly return to their initial values.

2.5 *Machine foundation*

The ground or foundation is thermally inert and reacts only delayed to a change in the ambient temperature. As a result, air stratification occurs and machine parts close to the ground are usually colder or warmer than those remote from the ground.

3 METHODOLOGY OF THERMO-ELASTIC FEM SIMULATION COUPLED WITH THERMAL MEASUREMENT

FE models play an important role in the assessment of the thermal behaviour of components and entire machines. With the help of these models, it is possible to draw conclusions about the temperature and deformation behaviour, provided that 3D CAD models are available. This is typically the case for all new and relatively modern machines. With older machines, 3D CAD data is often not available, so the modelling effort often exceeds economic limits. Here, measurement based compensation methods are usually the preferred choice. For new machine designs, the simulation accompanying the development can be used to locate thermal problem areas and optimize the thermal behaviour through design improvements such as thermal symmetry. However, experimental model verification is not fully possible during the design phase until a physical prototype exists.

The goal of this scientific investigation is the effective preparation of a thermo-elastic FEM model for thermal analyses and for use in thermal error compensation algorithms, either directly in MOR-FEM simulation models or indirectly to obtain training data for regression based models.

3.1 *Design and structure of a thermo-elastic FEM model*

Based on a reduced CAD model of the entire machine tool, a thermo-elastic FE model is created. ANSYS Mechanical was used as simulation tool here. With the help of this software, it is possible to carry out a static-mechanical analysis on top of a thermal analysis (Fig. 6) in order to obtain the deformation field for a computed temperature distribution. From the deformation simulation, the relative or absolute displacements of the tool center point (TCP) in all three spatial coordinates (x, y, z) can be determined [Ess 2012].

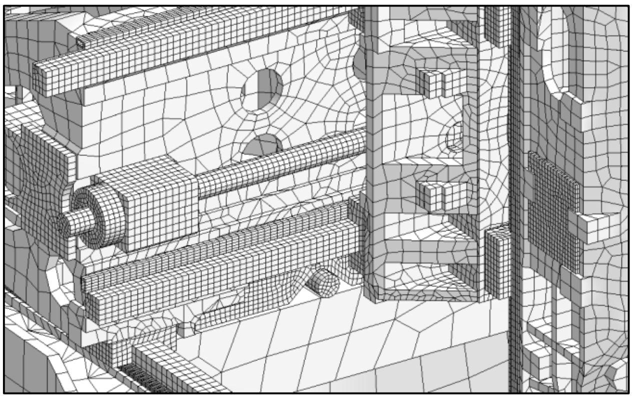

Figure 4. Volume mesh for a finite element analysis

The following requirements are placed on the model:

- Inclusion of all relevant boundary conditions (thermal input parameters),
- Material parameters have to be known or obtained from parametrization measurements,
- Consideration of different axis positions (investigation of the entire workspace),
- Computation time within the economic limits for available simulation hardware,
- High prediction accuracy of desired output variables.

The first point qualifies the model for almost all possible load cases that may occur during operation. The most important heat sources and sinks, convection influences of the environment and cooling systems are considered. The use of cooling lubricant in the workspace is currently being modelled using modified convection boundary conditions on the contact surfaces, which accordingly still creates a significant error. However, this topic is currently being investigated in another research project. For the second point, it must be assumed that the material data for all components is available and accurate within acceptable tolerance limits, since an experimental investigation is rarely possible. For the third point, the model is divided into several subassemblies in order to allow for different axis configurations. Only stationary calculations are performed at individual fixed positions. The next item is a compromise between computation time and mesh refinement of the model. The last point is the most important, because a compensation based on simulation data can only work with a physically correct model. For this purpose, the model adjustment with measurement data under controlled boundary conditions is necessary.

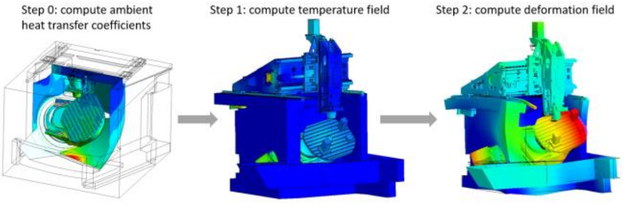

Figure 5. Principle of thermo-elastic FEM

3.2 *Experimental investigations in a climate chamber*

For the verification of a model of an entire machine tool a multitude of different investigations are necessary. The most important aspect in the procedure and the creation of a measurement plan is the decoupling of the internal heat sources and sinks from the environmental influences. In general, only the variation of a single parameter per experiment is useful.

Possible (load) parameters are:

- Axis to be moved and motion profile (axis load),
- Cooling lubricant application,
- Ambient Temperature.

The following scenarios are possible machine states (operating parameters):

- Machine switched off at varying ambient temperature,
- Warming up the machine after switching on without moving axes at constant ambient temperature,
- Machine in position control with changing ambient temperature,
- Cyclic movement of one or more machine axes at constant ambient temperature,
- Air-cutting with cooling lubricant,
- Cutting operation with/without coolant.

For the thermal investigation of the DMU 80 evo, the following measurements were performed in a climate chamber:

- Cyclic machine axis movements at constant ambient temperature (heat response measurement).
- Machine in position control with changing ambient temperature (ambient temperature change measurement).
- Machine switched off while ambient temperature is changed (convection influence measurement).
- Warm-up of the machine at a constant ambient temperature (warm-up measurement).

For the experimental investigations, a variety of different sensors are needed. In addition to temperature sensors, distance measurement sensors (displacement sensors) are needed, which can measure length changes with submicron precision. Both contact-based displacement sensors (induction based sensors, Fig. 8) and non-contacting displacement sensors (eddy-current sensors) can be used. Especially the latter are required for rotating machine parts or moving components. Other measurement equipment for measuring thermal deformations can be laser interferometers or photogrammetry. Specially developed probes and defined test pieces can also be used to measure thermal displacements of the TCP.

A distinction is made between relative and absolute displacement measurement. For relative measurements, the displacement between the measuring tool and a test workpiece is recorded over time. The result is a temporal trend curve, which can be used to draw conclusions about the thermal machine behaviour. Measuring tools can be touch probes (contact measurement with defined test force, Fig. 7) or eddy-current sensors (non-contacting), test workpieces can be simple geometric shapes or standardized parts. Relative error measurement is the most important for practical use, since it measures the actual difference (=error) between the NC program and reality. Also, the measuring effort is low compared to other methods. A disadvantage of relative methods is the lack of traceability to the cause of the error. The knowledge whether the error is caused by an inclination of a particular axis or by the deformation of the table unit remains unclear. In order to consider the error causes separately from each other, several measurements in the form of e.g. single axis measurements are necessary, which can be analysed separately. However, this always requires a known thermal machine condition (steady-state), which is best achieved in a climate chamber. A further disadvantage is the unknown initial error at the start of the experiment. Since the starting value differs for each measurement, it is necessary to set the start values to zero.

The determination of the relative displacements for each coordinate axis is the difference of the absolute coordinates of the test workpiece and the TCP:

$$\begin{aligned} rel\_Displacement_X &= \Delta(MP_{table})_X - \Delta(TCP)_X \\ rel\_Displacement_Y &= \Delta(MP_{table})_Y - \Delta(TCP)_Y \\ rel\_Displacement_Z &= \Delta(MP_{table})_Z - \Delta(TCP)_Z \end{aligned} \tag{3}$$

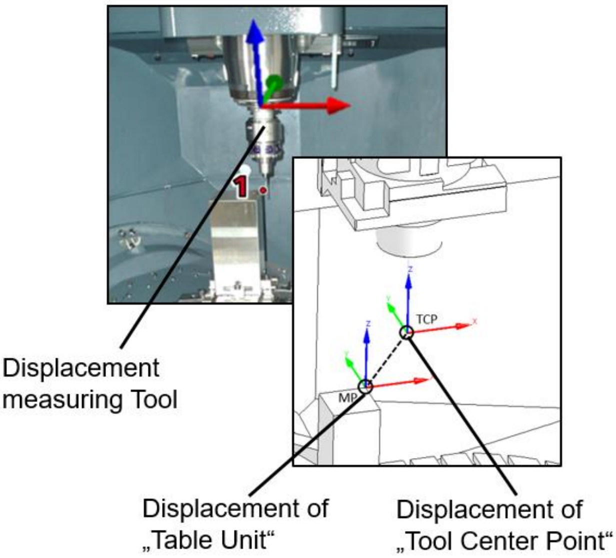

Figure 7. Relative displacement measurement between TCP and workpiece using a tool mounted touch probe

For the verification of a simulation model, the relative measurement is only conditionally suitable as a stand-alone method. For the determination of the absolute displacement, additional measuring setups in the form of additional measuring rods outside the machine with provided measuring points are required. The requirements for the measuring rod as a fixed reference point are a high thermal stability (i.e. very low coefficient of thermal expansion, e.g. due to special steel alloys such as Invar® steel) and a high mechanical stability.

In addition to high rigidity and vibration damping, this includes a stable coupling to the ground. An example of a test setup with measuring rods is shown in figure 8.

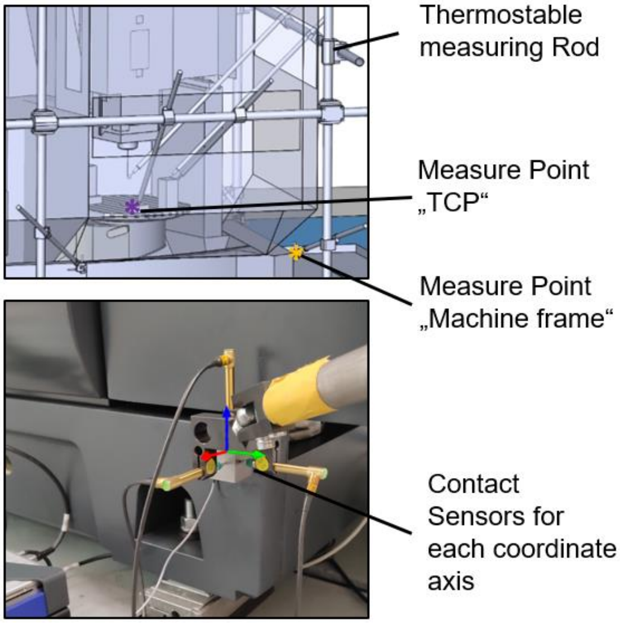

Figure 8. Measurement setup for determining the absolute displacement of the TCP (top) or the machine frame (bottom)

Here, the disadvantage is that absolute measurements are usually difficult on a machine tool with an enclosed workspace (housing). In practice, guidelines for handling hazardous substances, especially when using cooling lubricants, also prescribe sealing the machine workspace.

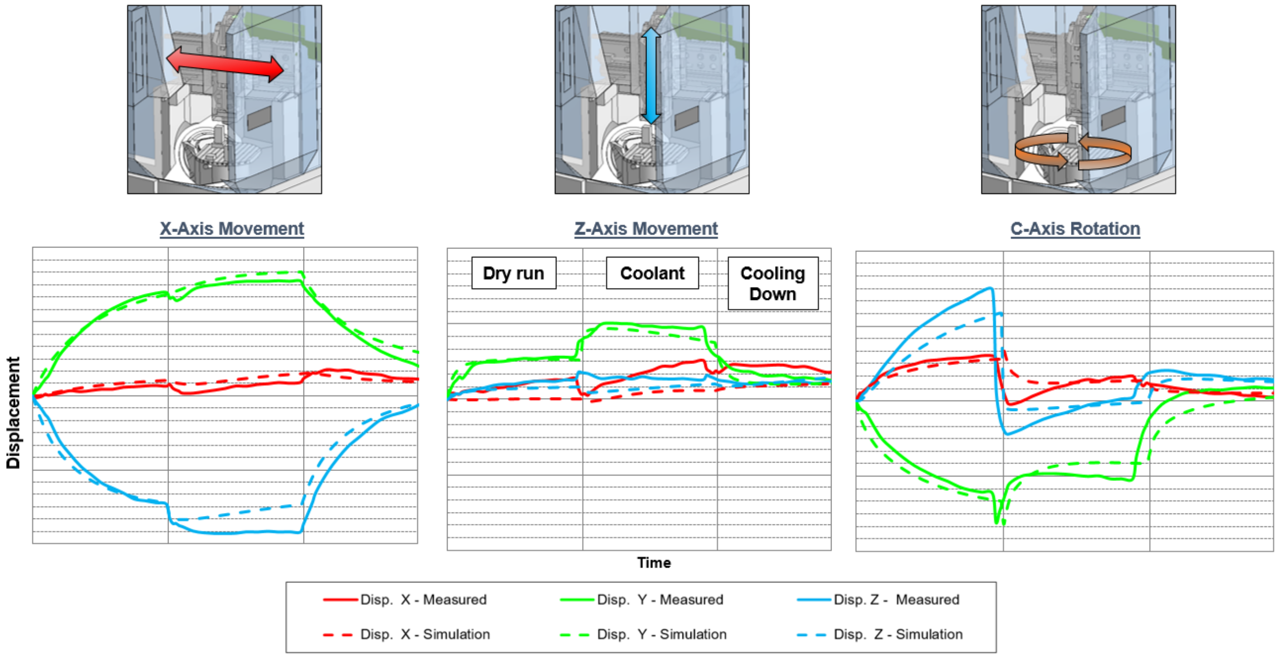

Figure 6. Relative displacement of TCP for single-axis movements at constant ambient temperature, simulation vs. measurement

Figure 9 shows an example of some relative displacement measurements in comparison to the simulated values. Three load cases are shown, where each represents a single axis movement (x, z and c axis) and is further structured into dry air cutting, air cutting with flood cooling and cool-down in stand-by. The figure shows a good agreement between simulation and measurement and also highlights the usefulness of single-axis load cases. While relative error measurements do not allow the differentiation between tool and table error, targeted heat sources can make sure that only one or a few sources are active at one time and thereby make it easier to determine which simulation parameters need to be adjusted to better match the real machine tool thermal behaviour.

4 EXAMPLE FOR AN APPLICATION OF THE METHOD ON THE FIVE-AXIS MACHINE TOOL DMU 80 EVO

The method was tested and successfully verified on a 5-axis milling machine of type DMU 80 evo of the manufacturer DMG Mori in the climate chamber of the Fraunhofer Institute for Machine Tools and Forming Technology IWU in Chemnitz. Beside the thermally asymmetrical design, the machine tool comprises some highly complex components (cooling systems, workspace climatization). It is a very compact machine with high cutting capacity and little space requirement.

The climate chamber has an air temperature control ranging from 10 °C to 40 °C with a tolerance of ±0.1 K and an air humidity control of 10 - 90 % rH. The hourly air exchange in measuring mode is up to 20,000 m³, with an interior size of 10.7 x 7.5 x 5 m. Due to a special design of the air inlets, the air speed is less than 0.2 m/s preventing forced convection despite the high air exchange rates. The foundation is decoupled from the concrete floor and is fully temperature controllable.

Several measurements were performed with moving machine axes at a constant ambient temperature of 21 °C (see Fig. 10). In addition, there were measurements with changing ambient temperatures. In the second measurement category, however, the machine was kept in stand-by in order to decouple the thermal effects from each other. The results of a three-day ambient temperature change are shown in Fig. 10, where the temperatures were simulated based on a possible scenario of summer in a non-air-conditioned factory hall.

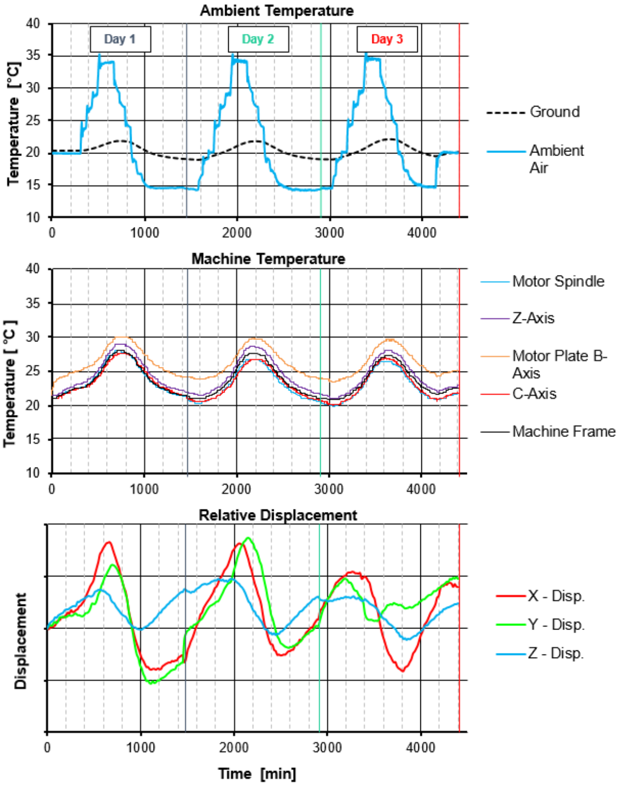

Figure 7. Changing of ambient temperature (3-day-cycle) with machine tool in stand-by

Further measurements were carried out to investigate the warm-up behaviour of the machine to determine the initial value. In practice, this would correspond to a change in the location of the machine or to a start-up after a long break in operation. An equally important measurement was the influence of the ambient temperature on a switched-off machine.

5 SUMMARY AND OUTLOOK

Using an extensive set of measurements performed in a climate chamber, a thermo-elastic FEM model of a five-axis machine tool was successfully validated. The measurement scenarios were selected in such a way, that the relevant thermal effects in the operation of a machine tool could be studied separately. By splitting the investigation into internal heat sources (heat generation during machine operation) and external ambient influences (changing ambient temperature), important insights into the thermal machine behaviour could be gained. A significant improvement of the simulation model was achieved with the help of these investigations.

The simulation model was used to generate training data for a characteristic diagram based compensation model. With the subsequent test of the model, the thermal error was reduced by about 90 % in the training data and 60 % in independent test cases [Naumann 2023].

For future work, further investigations are necessary, especially concerning the use of cooling lubricant in the workspace, since this is where the model is still most prone to errors. This has a negative effect on the effectiveness of the thermal compensation. Another focus is the evaluation and development of new measurement concepts, especially in the field of absolute displacement measurement. Optical and non-contact measuring methods in a thermally stable measuring chain should be used more and more to gain more insights about the thermal machine behaviour.

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