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# DESIGN IMPROVEMENT OF THE CUTTING FLUID SUPPLY OF A LARGE 5-AXIS MACHINE TOOL

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## INTRODUCTION

Thermally induced deviations are the major cause of the lack of repeatability in production and measurement systems (Bryan [1]). Thermal deviations are caused by internal and external influences. Internal influences refer to heat losses in the machine elements, such as drives or bearings. External influences refer to the interaction between the mechanical system and its surroundings. These include effects such as the convective heat exchange with the environment or the process cutting fluid. Schellekens et al. [2] pointed out that the thermal isolation of the machine from external influences is hard to achieve due to the complexity of the heat transfer mechanisms. In order to understand and predict the effect of the internal and external influences thermo-mechanical models can be used. Thermo-mechanical models are based on the finite element (FE) discretization of the physical field equations, i.e. the heat transfer and elasticity equations. Several examples of physical models can be found in the literature. Mian et al. [3] studied the effect of the change of the environmental temperature in a 3-axis machine tool. The authors stated that the initial thermal state of the machine is usually unknown. They defined a settling time as the time required for the machine tool structure to be in equilibrium with the environment. Ess [4] used FE for the simulation of the thermo-mechanical response of machine tool assemblies. The machine elements connecting the different structural parts of the machine tool were represented by macro models accounting for the thermal conductivity, thermal capacity and mechanical stiffness. The effect of the direct measurement system was also included for the calculation of the resulting tool center point (TCP) error.

One application for physical models is the development of a state observer for the online compensation of thermal errors in machine tools. Thiem et al. [5] developed a thermo-mechanical FE model of a parallel kinematic machine. The model aimed at compensating the elongation of the ballscrew of the mechanism in the axial direction. The authors measured the resulting thermal errors by means of laser interferometry. The measured deviations were later used to optimize the most uncertain parameters of the model, enabling the use of the prediction for online thermal error compensation. The authors claimed that the results were comparable to compensation strategies based on empirical models, such as characteristic diagrams.

Another use for thermo-mechanical models takes place during the design phase, contributing to reduce the time required for the development of a new machine tool prototype. Mayr et al. [6] used the Finite Difference Element Method (FDEM) in order to efficiently compute the thermal errors of machine tools. The authors applied this approach to improve the design of a machine tool frame. The proposed design, which was based on a more symmetric construction, was evaluated by computing the position and orientation errors at one point of the working space. Sun et al. [7] used physical models for the improvement of thermal response of a 3-axis ultra-precision grinding machine. The heat losses at the linear motors and the spindle had a major influence on the thermally induced errors. This work redesigned the structural parts close to the heat sources in order to enhance the heat dissipation and reduce the heat transfer from the sources to the guideways. Sun et al. developed a FE model, which they validated exclusively with structural temperatures. The temperature rise for the studied load case was reduced after the design optimization both in the simulation and experimental results. The model showed that the straightness error motions of the Z-axis improved after the structural optimization. These works demonstrate the feasibility to use physical models in the design optimization of the thermal behavior of a machine tool.

## DEVELOPMENT OF THE THERMO-MECHANICAL MODEL

This paper focuses on the development of a thermo-mechanical model of a large 5-axis machine depicted in Figure 1. A rotary table is located in the workpiece side and a rotary head on the tool side. The kinematic chain according to ISO 10791-1:2015 [8] is: H [w B X b Z Y A (C) t]. The thermo-mechanical models describe the thermally induced TCP deviations by means of a FE discretization of the machine tool structure. The focus of model developed in this work is the evaluation of the effect of external heat sources, namely the environment and the cutting fluid. For this study the influence of the internal heat losses (e.g. friction in the bearings) is minimized by moving the axes at sufficiently low feed rates.

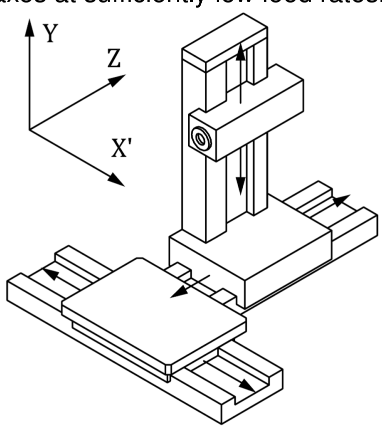


*FIGURE 1. Schematic of linear axes of the machine tool adapted from ISO 10791-1:2015 [8]*

The main goals of the cutting fluid are removing the chips, reducing tool wear and tempering the structure. The introduction of fluid media on the structure modifies the thermal response of the machine tool, changing the position and orientation errors. The machine tool under investigation supplies cutting fluid in three different ways. The bed cutting fluid delivers the fluid through two nozzles located at the back to the Z-axis. The cutting fluid is supplied also on the spindle head and through a shower located on the upper part of the housing of the working space. Previous measurements, presented by Hernández-Becerro et al. [9] and Blaser et al. [10], showed that the effect of the bed cutting fluid have the largest influence on the thermally induced TCP errors in this machine tool, as it affects a larger part of the structure. The supply of fluid media modifies the heat exchange between the structural parts, where the boundary conditions transition from natural convection with the air to forced convection. This leads to a switch in the boundary conditions, which needs to be correctly handled. The values of the heat transfer coefficients (HTC) are estimated from simplified CFD simulations of the fluid channels. Due to the high pressure of the fluid, required to reach the working space and remove the chips, the fluid does not affect homogeneously the bed. This is represented in the model by considering a spatial distribution of the HTC over the cutting fluid channel. The cutting fluid temperature is controlled by an external unit, whose set temperature is a sensor close to the machine tool bed partially capturing environmental influences.

The convective heat transfer between the environment and the structure is caused by natural convection. The values of the HTC can be estimated by means of empirical formulas, computational fluid dynamic (CFD) simulations or meta modeling techniques, as presented by Pavliček et al. [11]. The environmental temperature in a non-acclimatized workshop varies over time and space. The model considers the different layers in order to accurately describe the stratification of the air temperature. A machine housing covers the working space, altering the convective heat exchange. This enclosure is also considered in the description of the boundary conditions, adjusting the values of the HTC.

In order to capture accurately the resulting TCP deviations, the model includes the effect of the measurement system. The direct measurement system consists of glass scales made of steel fixed to the structure in the middle. The relative TCP deviations are then partly corrected by the measurement systems.

The model evaluates the thermal response of the machine over 12 hours. The machine is exposed to an uncontrolled environmental temperature and a continuous supply of cutting fluid from the back of the Z-axis. Before the cutting fluid is introduced, the model is initialized with 14 hours of environmental temperature. This allows the model to transition from a homogeneous initial temperature to a realistic initial temperature distribution. The validation can be then performed by comparing the outputs of the model to measurements of structural temperatures and thermally induced TCP errors. The temperature is measured with direct-to-digital temperature sensors attached to the surface of the structure, with a resolution of 0.1 K and sampling time of 11

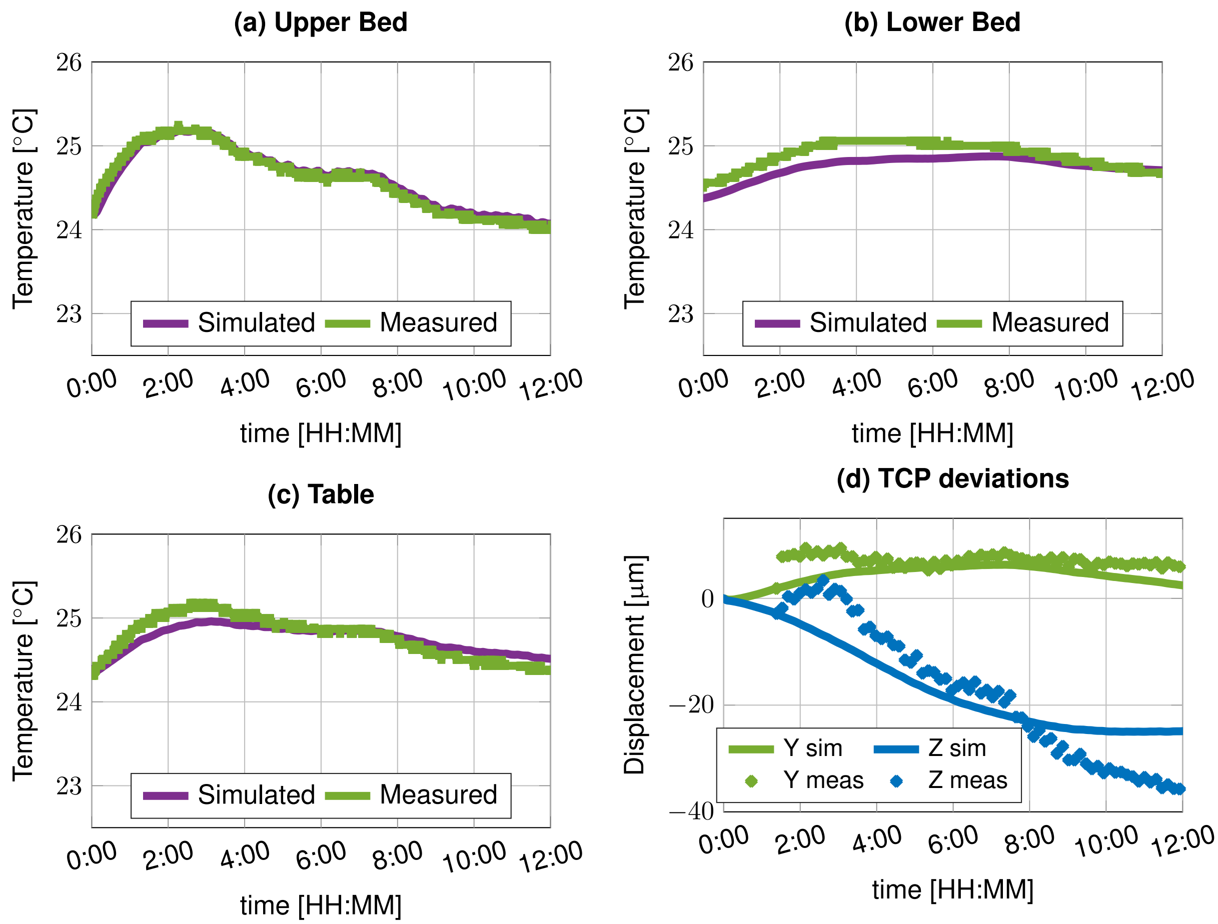


*FIGURE 2. Comparison of the outputs of the model and the measurements. (a) Temperature on the upper part of the machine tool bed (b) Temperature on the lower part of the machine tool bed (c) Temperature on the table (d) Thermal errors of the TCP relative to the workpiece*

s. Figure 2 compares the model results with the measurements on the machine tool. The model captures accurately the temperature distribution of surfaces closer to the cutting fluid, such as Figure 2(a) and 2(c). For surfaces further away from the influences of the cutting fluid, i.e. where the natural convection plays a major role, the accuracy of the temperature prediction is reduced, as displayed in 2(b).

The model is further validated with measurements of the deviations at the TCP relative to the table. The measurement procedure is based on the R-Test [12]. A precision sphere is placed on the table and a sensor nest mounted on an invar holder is located on the spindle side. The oil resistant LVDT sensors have a resolution of 0.06 µm and a repeatability of 0.01 µm. The TCP deviations are measured every 9 min and are compared to the output of the simulation. Figure 2(d) compares measured TCP displacements relative to the precision sphere with the model output. The first hours of the measurement are missing due to a problem with the data acquisition. The model can represent the trends of the thermal errors at this point of the working space in Y- and Z-direction. The maximum discrepancies between model and simulation are bellow 10 µm. The differences are caused by the uncertain boundary conditions describing the heat exchange with the environment as well as uncertainties in the expansion coefficients coupling the thermal and mechanical model. Due to the symmetry of the machine tool design the thermal errors measured in X-direction are small. The uncertainty of the measurement setup is not sufficiently small to capture the thermal errors in X-direction. Thus the thermal errors in X-direction are excluded from the model validation.

The validated physical model represents the behavior of the system under investigation and allows the evaluation of the underlying phenomena leading to the TCP deviations. The transient response of the bed after the introduction of the cutting fluid results in a deformation of the tool-sided axes of the machine tool. The machine bed requires a long time for the homogenization of the temperature field. This creates a transient deformation of the positioning error of the Z axis. The column moving along the Z-axis is greatly affected by the environmental temperature fluctuations. When the room temperature increases, the tool-sided axes expand in the negative Z-direction resulting in TCP errors illustrated in Figure 2.

At the position of the axes where the model is evaluated, the thermal growth of the tool-sided axes is comparable to the growth of the workpiece-sided axes. This results in thermal errors below 10 $\mu$m in Y-direction. However, evaluating the deformation at other positions of the Y axis, larger thermal errors occur at the TCP. These effects are dominated by the high sensitivity of the machine tool column to the environment.

## PROPOSED DESIGN MODIFICATIONS

The introduction of the cutting fluid into the structure of the machine creates a transient thermal response. This transient phase has a negative repercussion on the machine tool repeatability. The cutting fluid contributes in removing the chips from the guideways of the Z-axis. Therefore, supplying the cutting fluid directly to the working space without affecting the structure of the bed is not an option for the machine tool manufacturer. The new design of the cutting fluid supply needs to reduce the transient phase in order to ensure the repeatability of the machine tool. An homogenization of the supply of the cutting fluid with several inlets for the fluid along the guideways of the Z-axis is proposed. The redesigned supply can be included in the model by introducing homogeneous boundary conditions along the channels of the Z-axis, representing the forced convection of the fluid media. Figure 3 depicts the deviations of the guideways of the Z-axis in Y-direction 2 hours 30 min and 6 hours after turning on the cutting fluid. The modified supply ensures a that the thermal deviations in Y-direction are constant along the whole stroke of the Z-axis. This reduces the angular errors, which are more challenging to account for in online compensation strategies.

The cutting fluid temperature is regulated by an external unit. By setting the environmental temperature as reference, it is ensured that the whole machine tool is exposed to the same temperature minimizing internal gradients. In the current machine tool design, the reference temperature for the cutting fluid control is a signal measured on the machine tool. This signal is influenced not only by the workshop environment but also by the structural temperature of the machine tool bed, which results in a negative effect. If the machine tool bed is warming up, the cutting fluid warms up following the set temperature. A new reference sensor for the fluid temperature control is proposed, measuring the unaffected workshop temperature oscillations. This is introduced in the simulation by modifying the cutting fluid temperature for the corresponding boundary conditions. The proposed set temperature leads to a reduction of the resulting TCP errors.

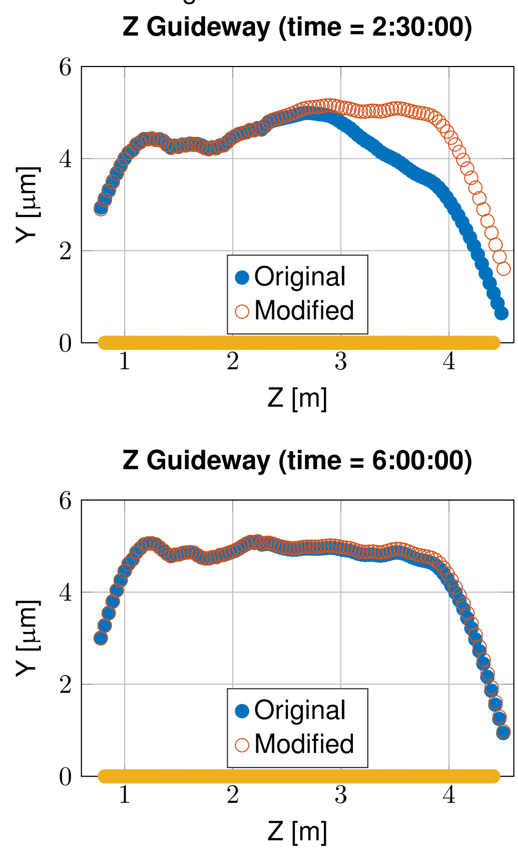


*FIGURE 3. Deformation of the Z-guideway in Y-direction of the original design and the modified cutting fluid supply*

After modifying the supply of the cutting fluid, the focus is reducing the sensitivity of the column of the Z-axis to the environment. One design alternative is to introduce cooling fluid along the structural parts exposed to environmental changes. In order to avoid the introduction of a separate external unit, the cooling fluid needs be delivered by the same cooler unit used for the cutting fluid. This structural cooling is introduced in the model by modifying the boundary conditions of the structural parts in contact with the fluid. The simulation shows that tempering the column of the machine tool only enlarges the sensitivity of the structure to the environment, increasing the TCP errors. The option to include coolant into the columns is further investigated when the reference temperature is kept constant. A constant temperature succeeds in damping the oscillation of the thermal errors due to the changes in the room temperature. However, increasing the amount of fluid media implies a higher energetic demand, which is not an optimal solution.

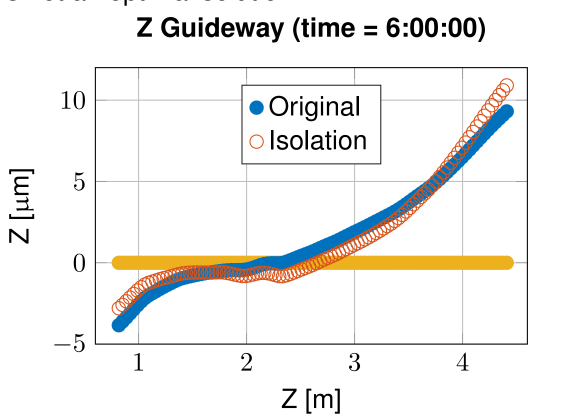


*FIGURE 4. Deformation of the Z-guideway in Z-direction of the original design and with the isolation in the Z-axis column*

Another alternative for decoupling the column from the environment is the introduction an a thermally isolating material on the surface of the structure. The Z-axis is a large column providing the required stiffness to the structure. Most of the heat sources are located far from this part and heat losses are effectively dissipated by the cooling system. Therefore adding a thermally isolating material only contributes to the decoupling of the structure from the environment without hindering the heat dissipation of the heat sources. This design modification is introduced in the model by reducing the HTC of the affected boundary conditions. The introduction of the cutting fluid and the increasing environmental temperature lead to a thermal expansion of the machine tool bed. This is illustrated in Figure 4, depicting the thermal deformation of the Z guideways 6 hours after the cutting fluid is connected. Figure 4 shows that the back of the Z-axis deforms in positive Z-direction and the front in negative direction, indicating a thermal growth of the bed. In Figure 5 the thermal deformation of the Y-guideways is shown after 6 hours with cutting fluid. In the original design the column expands and tilts leading to a deformation in the negative Z-direction. This deformation is further enhanced by the expansion of the remaining tool-sided axes, leading to a resulting error at the TCP relative to the workpiece depicted in Figure 6. By reducing the convective heat exchange between the Z-axis and the environment, the Z-axis deforms into the positive Z-direction. This displacement is mainly influenced by the expansion and tilting of the machine tool bed. The deformation into the positive direction of the Z-axis has positive effect, counteracting the expansion of the Y-, A- and (C)-axis.

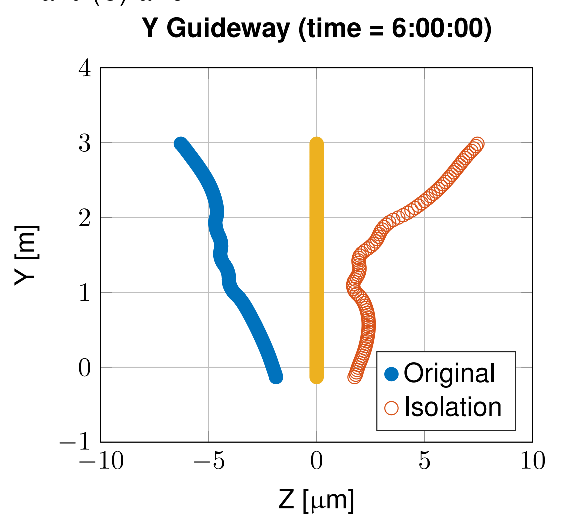


*FIGURE 5. Deformation of the Z-guideway in Z-direction of the original design and with the isolation in the Y-axis column*

The thermo-mechanical model shows that combination of the modification of the cutting fluid supply, the cutting fluid reference temperature and the isolation of the Z-axis from the environment results in a reduction of the TCP errors, as illustrated in Figure 6.

## CONCLUSIONS AND OUTLOOK

This work investigates the external effects influencing the thermal behavior of a large 5-axis-axis machine tool. A thermo-mechanical model of a whole machine tool structure is developed and

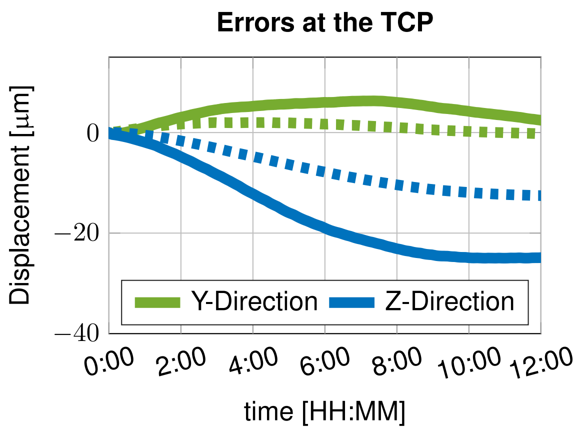


*FIGURE 6. Simulated TCP errors relative to the workpiece. Comparison between the original design (solid lines) and the proposed design modification (dashed lines)*

validated with experiments. Several design measures for the optimization of the cutting fluid supply and the response of the machine to the environment are proposed and verified by simulation. The thermally induced TCP errors are reduced over 50% in the working space by design modifications.

Future work concentrates on the implementation of the proposed design modifications in the next machine tool prototype. The remaining thermal errors, which are not possible to eliminate by design, will be compensated with models based on online measurements of the TCP deviations.


## ACKNOWLEDGMENTS
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