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Simulation-based approach for optimized tempering of concrete machine frames by thermo-elastic FEM and model coupling

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Abstract
The thermal stabilization of machine components by demand-actuated temperature control opens up far-reaching potential for minimizing thermo-elastic deformations of machine tools while reducing energy requirements. High-performance concrete materials offer opportunities for the integration of cooling circuits, which must be operated with adapted control strategies. For example, demand oriented cooling in the vicinity of existing heat sources can be realized. The main aspect of the research project deals with issues concerning the best possible positioning and design of the cooling circuits. For this purpose, CFD and FEM simulations are created, integrated into key parameters and optimized and converted by methods of model order reduction to a fast computable digital model of the component (in this case a machine frame).

cooling system, Finite Element Method, machine tools, machine frame, heat transfer coefficient

1. Introduction

Thermal measurements on machine tools show repeatedly that despite the thermo-symmetrical design it is not possible to achieve a uniform temperature distribution. Feasible causes are asymmetric drive arrangements even on symmetrical structures, one sided external heat sources such as solar radiation or thermal losses from the machine and/or the process in the working space [1, 2]. These local or area wide heat inputs can have a significant influence on the resulting deformation behavior of the machine tool structure, e. g. the machine frame [3, 4]. In order to compensate for this effect and the resulting TCP error, the heat must be dissipated as efficiently as possible.

In order to reduce thermally induced displacements, EPUCRET has carried out an appropriate temperature control of concrete frame structures. Initially, simple prismatic bodies were measured under defined thermal stress series in order to be able to independently adjust the cooling system from the central control unit. For example, the error in straightness of guide rails has been reduced from ±35 µm to ±2 µm. In subsequent tests, this approach was applied to complete machine tools, where several individual circuits are coupled or work separately. The most important TCP shifts were measured and reduced by at least 50 %. In this context, energy aspects have not been taken into account [7] and transferability to other systems is not known.

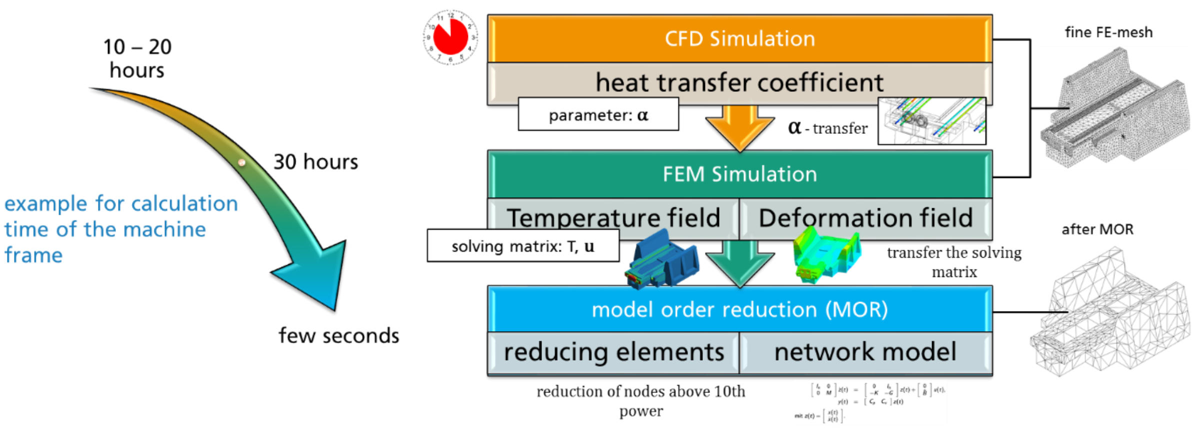

Figure 1. Decoupling approach

For this purpose, cooling circuits are usually integrated into active components and passive structures, which are subsequently adapted to the temperature of the structure [5]. The use of high performance concrete (HPC) in casting opens up completely new possibilities for the integration of cooling liquid circuit structures for an active temperature control [6].

As the example DMG MORI [8] shows, structurally integrated cooling circuits are already established. These stabilize precision-relevant components, such as the machine frame or the gantry, but also linear guides and drives. In this way, the heat

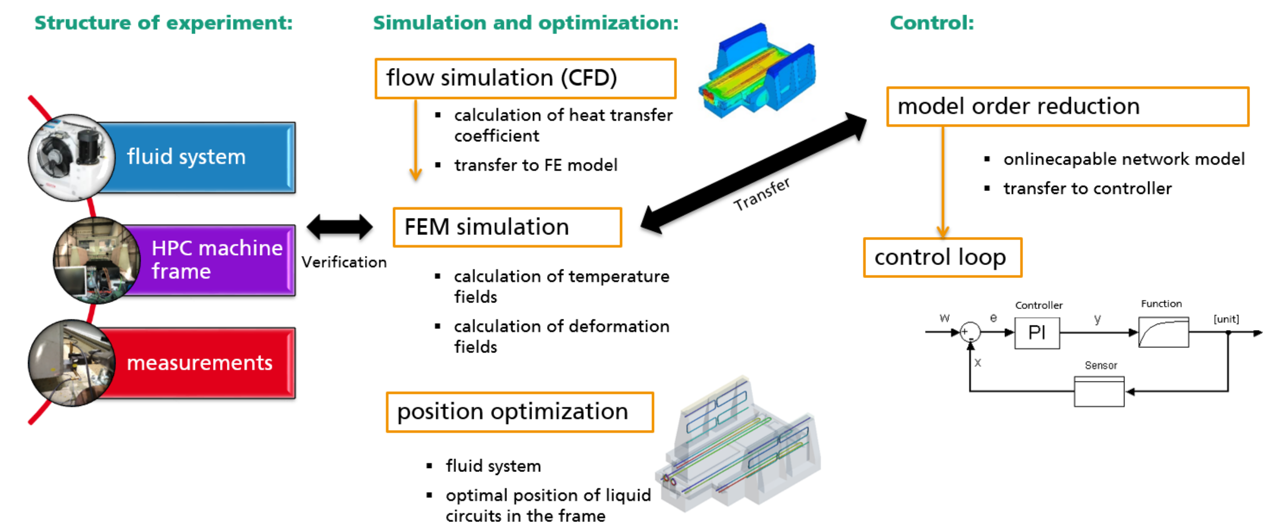

Figure 2. Methodology for calculation the optimal liquid circuit

input from internal heat sources can be dissipated, which leads to an improvement of the thermal behavior.

The aim is to present the methodological approach for the simulation-based analysis and optimization of cooling systems in machine frames made of HPC.

Figure 1 shows the decoupling approach for a faster calculation time without reducing of the model accuracy.

2. Methodology to use heat transfer coefficient in FE-models

Thermal stabilization of machine and machine components through adapted and demand-oriented temperature control opens up far-reaching potential for minimizing unwanted thermo-elastic displacements at the tool center point (TCP) while reducing energy consumption. High-performance concrete materials offer in this context a large variety of possibilities for the integration of adapted temperature control circuits in various forms, e.g. meander, spiral structures etc., which can be operated with adjusted control strategies as needed and thus energy-efficient. For example, an active temperature in the vicinity of existing heat sources can be realized, whereby the effect of unwanted heat sources can be minimized and used for more homogeneous temperature distribution of the machine frame.

As part of a transfer project in the Collaborative Research Center [9] research project, the goal is to consider the best possible positioning and design of the cooling circuits in the geometry of the machine frame as well as heat sources arising in the production process already in the development phase. For this purpose and as a basis for a demand oriented temperature control system, a suitable model is required. Therefore, the CFD and FEM simulation tools are used in a first step (fig. 2), whereby the tempering system is created taking into account all boundary conditions. These are for example environmental influences, flow velocity of the fluid in the tempering circuits or geometrical influences like circuit length and diameter. The heat transfer coefficients on the inner surface of the tempering system can be calculated in time-consuming calculations by using CFD simulation. In order to reduce the simulation effort, a procedure was developed, which transfers the significant heat transfer coefficients from the CFD simulation as input data to the FEM simulation. Moreover, it was calculated the resulting temperature fields and deformation fields. For the mapping of the heat transfer coefficients, the cooling circuits of the fluid

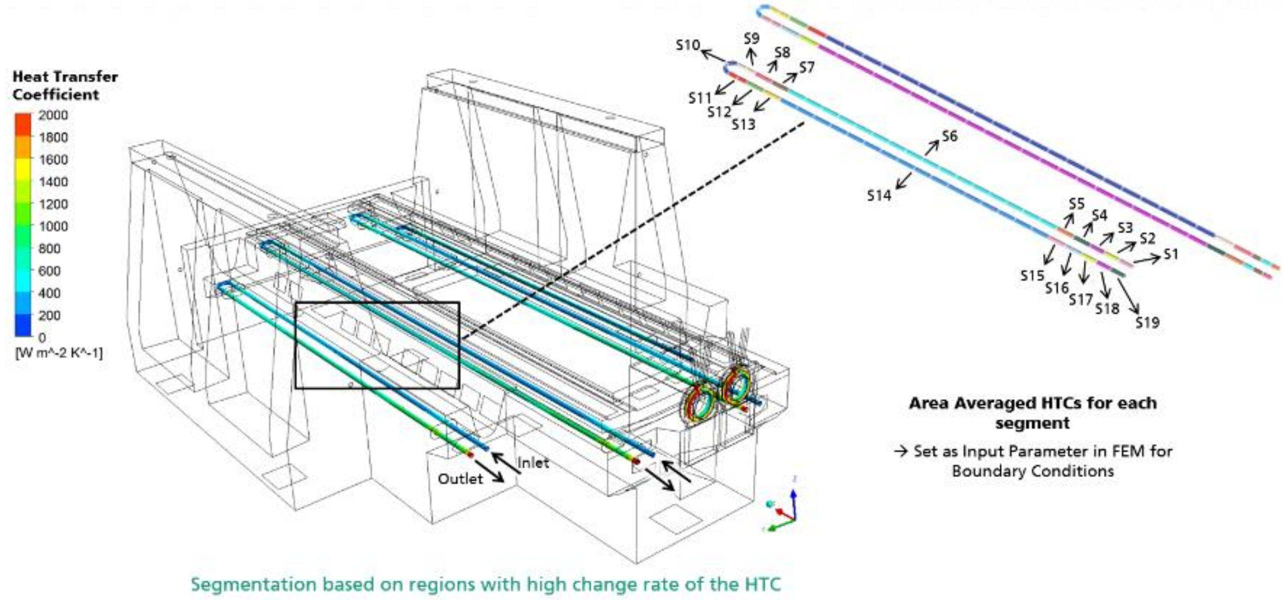

Figure 3. Segmentation of the circuits

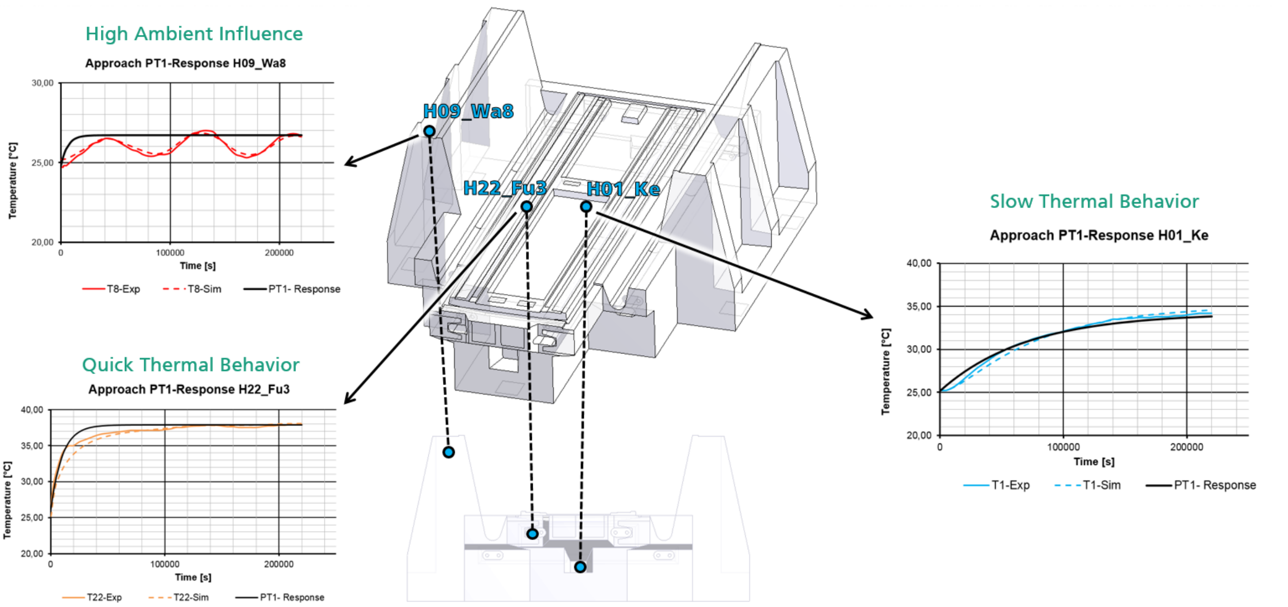

Figure 4. Transient thermal behaviour of the machine frame

system are subdivided into adaptive segments. Heat transfer coefficients are assigned to each segment as a boundary condition (convection). The level of detail of the segmentation depends on the rate of change of the HTC values. Areas of high rates of change such as inlet and outlet areas, deflections are segmented in detail whereas is roughly segmented. Further information to the procedure for segmentation is given in[5]. In the present example, the fluid circuits are divided into 19 segments. For each segment, the area-averaged HTC is calculated and then assigned as an input parameter to the FEM boundary conditions (see Fig. 3). For automatic FEM simulations, a parameterized model to calculate different thermal load cases and the resulting thermal effects of the machine frame are used. For further optimization of the calculation effort of the FEM simulation methods for model order reduction [10] are applied. The modification leads to a model with low calculation time, which provides the parameters for a decentralized controllable pump system. Therefore, the nonlinear and multi-input-multi-output temperature control system of a machine frame can be investigated and commissioned. The main goal of this new approach is to create a homogenized temperature field of machine frames.

3. Sample Application for a cooling system in an machine frame

The transfer of the developed method for the position optimization of the cooling circuits is carried out on a real machine frame, which consists of high performance concrete, steel reinforcement and a cooling system.

Figures 3 and 5 show the CAD-model of the machine frame together with an autarkic and mobile 5-spindle parallel processing unit. Inside the machine frame, six independent cooling circuits and 23 temperature sensors for a thermo-stabile structure behaviour is integrated. The research goal is to develop a decentralized controlled tempering concept for thermo-stabile machine frames and structures. The measurement of the machine frame amounts circa 5 x 3 m and has a weight of 18 t. Depending on the position (see Fig. 4), the machine frame shows a different time behavior. While areas around the vertical wall structures are almost exclusively affected by the environment (radiation), areas in the inner structure are thermally sluggish. Time constants from 20h to 29h were identified. Other areas closer to components or cooling circuits react faster, with time constants of 5000 s to 10000 s. The machine frame can be separated in three areas referenced to the surface: area for the guide rails, area for the chip transport and an area of the stringboard with the inclusion of the processing unit.

The machine table is positioned on the guide rails and can be driven in a linear direction. A chip conveyor is between the guide rails and the stringboard. The two main drives for the machine table are placed frontal on a water-cooled flange. The other four cooling circuits are placed nearly the chip canal and the guiding rails to lead heat fluxes away quickly. For the experiments and verifying of the FE-simulation of the machine frame the cooling circuits have a warming function, because the influence of the heat conduction effects could be better displayed.

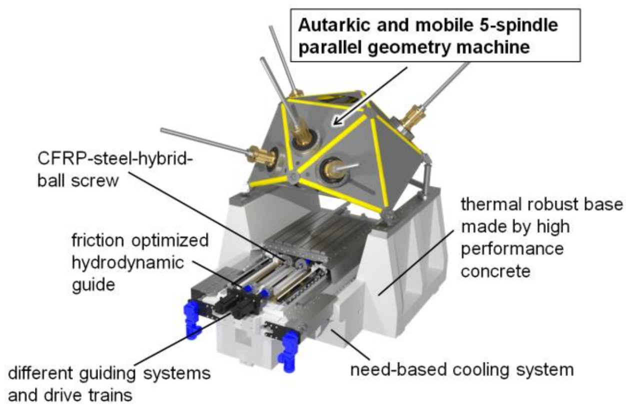

Figure 5. Machine frame with processing unit

The modelling work is concentrated only on the machine frame with the integrated cooling system since the machining unit is equipped with a separate tempering system. Based on the CAD-data a computation-intensive CFD-model in CADFEM Ansys CFX was created for calculating the heat transfer coefficient along the six cooling liquid circuits. The calculation time needs more than 20 hours per load case. Subsequently, the results of the flow field inside the liquid circuits are used for computing the heat transfer coefficients and transfer on the segmented circuits in the FE-mesh for the thermal-mechanical simulation. According to that, the computing time for transient temperature

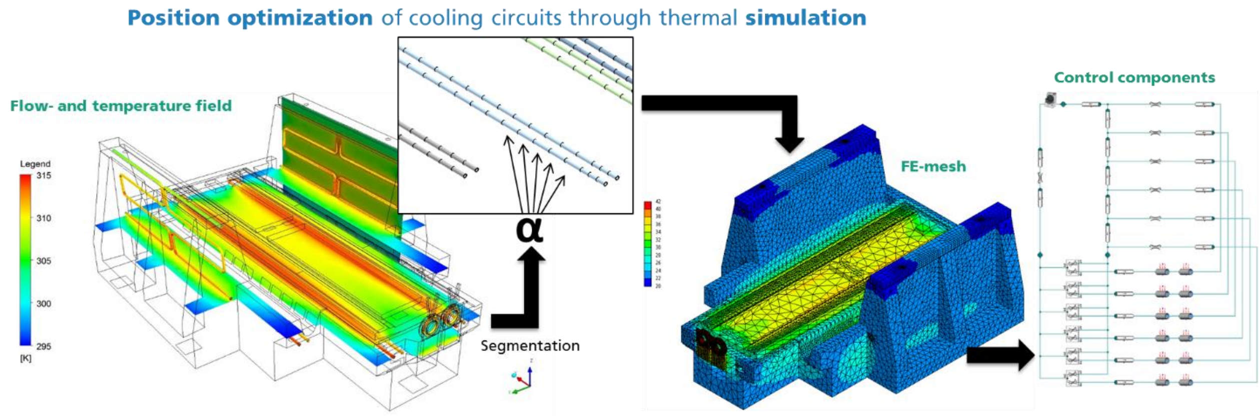

Figure 6. Computing example of cooling system in a machine frame of High performance concrete

field and resulting deformation field of the machine frame geometry could be reduced to 30 min.

Figure 6 presents one exemplary load case for ten liquid circuits inside the machine frame. The four additional cooling circuits have been added as part of a position optimization to create additional spheres of freedom for the control of the temperature fields. Because vertical wall structures with a large hight to thickness- ratio react directly to environmental influences such as changes in ambient temperature or solar radiation, additional cooling circuits are available. The subdivision into four independent cooling circuits can also compensate for asymmetrical heat radiation. The results shows the flow simulation on the left side of figure 6 and on the right side the computed temperature field of the thermo-mechanical simulation. The next steps are to use the MOR method for further time reducing and link the resulting temperature fields to the controlling system for the volumetric flow rate in cooling system.

4. Conclusion and Outlook

This paper presents a new methodology for optimization the inner tempering system of machine tool frames. Therefore, an approach to transfer the significant heat transfer coefficient from of the CFD simulation to the thermo-mechanical simulation for calculation the resulting temperature and deformation fields was developed. This FE-model is the basic for a network model, which, based on the MOR method and will be used for optimization calculations in the future. Also the position of the tempering liquid circuits can be optimized based on the model. The next steps are that the new methodology will be validated a real demonstrator machine frame with eight included cooling circuits which will be controlled through decentral controlling system.

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