

Chapter 10

Modelling of Thermal Interactions Between Environment and Machine Tool

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Abstract Thermal boundary conditions, such as heat flux, play an important role in the overall context of representing machine tools' thermal behaviour and their interactions with the environment in a way that is close to reality. In this contribution, the machine tool–environment interface is represented based on the finite-element method and the required parameters are assigned. The term “environment” refers in this paper to the surrounding atmosphere and sometimes the foundation. The approach includes the determination of the relevant environmental boundary conditions, such as convection and heat radiation, and the description of how to integrate them systematically into the finite-element model.

10.1 Introduction

Comparing measurements and simulations, it can be seen that the computational analysis of the machine tools' thermal behaviour and performance evinces an obvious potential for improvement potential concerning their reliability in terms of quality and quantity (Neugebauer et al. 2009; Großmann et al. 2013). Particularly in the field of the coupled analysis of thermal properties and properties from structural mechanics, there is a lack of sufficiently exact knowledge of the description of interactions between the environment and the machine tool. As a rule, this limitation arises from difficulty in describing the environmental conditions as precisely

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as necessary. The values found in simulation—for heat flux density, heat transfer coefficients and heat emission parameters—frequently differ by more than 50 % from those measured. This phenomenon is, for instance, based on the fact that in transient thermo-elastic simulations, the use of homogeneous environmental temperatures results in convection and radiation conditions that are insufficiently exact. Finally, the complex feedback between the thermal effects of conduction, convection, and heat radiation, as well as their non-linear characteristics, complicates a reliable mapping of the different influencing factors. However, the most exact possible prediction of the machine properties directly depends on the quality of the input data that provide the boundary conditions for the simulation models.

Concerning the representation of interaction between structure and environment due to convection, empirical calculation guidelines exist for simple geometric bodies given defined assumptions (VDI 2006), which have to be chosen for each real case of application on a machine tool. However, this analytical strategy of determination of heat fluxes does not provide a sufficiently exact prediction of complex thermal machine tool properties. Consequently, in this subproject, boundary conditions found by calculations are also used. In addition to the analytical calculation, fluid simulation is employed as a new approach to determine the thermally relevant parameters for convection, heat transfer and heat radiation.

10.2 Approach

In an innovative strategy, minimal models are generated for the modelling of boundary conditions, which become a part of the structural mechanical finite element (FE) simulation to calculate the thermo-elastic displacements of an assembly. To determine the relevant boundary conditions for convection, not only analytical computations are carried out, but also CFD simulations by means of ANSYS-CFX. For this purpose, it is necessary to model the corresponding FE meshes to map the flow conditions around the assembly. The flow model applied first considers a laminar flow for immobile assemblies, such as the machine column in standstill position. Based on this, the moving assemblies (such as the moving machine column) are investigated, and this makes it necessary to represent forced flows.

A FE model needed to verify the machine tool to be explored has to be generated at the beginning. The minimal models of complex assemblies, such as mounting systems and ball screws, as they are described here and to be developed in the other subprojects, will be integrated into this model later on. The parameters for the minimal models are identified to represent the heat transfer behaviour. The parameters found are introduced afterwards in the mechanical FE model for the thermo-elastic displacements' calculation. This methodology is verified by means of examples from industrial practice. The options for an automated definition of the thermal environmental boundary conditions in the application of the FE method, which provides a uniform calculation algorithm and the integration of the known empiric calculation equations in order to express the interaction between the

machine tool structure and its environment, are enhanced. The procedures describing the transfer of heat are mapped by the three transfer mechanisms of thermal conduction, convection, and radiation (Baehr and Stephan 2004). The temperature field thereby derived shapes the basis for the calculation of the thermally induced displacements. The consequences of the resulting displacements of the tool centre point (TCP) directly affect the machine tool's machining accuracy and are thus significant when deducing and evaluating design measures or correction methods.

10.3 Results

10.3.1 Modelling of Thermal Influences and Interactions

The thermal convection and radiation transfer mechanisms mostly occur in parallel; however, they are sometimes linked to different conditions. The amount of the transferred heat flux due to radiation strongly depends on the temperature level. This is caused by the fact that when calculating the heat fluxes due to thermal radiation, absolute temperature enters in the fourth power, whereas we have a linear relationship in convection. Because the surfaces that are involved in the transfer by radiation are sometimes very large, in every case it must be determined whether thermal radiation should also be taken into account in the representation of the boundary conditions even at room temperature.

Heat transfer procedures between the structure and the environment were evaluated in terms of their relevance based on fundamental investigations and comparisons of thermal radiation and convection, which are, in turn, based on analytical calculation methods and the use of numerical approaches, as well as sensitivity analysis executed for an assembly chosen as an example.

10.3.1.1 Representation of the Boundary Conditions for Convection

In addition to analytical calculation methods, various numerical methods are available to calculate the energy transfer by thermal convection.

Numerical Versus Analytical Calculation

Analytical method For solids with simple geometries, it is possible to analytically calculate the heat fluxes transferred to the environment by means of convection. Here, particularly in the case of free convection, simplifying assumptions have to be employed to make the known empirical computation equations usable. Thus, for

instance, a plane plate A_1 of 1 m^2 surface is chosen. To calculate the heat transfer coefficients with free convection, empirical equations from (VDI 2006).

$$Q_{\text{Konv}} = h \cdot A_1 \cdot (T_1 - T_2) \quad (10.1)$$

The heat flux transferred between the machine tool structure and environment is, according to Eq. (10.1), linearly dependent on the temperature difference $\Delta T = T_1 - T_2$ and the heat transfer coefficient h to be defined following Groth and Müller (2001).

Numerical method Temperature fields inside a structure can not only be calculated based on structural mechanical (mechanics) FE models, but also by means of Computational Fluid Dynamics (CFD). This does not only provide the option to analyse the temperature field inside the structure and the fluid, which is also involved in the model; the heat flowing on the boundary between the structure and fluid also permits an evaluation of the heat transfer coefficient. This qualifies this kind of numerical analysis to be applied to commensurable considerations of the boundary conditions found empirically and thus to detect existing deficits in the description of convection.

When comparing the two calculation approaches by tendency, it was possible to ascertain that the analytical determination of the heat flux between the surfaces and the environment predicts a more intensive heat transfer than forecasted by CFD simulation. Despite the relatively simple geometries analysed, the two procedures differ by maximally 35 % and thus indicate a clear need for action. It can be assumed that the “high-order” CFD simulation model provides more accurate results than the analytical procedure based on empirical equations. However, the considerations introduced do not permit us to conclude beyond doubt whether the trend towards the prediction of a higher heat transfer in the case of analytical calculation is also true for real component geometries. Figure 10.1 illustrates the higher growth of the heat fluxes in the direct comparison of the analytically and numerically computed heat fluxes, shown for a horizontal plate.

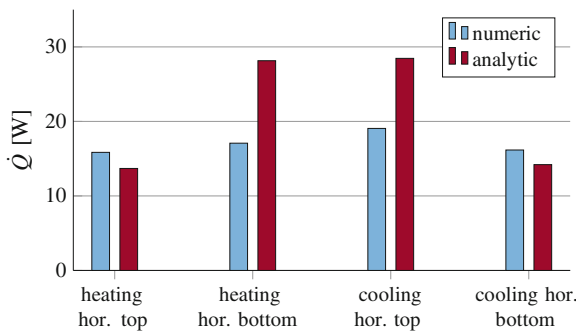


Fig. 10.1 Heat fluxes due to convection on a horizontal plate obtained from numerical and analytical calculations (high mesh density in the boundary layer)

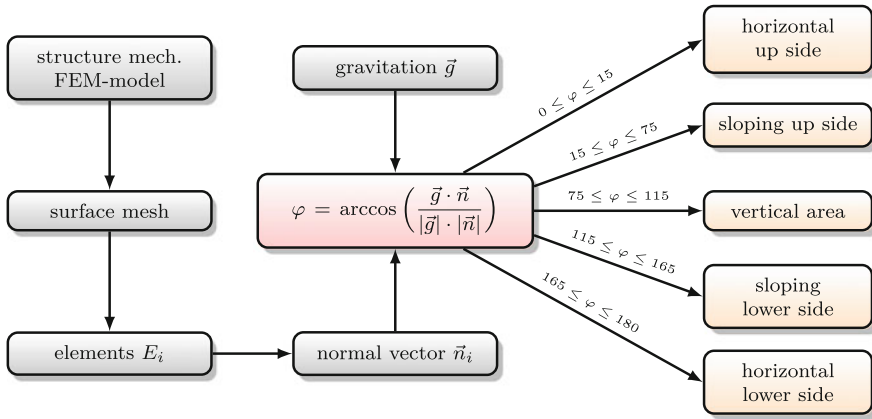


Fig. 10.2 Classification of the structural surface—algorithm

Systemised definition of heat transfer coefficients The heat flux transferred into the environment depends on two influencing variables—the difference in temperature between the structure and the ambient air—and the heat transfer coefficient, which, in turn, depends on several factors. One of them is also the difference in temperature so that the temperature field, which also changes, results in heat transfer coefficients of the problem that change as a function of time. Starting from the structural mechanical simulation model, the surface elements of the structure are identified according to their geometric properties (such as horizontal surface 0–15°, vertical surface of 75–105°, ...), which permits a classification into five different regions. In order to make this approach viable for real component geometries, it is necessary to define limits for the angle of inclination for the five areas mentioned above. As a rule, a value of ±15° is introduced for the deviation from horizontal and vertical alignment to distinguish the individual surface orientations. This classification is also used here as a distinctive criterion to express the position to the gravitation vector. The algorithm to classify the surface elements of the structure investigated is elucidated in Fig. 10.2 in a schematic diagram.

The result of this classification obtained for the machine column is shown in Fig. 10.3. The orientation of the elements against gravitation has to be defined, and the elements have to be grouped according to their distance from the foundation. Comprehensive measurements showed a clear influence of the foundation temperature on the air temperatures, particularly on the machine tool mounting, which, in turn, results in air layers of different temperatures.

To determine the individual heat transfer coefficients, analytical calculation rules are applied to the indicated areas, which take into account the geometric prerequisites in terms of free convection, see also (Neugebauer et al. 2010). The temperature stratifications and differences between the structure and the environment are taken into account. Thus, it is possible to determine the heat transfer coefficient in a systemised manner and to transfer (port) the results to the corresponding surface elements.

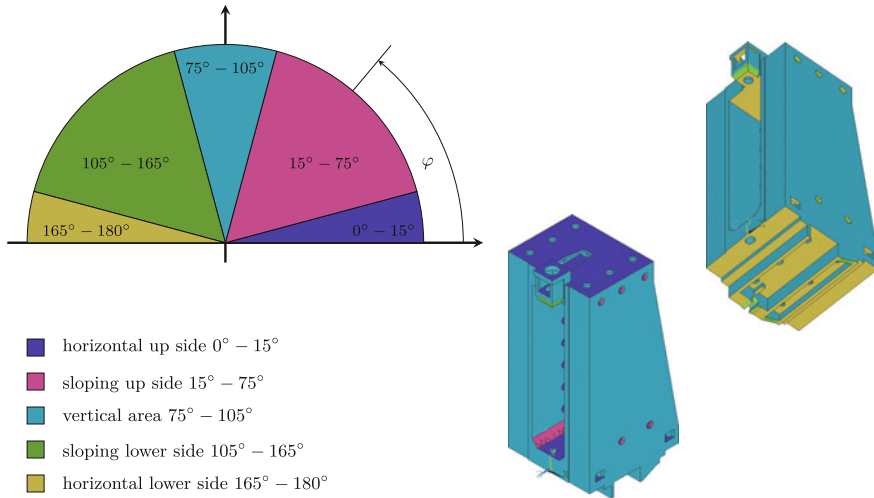


Fig. 10.3 Classification of the structural surface, shown for the machine tool column

As can be seen from the flow simulations for the load case of a machine column heated by an external heat source, different flow velocities are established in the surrounding air. This phenomenon mainly results from the structural formation of the geometry. Figure 10.4 clarifies the so-called “chimney effect” inside the machine tool structure. The sectional view through the surrounding air makes it possible, among other things, to analyse the flow velocities. Factors like these that influence the heat transfer between structure and environment either cannot or can only be incompletely captured by means of empirical computation equations. Flow simulation can provide essential results here, which could otherwise only be identified by experiments with great effort. The transferred heat fluxes are not only affected by the flow velocities mentioned above, but also by the differences in the structural and environmental temperatures, and, consequently, have to be considered. CFD simulations can guarantee that the structural areas affected thereby are correctly identified.

10.3.1.2 Representation of the Radiation Boundary Conditions

Analytical approach The analytical computation of the heat flux from a plane plate to the surrounding air due to radiation functions without the determination of the radiation coefficient. This coefficient is 1.0, if radiation is transferred between the surface and the overall hemi-cube. Thus, another factor is that only the emissivity is entered into the calculation. The transferred heat flux is only influenced by the difference in temperature, the emissivity and the area of the surface. Heat flux is calculated by means of the equations below (VDI 2006), capt. 5, Formula (10.5)

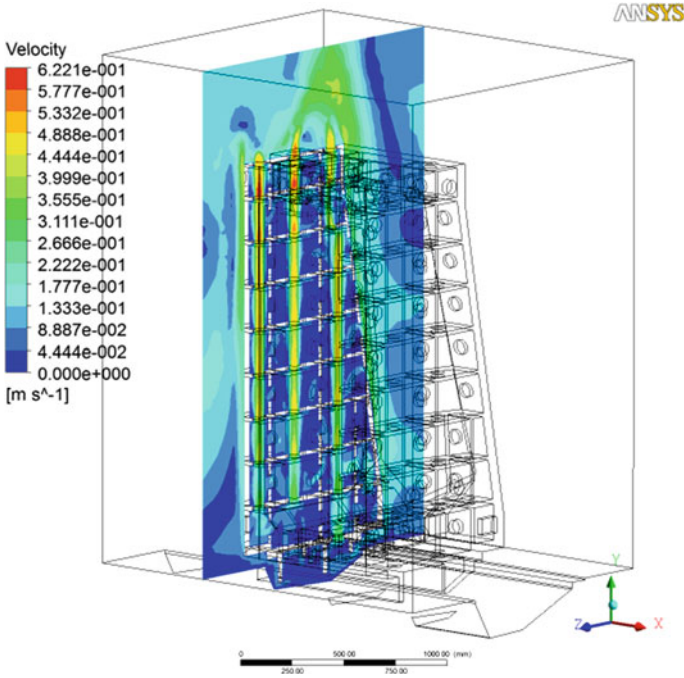


Fig. 10.4 Flow velocity of air around the machine tool atmosphere (free convection)

$$Q_{str} = \sigma_{12} \cdot A_1 \cdot \left((T_1)^4 - (T_2)^4 \right) \tag{10.2}$$

$$\sigma_{12} = \sigma_{se_1 e_2} \frac{v_{12}}{1 - \frac{(1-\epsilon_1)(1-\epsilon_2)A_1}{A_2} (v_{12})^2}$$

Since the heat flux transferred due to thermal radiation into the environment is mostly directed in parallel to the heat flux by convection, it is possible to formulate a heat transfer coefficient h_{str} valid for thermal radiation by means of linearisation of the temperature difference $T_1^4 - T_2^4$ between the wall temperature T_1 and the fluid temperature T_2 . Heat flux according to radiation according to Eq. (10.2)

$$\begin{aligned} Q_{str} &= \sigma_{12} \cdot A_1 \cdot \left((T_1)^4 - (T_2)^4 \right) \\ &= h_{str} \cdot A_1 \cdot (T_1 - T_2) \end{aligned} \tag{10.3}$$

can be calculated by using the binomial formula

$$(T_1)^4 - (T_2)^4 = (T_1 - T_2) \cdot (T_1 + T_2) \cdot \left((T_1)^2 - (T_2)^2 \right) \quad (10.4)$$

in a linearised manner.

$$h_{\text{str}} = \sigma_{12} \cdot (T_1 + T_2) \cdot \left((T_1)^2 - (T_2)^2 \right) \quad (10.5)$$

Numerical approach The FEM software ANSYS applied involves three distinct strategies to calculate radiation effects on three-dimensional models for a numerical analysis based on structural mechanical models:

- Application of surface effect elements to model surface effects
- Use of a radiation matrix in the form of a superelement in a thermal analysis
- Use of a radiosity solver

The method mentioned first, based on surface effect elements, is suitable to model radiation effects between a surface and a point, and was employed for numerical implementation. The methods mentioned second and third, using the radiation matrix and the radiosity solver, can be used in a more general sense and also makes it possible to model the interaction between several surfaces and the environment. It takes more calculation time to create the radiation matrix by means of the radiosity method for large models. A limitation when using the radiation matrix arises from the option of defining temperature-dependent emissivities dropped here; this, however, is not relevant for an application to a machine tool structure.

Numerical versus analytical computation The numerical solution quantifying the radiation to the environment does not appreciably differ from the analytical one. This is made clear by the difference of approx. 16 % obtained for two surfaces that are in a position vertical to one another. Figure 10.5 shows the results gained for both the analytical and numerical solutions of the problem in comparison.

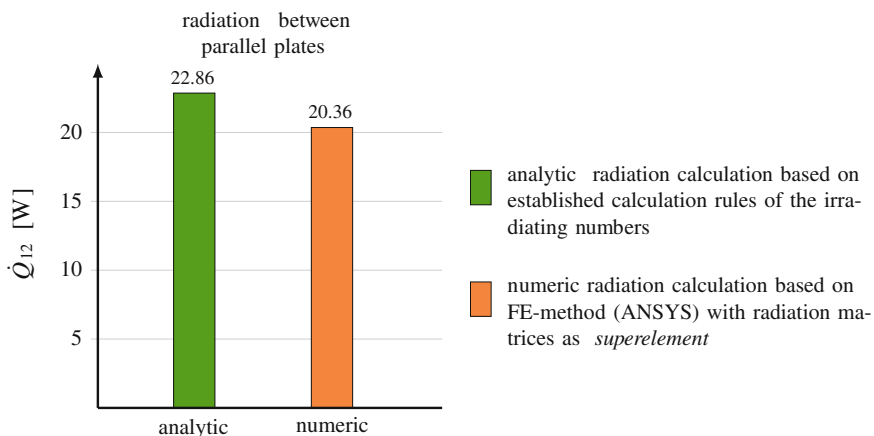


Fig. 10.5 Analytical and numerical computation results in comparison

The introduction of an overall heat transfer coefficient (compare Zwingenberger 2014) $h_{ges} = h_{str} + h_{konv}$ makes it possible to represent the interaction with the environment for convection and thermal radiation in a combined manner and at the same time reduces the calculation time when using the Finite-Element method, since it is not necessary to run additional iterations because of additional nonlinearities.

10.3.2 Sensitivity Analysis on a Machine Tool Structure

The influence of each individual thermal boundary condition in the total heat flux was evidenced by a sensitivity analysis, shown for a column assembly and spindle unit, as well as the required components, consisting of linear guidances, ball screw, roller bearing and feed drive. The model used is based on a prototype-like machining centre by the firm Auerbach Maschinenfabrik GmbH. In Fig. 10.6, the analysed part of the machine structure is shaded. The main spindle of the prototype is represented by a dummy with no machining function; it represents the main spindle in terms of geometry and mass.

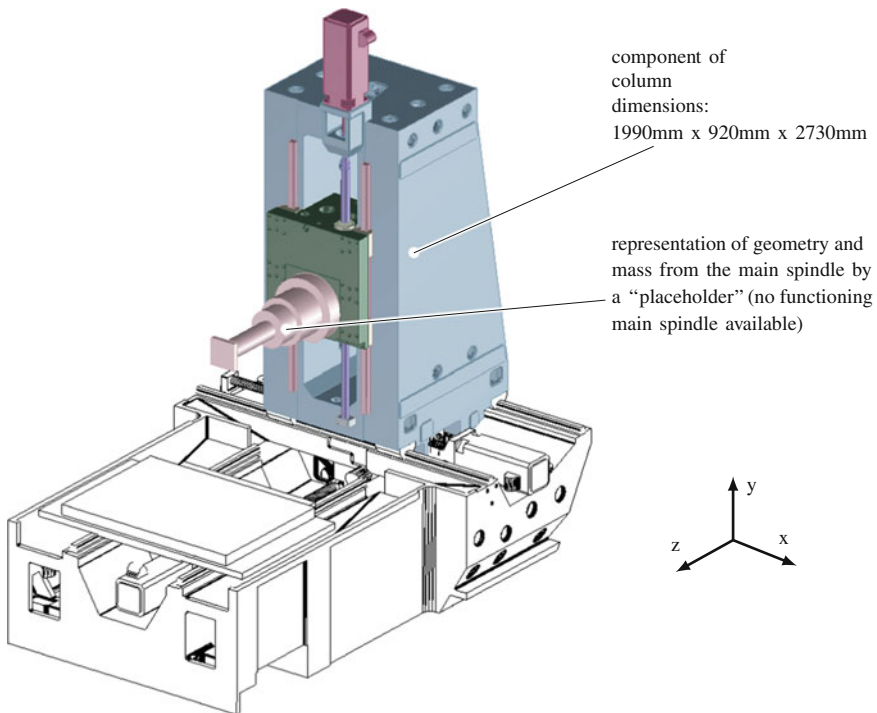


Fig. 10.6 Components of the simulation model for sensitivity analysis (Auerbach ACW630)

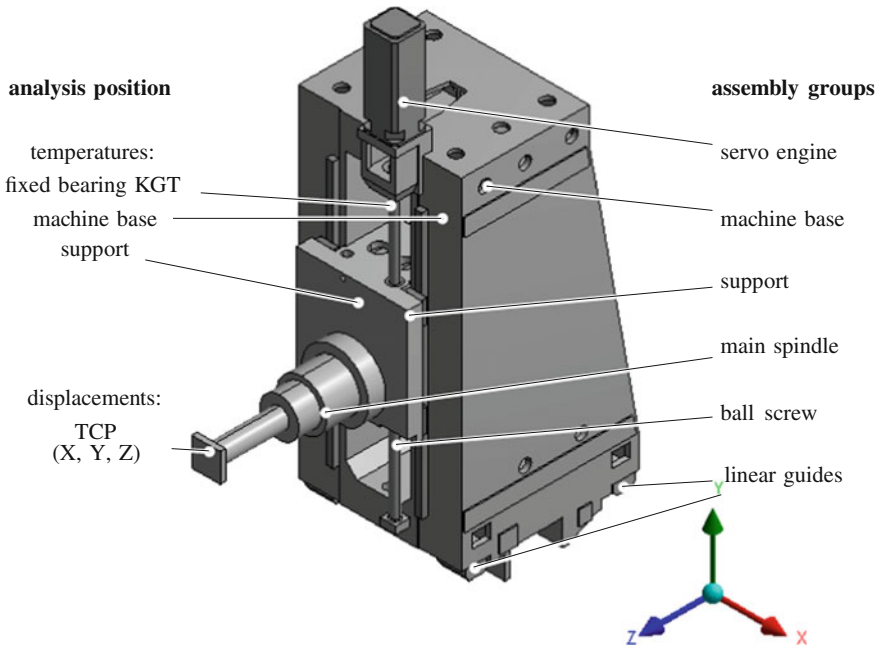


Fig. 10.7 Analysis positions on machine tool column

The partial model of the machine tool structure is illustrated in Fig. 10.7. Since the structure's sensitivity was checked regarding the thermal boundary conditions, that is, a comparison between the effects of convection and thermal radiation, fundamental conclusions in this case are made possible by considering an individual complex assembly from the machining centre. The load case assumed takes into account the heat flux from the feed drive, which brings into action the vertical slide motion. The heat source is assumed to be 250 W independently of the real load cycle; it is defined as a heat source rate in the feed drive. The heat flux dissipating into the environment as well as adjacent assemblies as power loss of the feed drive was derived from the servo-motors' parameters. The splitting of the heat flux from power losses into convection, thermal radiation and thermal conduction on the motor flange largely depends on the mounting conditions, above all on the thermal conduction into the machine tool structure, and cannot be expressed in a generalised way. However, as has been shown by investigations of the thermal losses and their introduction into the machine tool structure, the relevant share is transferred by thermal conduction via motor flange to the adjacent components (Neugebauer et al. 2009). A temperature boundary condition assumed to be 20 °C on the linear guides in X direction defines the interface with the machine bed.

Influences of convection and radiation Figure 10.8 indicates the temperatures under different convection boundary conditions for chosen analysis positions

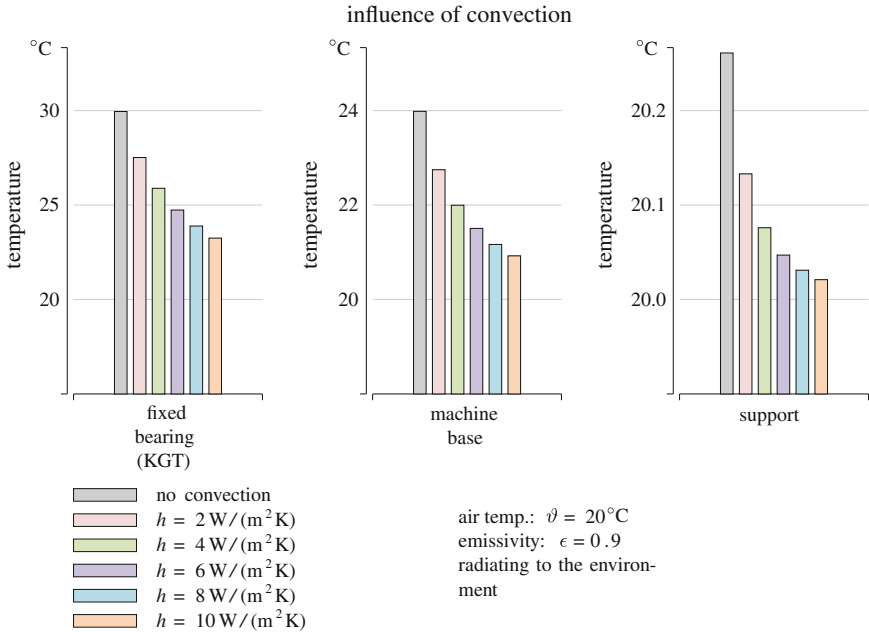


Fig. 10.8 Influence affected by convection on the temperature field (chosen measurement points)

(see Fig. 10.7) on the assembly investigated. The thermal interactions between the structure and the environment are characterised by defined boundary conditions for the thermal radiation (emissivity $\epsilon = 0.9$) and a constant ambient temperature of 20°C . There are no interactions between the individual parts of the structural surface, which would permit a heat flux at an assumed temperature difference due to visual contact. The heat transfer coefficient varies from simulation to simulation, but remains constant during the calculation of the stationary state.

On the positions evaluated on the structural surface, the mean variation of the heat transfer coefficient results in a deviation of 22.4 % on the rigid bearing of the ball screw of the vertical axis, and 1.2 % on the slide. Since the temperature difference diminishes as a function of the heat source distance, the heat fluxes between the structure and the environment also decrease, which finally results in a reduced influence of the boundary conditions defined.

The varied boundary conditions for radiation in the sensitivity analysis include the interaction between the structure and the environment. For a comprehensive analysis and a representation of all effective heat fluxes induced by radiation, interaction between the individual assemblies has to be taken into consideration, if they are in mutual visual contact. In the concrete case, for a consideration like this, it is necessary not only to include the structural assemblies, but also the entire machine tool cover. Since the machine tool structure investigated had no cover, and the interaction due to thermal radiation between the assemblies and for an individual

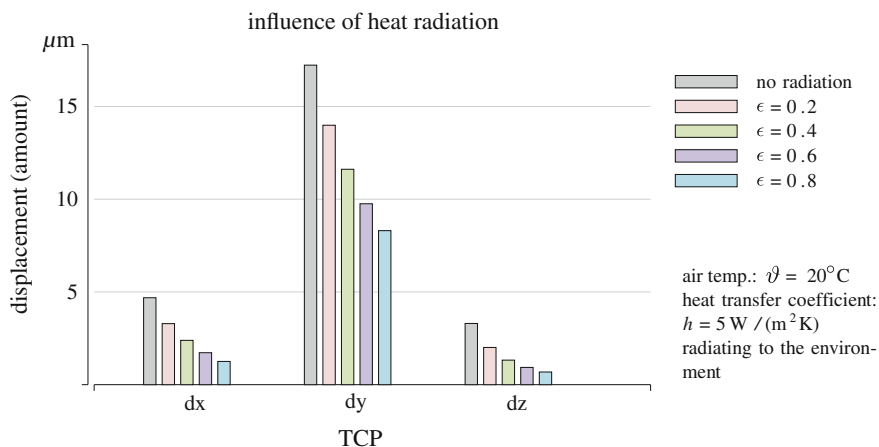


Fig. 10.9 Influence of thermal radiation on the thermally induced TCP displacements

component (in the case of radiation to itself) would cause considerable calculation efforts, sensitivity analysis was limited to radiation into the environment.

The influence of the used radiation boundary conditions used on the simulation outcomes can be taken from Fig. 10.9. The convection boundary conditions acting in parallel are identical for all variants investigated, and defined by a uniform heat transfer coefficient $h = 5 \text{ W}/(\text{m}^2 \text{K})$ and an ambient temperature $\eta = 20^{\circ}\text{C}$, which is also chosen as a constant. Emissivity is defined as a variable parameter between $\epsilon = 0$ (without thermal radiation) and $\epsilon = 1$.

Analysis The sensitivity analysis executed on the assembly introduced indicates that both thermal effects explored—free convection and thermal radiation—make up similar percentages of the overall heat flux. Thus, both heat transfer mechanisms have to be considered here with sufficient accuracy, when analysing the interaction between the machine tool structure and the environment, in order to be able to capture the heat flux transferred on the boundary surfaces to the environment in terms of quality and quantity in a manner that is closely to reality.

When expending the load cases considered by the traverse motions of the individual assemblies and the resulting air motions, the share of the heat flux transferred due to thermal radiation is reduced significantly for the surfaces situated in the area influenced by forced air flows. For the part of a machine tool structure without a machine cover, like that studied here, the interaction between parts of the structural surface that are in mutual visual contact is relatively minor. If a machine tool cover exists, then areas of the machine surface are separated from each other, which means that visual contact is avoided and, at the same time, that a percentage of the emitted radiation is reflected by the cover and absorbed by the structural surface. This effect normally also appears inside the machine tool structure, at the interaction between the walls of cavities; however, it remains unconsidered in the chosen definition of the radiation boundary condition to the environment.

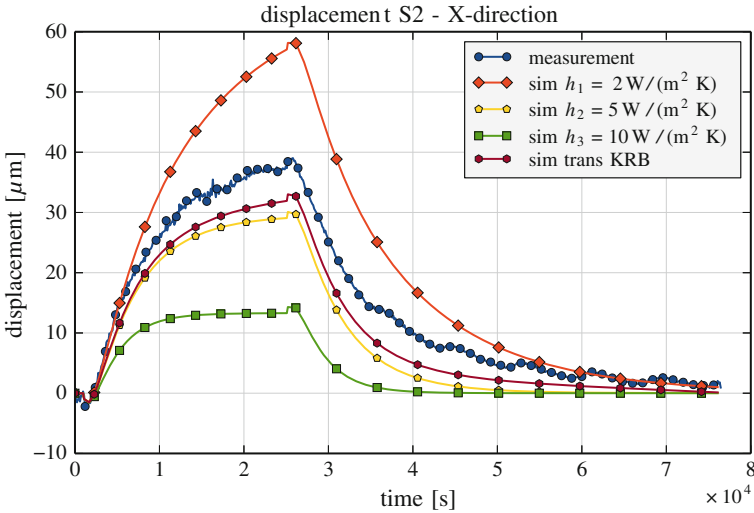


Fig. 10.10 Thermally induced TCP displacement in X axis direction

10.3.3 Verification in Experiment

Figure 10.10 elucidates the displacement on the spindle collar for the X axis direction. The stationary simulation initial state is used as a homing position, which means that the value at the point in time $t = 0$ is subtracted from all displacement values. Consequently, only the displacements caused by the temporally changed temperature field are outlined and shown.

The TCP displacements are reproduced in a manner close to reality in terms of quality and quantity by means of the simulation with transiently adapted heat transfer coefficients. In general, looking at the thermal displacements calculated, it can be ascertained that the method introduced for transient adaptation of the heat transfer coefficients provides the most reliable prediction.

10.4 Classification According to the Goals of the CRC/TR 96 and Outlook

The activities executed in subproject B01 “Modelling of thermal interaction between environment and machine tool” describe the interface between the environment and the machine tool. The studies and work performed to determine the influences of convection and radiation were able to establish the scientific basis for improved modelling of the thermal interactions between the environment and the machine tool, shown for a machine column. The authors succeeded in classifying

surface areas by means of structural analysis and the assignment of individual heat transfer coefficients. Based on these outcomes, calculation models able to map the complete machine tool with all external surfaces and its geometrical features can be established. For this purpose, approximation functions allowing structural mechanical simulations to be used without CFD simulations have to be developed. These approximation functions contribute to an optimal transfer of the parameters obtained from flow simulation to the surface of the FE model. Based on these results, the structural mechanical FE model can be developed and calculated efficiently, reducing the calculation time. This makes it possible to calculate variants with different alpha values and to optimise parameters.

Initial preliminary studies on sensitivity related to the machine tool surface geometry and the relevant boundary conditions were executed to develop this approximation functions and to implement it as a software module. Based on these outcomes, the high quality and efficiency of the approximation functions to be developed have to be assured in connection with performance data analyses. In the first stage of application, the analyses are mainly carried out for free flows.

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