An extended procedure for convective boundary conditions on transient thermal simulations of machine tools

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Abstract

The need of reliable structural properties of machine tools in the development phase are becoming increasingly important due to mounting accuracy demands and shrinking development periods. The finite element method (FEM) is the most established tool applied in this context. Currently, calculating thermal properties and compensation of thermally caused shifts are mainly the focus of simulation studies due to high performance and the usage of dry processing. The accuracy with which thermal properties can be mapped today is measurably lower than current static and dynamic properties. The reason is due to strong interaction of the specific physical effects and the complexity of pertinent constraints. With constrained parameters the impact caused is defining the convective heat transmission. The heat transmission coefficient can be calculated analytically or numerically. This article is presenting a method that allows permanent adaptation of this coefficient to make it possible to better apply convective heat transmission to time-variable thermal simulations especially for mechanical based finite element models.

Keywords

thermal simulation, finite element method, machine tools, natural convection

1 Introduction

The static, dynamic and thermal properties of draft designs are very important particularly in the development phase to boost the machining precision of machine tools. A maximum precision knowledge of the structural properties (static, dynamic and thermoelastic deformation properties of the machine [6]) is needed for comparing necessary varieties, analyzing conceivable solutions and selecting the most suitable ones. The finite element method was implemented for calculating the relevant static and dynamic properties and it was applied in the design process due to its reliability.

In recent years the prediction accuracy for static and dynamic calculations achieved significant quality facilitates quantitative evaluation of the machining accuracy. In contrast, the simulation of thermal effects contain errors. In the machine tool development sector, the FEM is used for calculating static and dynamic machine characteristics that have a significant effect on operational accuracy and thus represent a measurable quality characteristic for the customer.

As a result of the continuous improvement in static and dynamic machine characteristics, misalignments due to thermal factors have increasingly come under the spotlight as accuracy limiting factors in development work. These factors cause up to 70% of machining inaccuracies in cutting produced workpieces [1].

2 Factors influencing the thermal behavior of machine tools

The factors specified in [6] that have an impact on the thermoelastic properties of machine tools are shown in Figure 1. Each of the mentioned factors are modeled either using substitute models for specific components that represent transmission properties without a significant remodeling the precise geometry [7], or using correspondingly defined constraints. Often, the machine elements included not only have an impact on heat conduction, but also function as sources of heat due to friction losses [2].

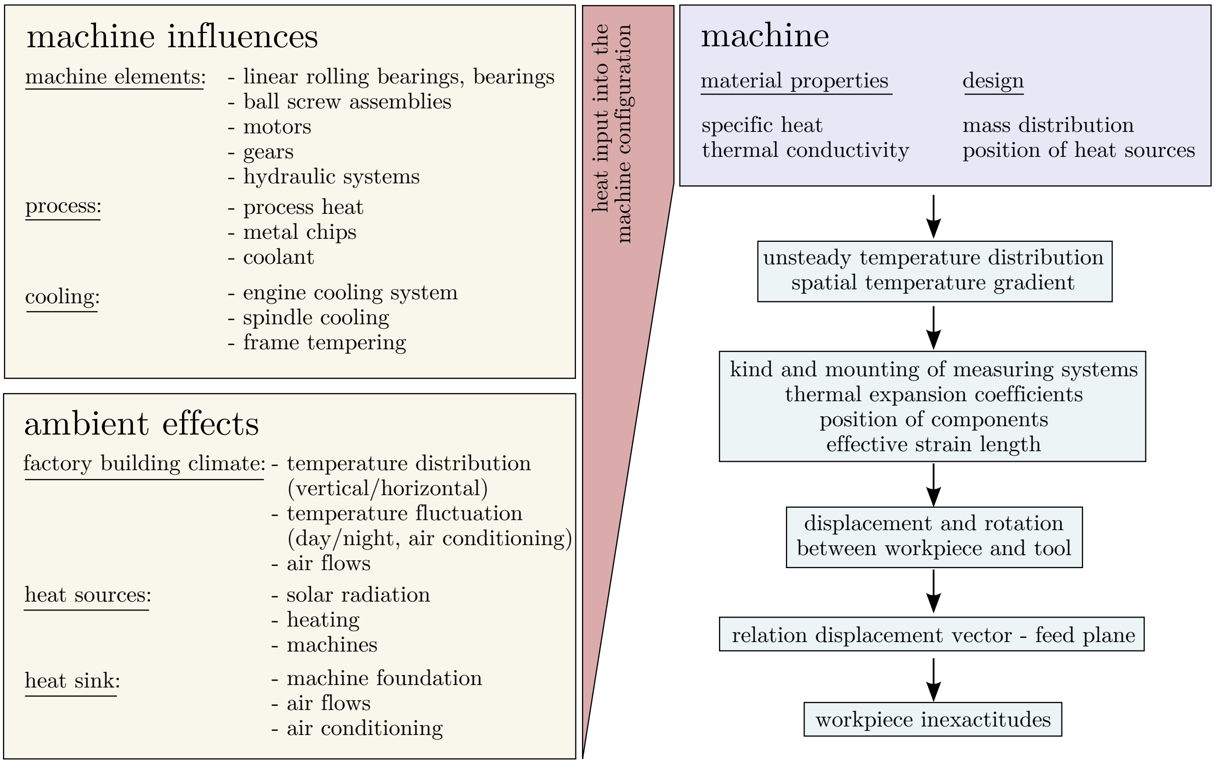


Figure 1: Thermoelastic properties of machine tools [6]

The thermal transition between the ambient air and machine structure has a definitive impact on a number of the specified factors, due to these convective boundary condition is very significant. Furthermore, the ambient temperature of each thermal load (mainly characterized by free convection) is superimposed as a load case. All the factors mentioned here bring an uneven and non-steady state temperature distribution in the machine so that thermal calculations generally have to be carried out as transient simulations.

3 Convective constraints with the thermal FEM-simulation of tool machines

Convection, as one of the most important thermal constraint, requires a definition of the heat transfer coefficient, ambient temperature and wall temperature of the structure for a complete description in the finite element model. The surface temperature of the structure is indicated from the calculated temperature field, although the heat transfer coefficient and ambient temperature have to be defined as constraints. While the ambient temperature is taken from readings, the heat transfer coefficient has to be calculated since this is not a variable that can be measured directly. Unfortunately, no precise rule for calculating the heat transfer coefficient applies, due to this constraint, empirically determined formulas are applied in specific cases [5], [3].

The position of the surface under consideration in relation to the gravitation vector is crucial for free convection. The cases shown in Figure 3 are distinguished.

Heat transfer coefficient α can be calculated according to the formula below:

$$\alpha = Nu \frac{\lambda}{l} \tag{1}$$

mit:	α	heat transfer coefficient
	Nu	Nusselt number
	λ	thermal conductivity
	l	characteristic length

The Nusselt-number, essential for heat transfer, is a dimensionless quantity which has to be determined on the basis of empirical calculation instructions for the particular cases depicted in figure 3. Hereby, the two cases of warming-up and cooling-down of a vertical wall (cases (a) and (b) in figure 3) are not being differentiated. However, for every other depicted orientation of a surface it is necessary to differentiate between warming-up and cooling-down as well as partly between different flow conditions. The Nusselt-number is a so-called similarity quantity which describes the relation between the heat transfer of the heat conduction and the convection relating to the heat conduction of the static fluid [4]. It has direct influence on the determined heat transfer coefficient which is also shown in eqation 1. The dependence of the heat transfer coefficient on the orientation of the surface in opposition to the gravitation can be seen in the diagram depicted in figure 2. The angle of the surface for various characteristic lengths has been changed, the other influencing factors remained constant ($\vartheta_{fluid} = 21^\circ\,C$, $\vartheta_{Wand} = 25^\circ\,C$).

The opposing orientations of the surface of a possible structure, depicted in figure 3, differ from each other partly in the ensuing heat transfer coefficient in a great measure. For example, on a horizontal oriented wall which is being warmed-up and therefore colder than the surrounding air, convection hardly takes place due to the fact that no flow detachment is possible.

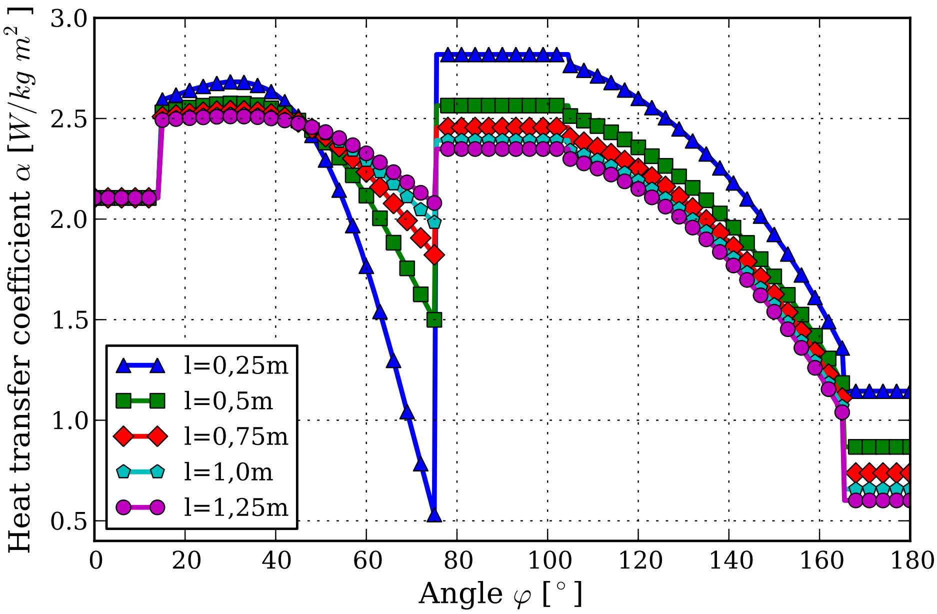


Figure 2: Effect of the surface orientation

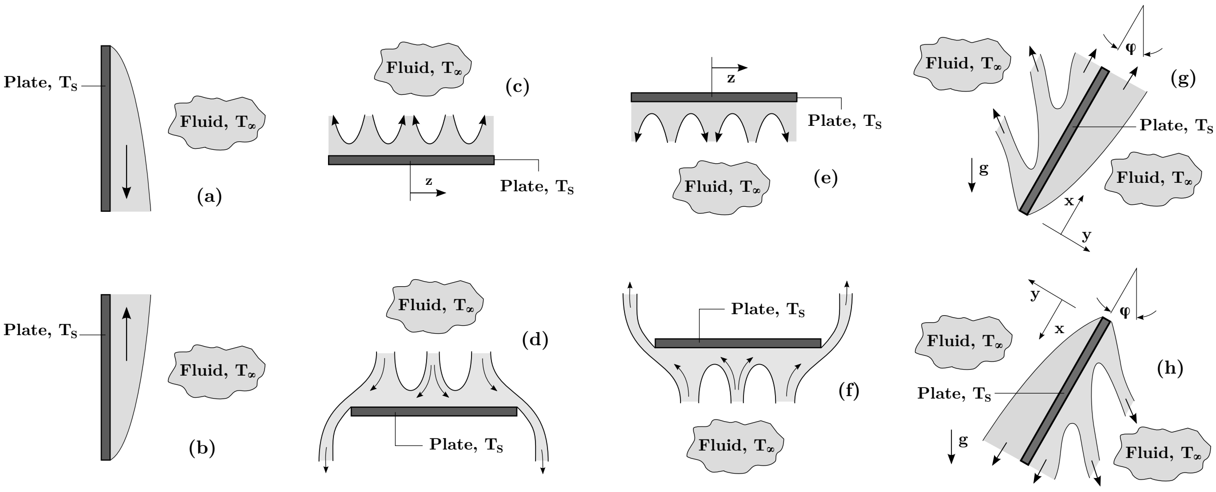


Figure 3: Distinctions of cases for the computation of the heat transfer coefficient [3]

4 Calculating and adapting the heat transfer coefficient

The heat transfer coefficient α essential to convection depends especially for natural convection upon the factors described in Figure 4. The temperature distribution of the structure and the orientation of the surface elements are results of the calculation via finite element analysis or given by the finite element mesh. The temperature-dependent material values are stored as a function determined from readings via regression [5]. Ideally, the ambient temperature are derived from measurements and it should not be presumed to be constant over the height due to the developing temperature gradient.

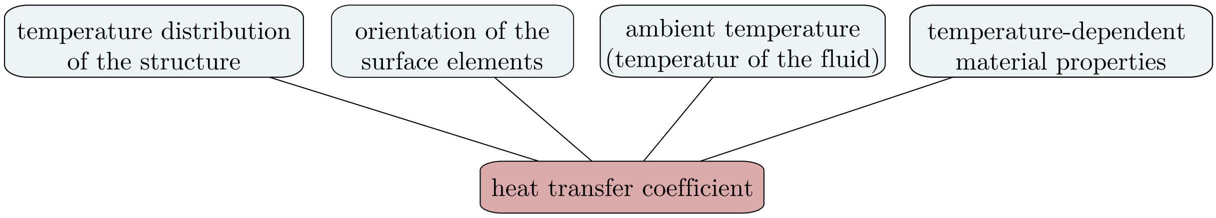


Figure 4: Factors influencing the heat transfer coefficient

With the approach described in Figure 5 the convection boundary condition can be adapted after each time step to the new conditions during a transient thermal simulation. A program was developed for calculation of the heat transfer coefficient. The Computation is based on the surface mesh of the machine structure, measured values of the ambient air, temperature-dependent material parameters and surface temperatures.

On the starting point ($t_1 = 0$) of the examined time-interval of a transient thermal simulation a steady load step is calculated, based on corresponding thermal boundary conditions out of measurements or data from experience. First of all, these boundary conditions are used to determine the distribution of the outer temperature of the structure. Hereby, usually data from experience of literature are used to formulate boundary conditions (e.g. heat transfer coefficients, etc.). In the following, the heat transfer coefficient can be determined anew on the basis of the provided temperature distribution and the temperature conditions valid for the next step in time. The heat transfer coefficient can be used for the following step in time to define the boundary conditions for the surrounding area. Among other things, the calculation program includes geometrical features of the model, temperature-dependent data from the material, the ambient temperature distribution (so far known) as well as the temperature distribution of the structure-surface from the calculation model after each load step.

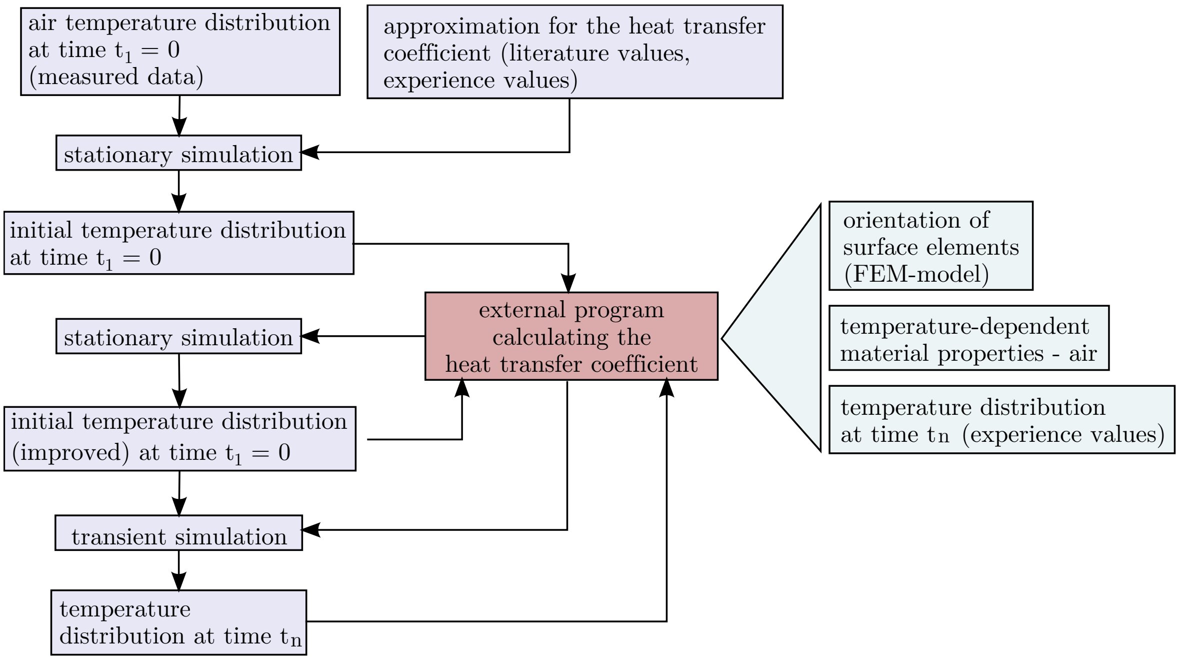


Figure 5: Procedure of a transient thermal simulation with permanent adapting of the heat transfer coefficient

5 Comparison of measurement and simulation

Comparisons of measurement and simulation show significant deviations (cf. Figure 6) of determined displacements, despite permanent adjustment of the convective boundary conditions to the changed temperature field. In this specific case for the changes of the ambient temperature, deviations in the chronological sequence and the absolute temperatures are foreseen. The lower graph in Figure 6 shows the thermal deformation on the tool center point (TCP) and the upper graph illustrate the simulated temperature profile. The temperatures are air-temperatures gained from the surrounding area, collected from various heights over the foundation of the machine. The data concerning the displacement in % refer to the highest determined displacement on the TCP.

For the simulation, the ambient temperatures measured values of the air temperature were used. This were determined in lucidly distance from the machine structure and outside the machine enclosure. In further experiments local ranges at the machine structure were considered intensively. The air temperatures were based on places of the machine, which permitted no unhindered air interchange with the environment. It was found that the consideration of air volumes separated from each other was necessary to describe the ambient temperatures sufficiently. In Figure 7 a) such ranges are marked. The measurement setup shown in Figure 7 b) explanation supplied, over the temperature distribution in the examined ranges.

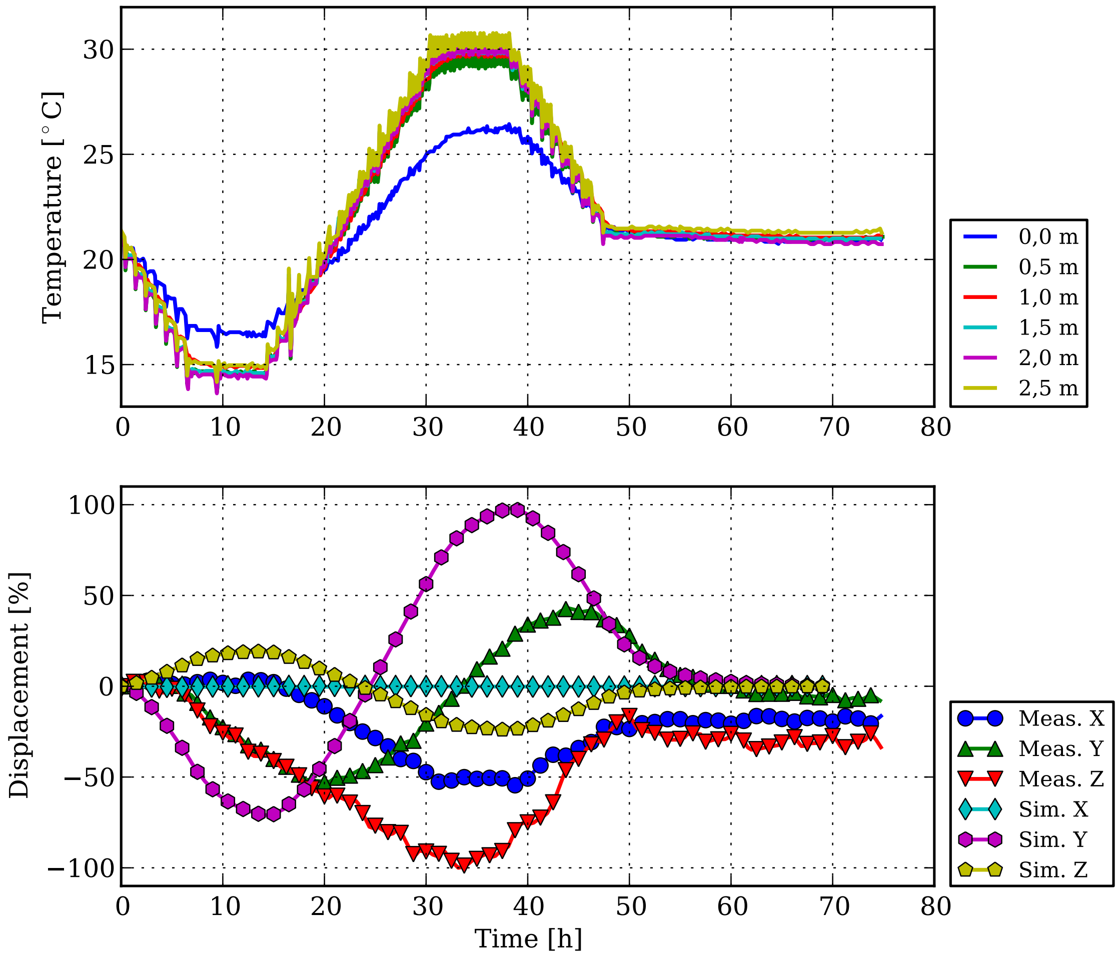
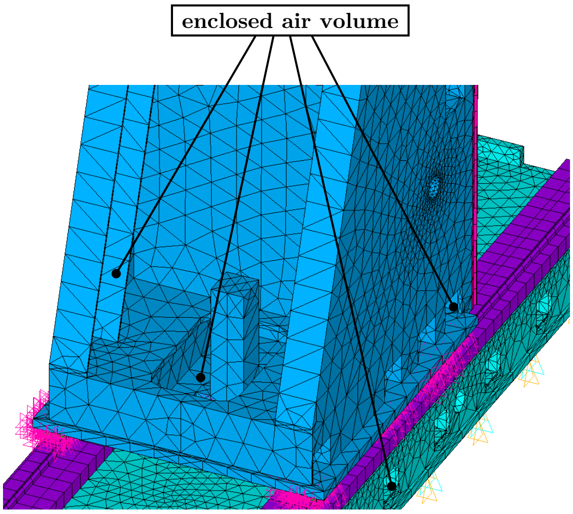
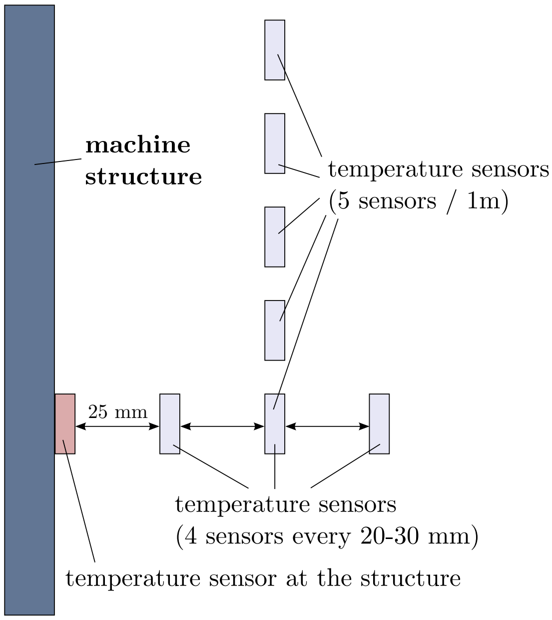


Figure 6: Displacement on the TCP of a machining center - comparison of measurement and simulation (load case: Ambient temperature process)

The detail measurement data obtained for individual ranges were used for further simulations (cf. Figure 8). The comparison of the simulation results and measurement are shown in the lower graph. The chronological sequence of the ambient air temperature is shown in the upper graph of the Figure. With the new and extended boundary conditions for the heat transfer the results of the simulation were considerably improved.



(a) Enclosed volumes



(b) Temperature sensors

Figure 7: Enclosed ranges at a machine structure and measurement setup for determination of ambient temperatures

6 Summary and outlook

As comparison highlight the difference between the simulation and measurements. The method showcased here for evaluating the temperature distribution indicates improvements in determining the temperature field particularly for structural FEM models after every step, while calculating new constraints for the load step. Additionally investigations clearly show the need for more knowledge of the pertinent constraints. However, this method will have to be improved significant to keep pace with high simulation precision.

A method for automatic determination of enclosed air volumes could help to make the described procedure suitable for daily usage. In addition it is necessary to improve the knowledge of environmental conditions of machine tools.

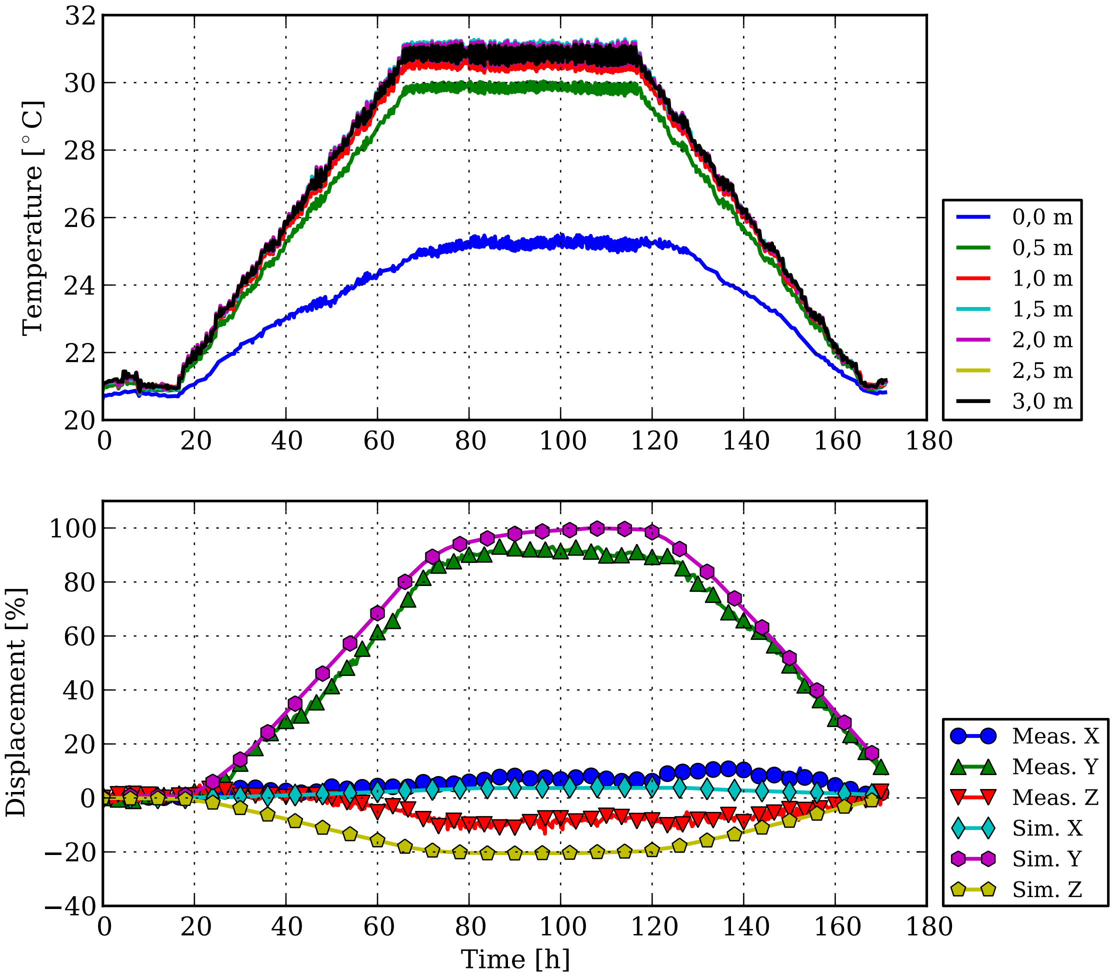


Figure 8: Displacement on the TCP of a machining center - comparison of measurement and simulation (load case: ambient temperature process with extended boundary conditions)

References

[1] Bryan, J. : International Status of Thermal Error Research. In: *CIRP Annals - Manufacturing Technology* 2 (1990), S. 645 – 656

[2] Grossmann, K. ; Jungnickel, G. : *Instationäres thermoelastisches Verhalten von Vorschubachsen mit bewegtem Wälzkontakt*. Technische Universität Dresden, 2003

[3] Incropera, F. P. ; DeWitt, D. P. ; Bergman, T. L. ; Lavine, A. S.: *Fundamentals of Heat and Mass Transfer*. 6. Ed. Chichester. John Wiley & Sons, 2006

[4] Oertel, H. ; Böhle, M. ; Dohrmann, U. : *Strömungsmechanik*. Vieweg Verlag, 2006

[5] VDI (Hrsg.): *VDI-Wärmeatlas Berechnungsblätter für den Wärmeübergang*. VDI-Verlag, 2002

[6] Weck, M. ; Brecher, C. : *Werkzeugmaschinen. Messtechnische Untersuchung und Beurteilung*. 7. Springer, Berlin, 2006

[7] Weidermann, F. : Praxisnahe thermische Simulation von Lagern und Führungen in Werkzeugmaschinen. In: *CAD-FEM User´s Meeting 2001*, 2001