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Simulation of Thermal Behavior in High-Precision Measurement Instruments

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Abstract In this paper, a way to modularize complex finite-element models is described. The modularization is done with temperature fields that appear in high-precision measurement instruments. There, the temperature negatively impacts the achievable uncertainty of measurement. To correct for this uncertainty, the temperature must be known at every point. This cannot be achieved just by measuring temperatures at specific locations. Therefore, a numerical treatment is necessary. As the system of interest is very complex, modularization is unavoidable to obtain good numerical results.

Keywords Black box · Changes of the refractive index due to vicinity influences · Control volume · Modularization of complex finite-element models · Temperature fields in high-precision measurement instruments

1 Introduction

In today's society, engineering miniaturization to nanometer scales is rapidly developing. Examples can be found in semiconductor technologies, micro-system technologies, high-precision optics, and bio-analytics. In accordance with Moore's law, the number of transistors on semiconductor chips doubles every 18 months. The trend is to higher densities of nanometer-sized structures on objects that are ever increasing in size. These structures have to be manufactured and analyzed.

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To comply with this development, completely new concepts for three-dimensional positioning and measurement at nm scales are necessary. The collaborative research center 622 "Nanopositioning and nanomeasuring machines" (NPMM) at the Technical University Ilmenau provides, in cooperation with national and international research establishments, the scientific fundamentals and technical equipment to position, touch, measure, analyze, modify, and manipulate three-dimensional objects with nm-scale structures. Our objective is to measure and position within a volume of $350\,\text{mm} \times 350\,\text{mm} \times 50\,\text{mm}$ with a reproducibility of less than 1 nm. Metrological and precision construction principles, and innovative optical and mechanical systems to touch lead the way to achieve that goal. Nevertheless, to improve the quality of measurement, the causes of uncertainty must be identified and minimized.

Temperature influences the uncertainty of measuring instruments in many ways, some of them subtle. Changes of temperature, and the associated gradients of temperature that generally result, give rise to several metrological effects that are not easily resolved. Temperature gradients along the laser beams of the interferometers in the NPMM cause variations in the refractive index of air, and thereby the wavelength of the laser, along the beam, leading to considerable uncertainty. These variations can be compensated numerically with significant effort, but the temperature must be known at every point along the laser beam. For various reasons, this is metrologically impractical. To capture the temperature, the thermal behavior inside the NPMM is numerically reproduced with the finite-element method (FEM). In such a FEM model, it is possible to determine the temperatures at every point. Knowledge of the temperature field allows the determination of the maximum uncertainty associated with thermal influences.

After several metrological evaluations, four plunger coils moving in the z-direction and the amplifier for the interferometers were identified as the principal heat sources. As can be seen from Fig. 1, the NPMM is a very complex and sizeable system. In particular, the interferometers and the plunger coils present a complex configuration of components. Hence, the thermal behavior within those components is of special interest, so a high mesh density is indispensable.

To simulate large-scale systems with high accuracy in a reasonable time, a metrologically supported method to modularize the FEM models was conceived. Therefore, smaller sections, e.g., the interferometers, are analyzed under well-defined circumstances and afterward simulated within defined constraints. The results are read out through a pre-defined control volume in the form of a black box and afterward conditioned mathematically. Then, a superior model is established, e.g., the model of the NPMM, which incorporates only the outer shell of the control volume. The inner parts, e.g., the amplifier unit, are no longer modeled. At the outer shell of the control volume, the previously determined values for the black box are applied. With this approach, results from a smaller model are transferred to a superior model without loss of accuracy and the resulting models gain clarity.

Only with metrologically well-defined constraints for the partial model and steady-state analysis is this modularization approach admissible. Another fundamental premise is that the NPMM is surrounded by a large, slowly varying temperature field.

All simulations mentioned in this paper were carried out with the FEM program, ANSYS 10.0. The transfer of the heat fluxes for the black boxes was performed

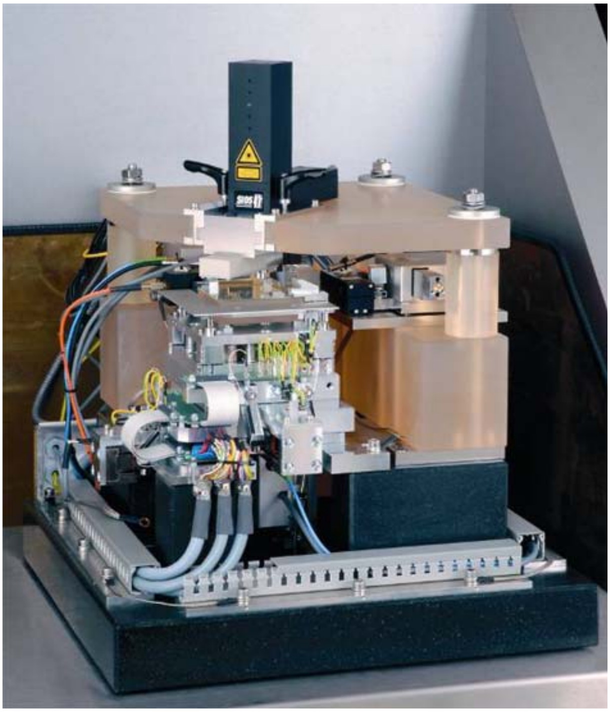

Fig. 1 Assembly of the Nanopositioning and Nanomeasurement Machine

manually, since an interpolation between the different mesh-structures of the consecutive models was required, and no commercial tool for doing so existed.

The consecutive models differ in their meshes; this implies that the "nodes" (points where the edges of the elements touch and where the "interaction" between elements takes place) vary in their spatial allocation. The results or degrees of freedom of a FEM model are commonly read out at nodes. Those results are calculated based on trial functions defined for every element. If the nodes vary in their positions with respect to each other, the results have to be interpolated based on the coordinates of the nodes and the trial function. To perform this interpolation automatically, the form of the trial function has to be known for every element. As the form of the elements varies throughout the model, a very complex algorithm would result. To avoid such a complex algorithm, the function for the heat transfer through the surfaces was fitted, and after that, radically simplified. The values resulting from this simplified function were interpolated linearly for the subsequent model's mesh and afterward standardized, so that the sum of the heat fluxes of the original model and the sum of the heat fluxes for the black box were the same.

As mentioned above, the temperature gradient along the laser beams is an outcome of the analysis. To read out those temperatures, the air surrounding the NPMM was modeled as a rigid body. Defining convection at the surface areas in the form of a convective heat transfer coefficient needs free surfaces and is therefore not possible.

Calculating the air flux inside the NPMM would require an extensive effort unlikely to provide the desired quality of results. Defining radiative exchange between components is nearly impossible due to the size and complexity of the FEM model. Therefore, only heat conduction is considered as the mechanism by which heat is transferred inside the model. In reality, convection and radiation cannot be neglected. A solution for this problem is provided by a thermal compensation model.

2 Thermal Compensation Model

The ratio of convection and radiation to total heat transfer cannot be estimated with a rule of thumb for a system as complex as the NPMM. A composite thermal resistance delivers a reasonable solution. This thermal resistance combines the thermal resistances for convection, radiation, and heat conduction as seen in Fig. 2. By converting this composite resistance back to a generalized thermal conductivity, radiation and convection can be included numerically in the model.

The generalized thermal conductivity was estimated with the aid of an experimental setup (Fig. 3). A heat source with known power output was placed in a volume with well-defined boundaries. In this case, the intrinsic heat of a 100-Ω platinum resistance thermometer (Pt100) was used to heat the surrounding air. Around the Pt100, several other temperature sensors were arranged to detect the heating. For the thermal steady-state case, the current and voltage through the Pt100 were measured, and the resistance, output power, and temperature were computed.

Based on this information, a FEM model was designed. As with the experimental setup, this model contains a polystyrene box for which the outer surface temperature is kept constant. Inside the box, four additional areas are defined where the temperature

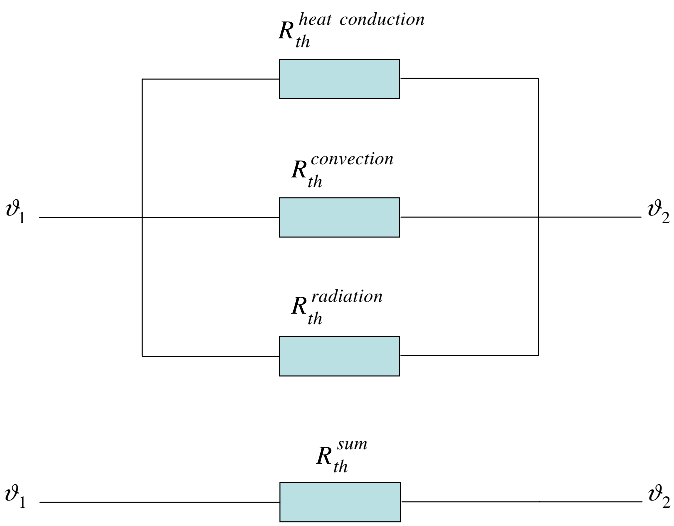

Fig. 2 Compensation model for the composite thermal resistance

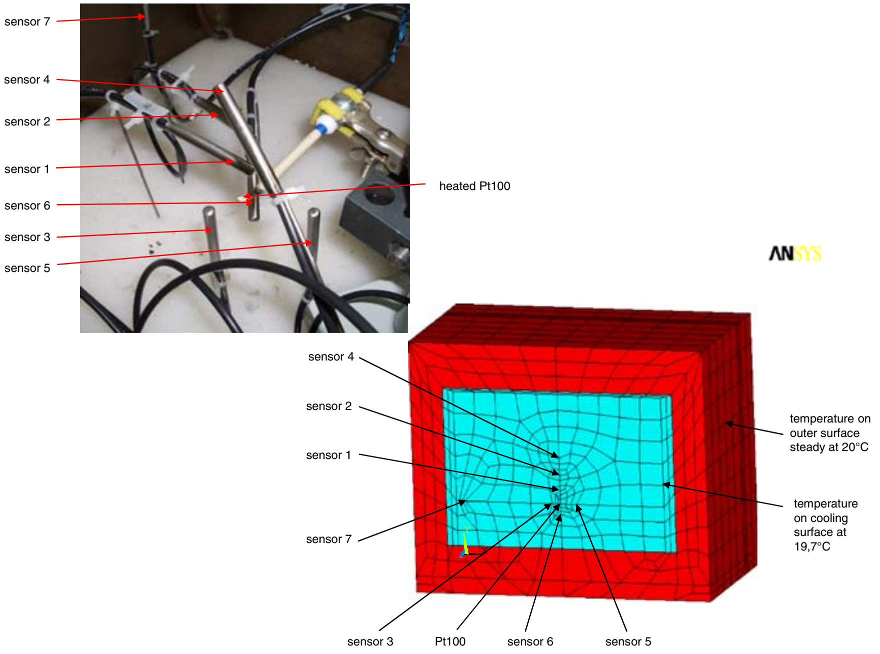

Fig. 3 Numerical and metrological survey on the thermal compensation model

is assumed to be 19.7°C. Those areas correspond to the cooled Cu plates in the experimental setup.

With knowledge of the measured temperatures, the power input, and the thermal constraints (laboratory temperature controlled at 20°C), the thermal conductivity in the FEM model was altered until the measured and simulated temperatures agreed. Inside the box, eight points were defined: on one, the power output was defined; on the others, the simulated temperatures were taken to be comparable to the measured ones.

The model for generalized thermal conductivity obtained in this way is temperature dependent and isotropic.

3 Analyzing the Interferometers Numerically and Metrologically

To achieve the modularization of the FEM model in a suitable manner, all constraints should be well known. To acquire the thermal behavior of the interferometers independent of thermal fluctuations of the laboratory, a thermal enclosure was created. For this, the interferometer was placed in a cooled polystyrene box. Around the interferometer, several Pt100 thermometers were arranged to determine the constraints of the polystyrene box and to acquire metrological data to evaluate the quality of the FEM model.

The FEM model was designed to be equivalent to the experimental setup (see Fig. 4). As in previous models, the polystyrene box was also included here. On the Cu

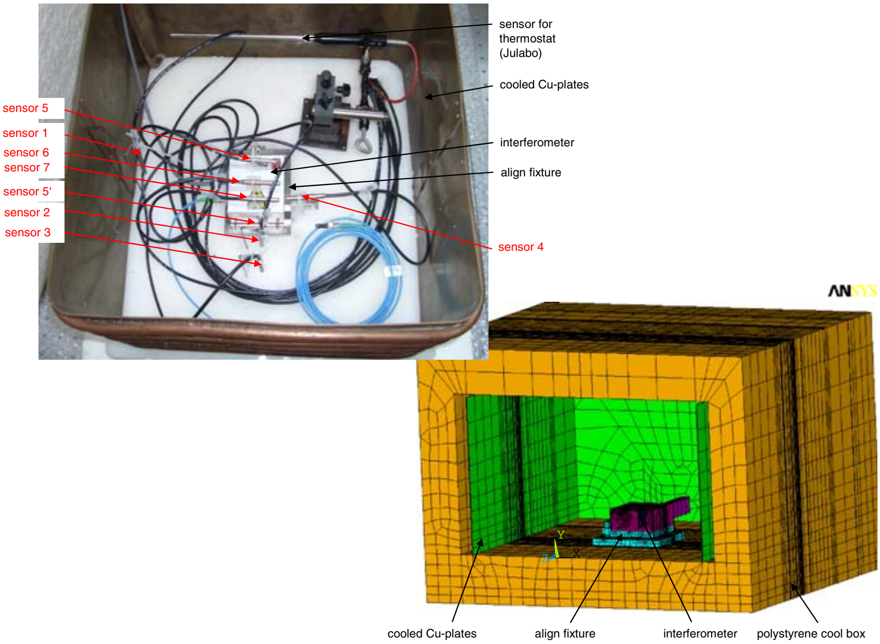

Fig. 4 Experimental setup for metrological (left) and numeric (right) survey on the interferometers

plates, the measured constraints were defined as fixed temperatures. The interferometer was placed inside the polystyrene box. There is an electronic circuit located inside the interferometer to amplify the incoming signals. This amplifier unit has a thermal dissipation of 0.156 W per interferometer. With this information, the first simulation was begun. A maximum difference of 0.3 K between simulation and measurement was obtained, which we consider to be excellent agreement.

The modularizing procedure was first tested for the FEM model of the interferometer. To modularize, it is necessary to first define a suitable control volume. "Control volume" is a term borrowed from thermodynamics, where a closed volume defines a surface through which thermal exchange with the surroundings occurs. In this case, incoming and outgoing heat fluxes are registered. Using control volumes, energy balances can be easily calculated. The surface integral of the function defining the heat flux through the control volume surface must equal the volume integral of the function defining the heat generation inside the control volume.

Using the control volume, a "black box" was constructed that defines only the incoming and outgoing signals of a system; the system itself is unknown. A black box "sees" the control volume from the point of view of the surroundings.

In the FEM model of the interferometer, a box around the interferometer was defined to be the control volume. The heat fluxes through the surface of this control volume were read out and, following the described procedure, used to form the output of the black box. In further steps, only this black box was used; the inner elements of the interferometer were deleted.

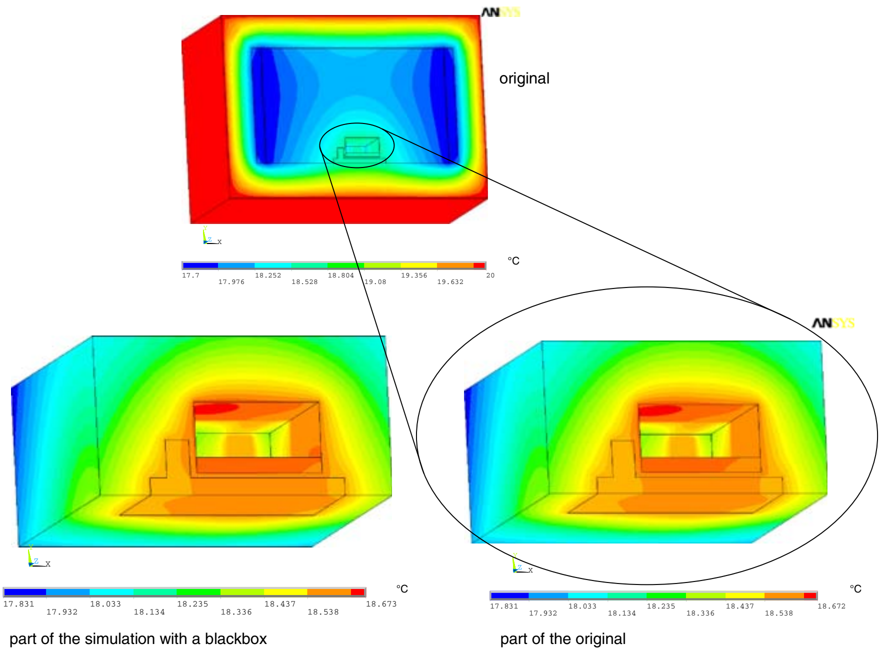

Fig. 5 Comparison of the results from the original FEM model and the results for the simulation with a black box

In Fig. 5, the results from the first simulation and the one with the black box are compared. The agreement between both simulations is very good. Respecting the given assumptions, modularizing large FEM models in this way has led to good results.

Equivalent to the procedure for the interferometers, black boxes were also established for the plunger coils.

4 FEM Model for the Nanopositioning and Nanomeasurement Machine

Figure 6 shows the procedure to modularize the whole FEM model. In the model for the NPMM, the black boxes of the interferometers and plunger coils are inserted. These black boxes contain no elements; only thermal exchange with the surroundings is implemented, with the assumptions being that our knowledge of the thermal constraints is adequate and that the temperature ranges and gradients of the different models are sufficiently consistent.

The constraints for this complex and large model were acquired by positioning temperature sensors inside the NPMM. Some additional sensors were used to acquire data to validate the FEM model. The metrological surveys were done for a maximum permitted load of 1 kg, where the plunger coils produce a thermal dissipation of 8 W.

In Fig. 7, we compare the measurements with the results of the simulation. At most points, very good agreement is achieved; only the data of three sensors differ by more than 0.3 K from the simulated data. This difference can be explained by the integrating

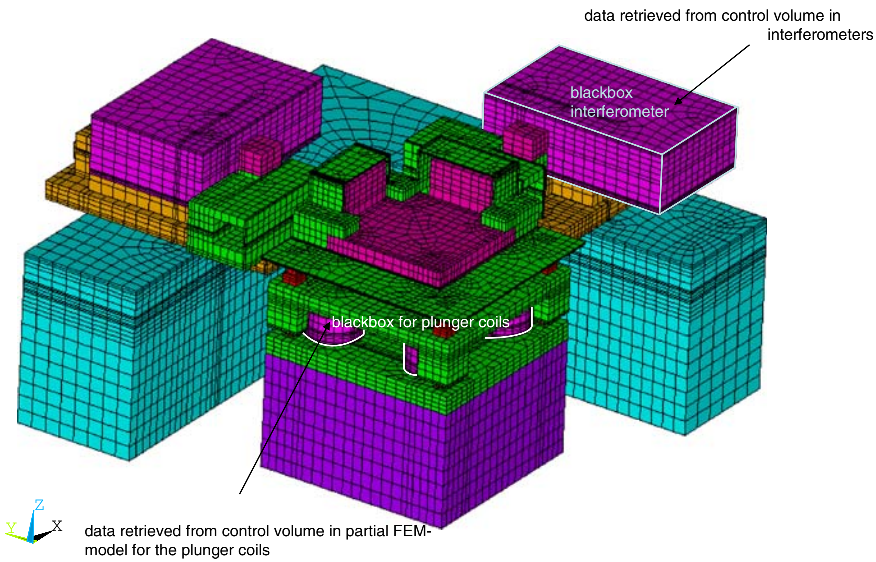

Fig. 6 Visualization of the entire FEM model for the NPMM with the black boxes

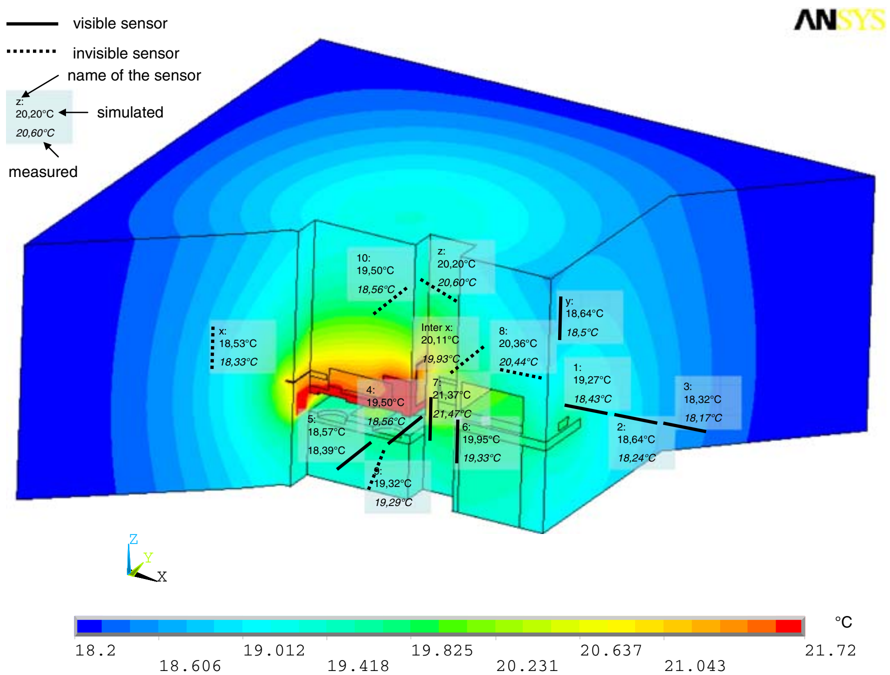

Fig. 7 Visualization of the results from the FEM model compared to the data of metrological surveys

behavior of the Pt100 thermometers. Figures 4 and 5 show that the sensors are large compared to the size of the interferometers. The sensors that differ by more than 0.3 K are placed in regions with large thermal gradients. Due to those gradients, the influence of the sensors' spatial integration becomes apparent. The data of the simulation were read out at the tip of the sensor, and the sensor's spatial integration was not taken into consideration.

Given the good agreement of the measurements with the FEM simulation, it is possible to draw conclusions from the simulation regarding how the temperature field is conditioned along the laser beams. By using the results provided by the simulation, the maximum thermal uncertainty of the interferometers can be computed.

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