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EXPERIMENTAL INVESTIGATION OF A BALL SCREW FOR INCREASING THE ACCURACY OF THERMAL FE SIMULATIONS

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ABSTRACT

Thermally induced displacements due to thermal expansions continue to present one of the main problem areas in the machine tool sector. To compensate displacements simplified thermal FE simulation models are developed, with which compensating calculations will be carried out online in the NC control computer in future (software in the loop). To increase the accuracy experimental tests are conducted on the machine components of the machine tool and compared with FE simulations. The experimental comparison forms the basis for exact simulation models, which are reduced in their complexity though, to subsequently be able to make quick predictions for temperature compensation. This paper describes the thermal investigation on the machine tool component of ball screws as well as the thermal FE model for comparing the heat transfer parameters to be examined.

Keywords: FEM simulation, ball screw, heat transition coefficient

1. INTRODUCTION

The finite element method is regarded as one of the most established methods for approximating the physical properties of machines and assemblies during development. Thermal simulations, especially transient calculations are, however, still a challenge in the field of computer-aided engineering (CAE), also in the sector of machine tool production. Among other things, this also results from the unknown boundary conditions since information for thermal FE simulations is known neither in literature nor by the manufacturers of machine elements. Hence, a test stand with which heat flow through a ball screw and other machine elements can be measured was built at the Institute for Machine Tools of the University of Stuttgart, Germany. An exact model, which is, however, reduced to its essential sizes, can be created and calculated by means of the measurements and a model comparison, which otherwise support the development. In future it is planned to use the model for the online calculation in the computer unit of NC controls as well and hence for the compensation of thermally induced errors (software in the loop).

2. TEST SET-UP

Figure 1 shows the scheme of the complete test set-up with the measuring system used. The test object presented in this paper is a ball screw with nut and spindle with four-point preload by the company NSK. The preloaded ball screw is used for generating feed of moving slides in feed drives of machine tools. For the experiment the nut of the ball screw can be heated with a heating mat ($P_{el}=\dot{Q}$). The electrical power of the heating mat is continuously controlled through a phase control. A constant heat flow of about $\dot{Q}$=20 W is adjusted corresponding to a typical friction dissipation. The electrical power is measured with a power analyzer, LEM Norma D4000, through a switch control. The nut is shielded from the environment with suitable insulating material to avoid convective influences. The ball screw spindle is mounted on two aluminium blocks, via which the heat flows into a solid machine bed. The temperature is measured with six temperature sensors of the type Pt1000. These are wired to an NI terminal block using a four-wire configuration, which in turn is connected to a PC via a GPIB connection. A heating phase and a cooling phase of the test object can be measured and recorded on the temperature sensors by the input of heat with a constant quantity.

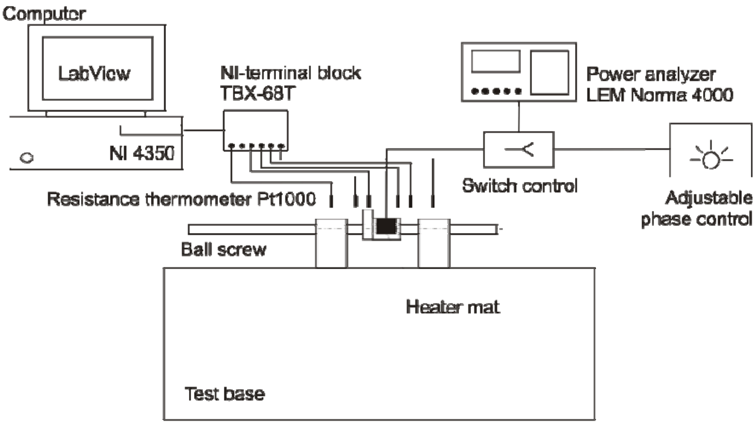

Figure 1. Schematic set-up to determine the heat transition coefficients of a ball screw

3. TEST PROCEDURE AND EXPERIMENTAL RESULTS

The test is carried out following ISO 230-3 Part 3 in order to put it on a universally applicable basis [1]. The standard allows a heating phase of four hours for measuring the temperature of machine tools and a subsequent cooling phase of two hours. Hence, an experiment takes six hours. The room and initial temperature is approx. $T_0 = 20$ ° in the presented experiment.

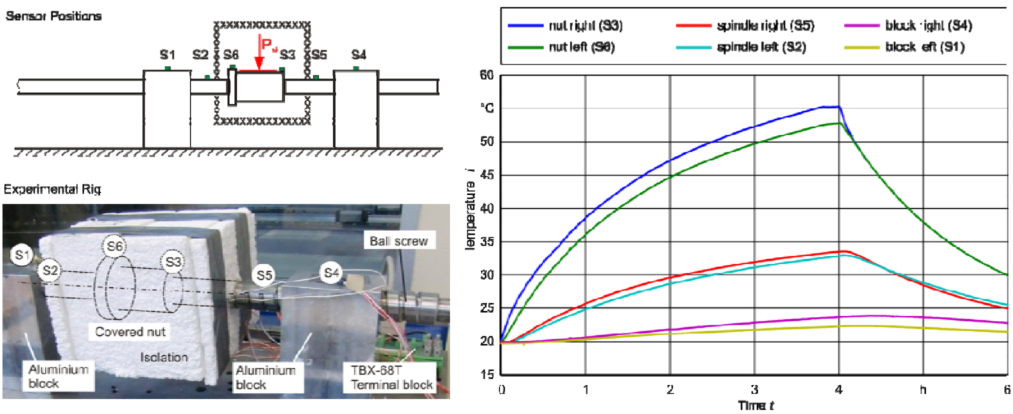

Figure 2. Arrangement of sensors and test stand, heating and cooling curves of a ball screw

Figure 2 on the left shows the test stand with the arrangement of sensors and the heating and cooling curves of the six measured positions on the right. The typically transient course for the thermal heating and cooling of components can be seen immediately. After a heating time of four hours, the stationary balance is not quite reached yet or rather the heating phase is not finished yet. The nut of the ball screw reaches temperatures of approx. 53° (S6) and 55°C (S3) at the outer ring after four hours of heating. The resistance sensors S2 and S5 of the type Pt1000 are fixed on the spindle beside the isolation. Two additional sensors (S1 and S4) measure the temperatures at the aluminium blocks. Of interest here are the heat energy flowing through the nut and the drop in temperature on the rolling elements and the lubricant. Located between the nut of the ball screw and the spindle are approximately 117 bearing rolling balls with a diameter of $d_b = 6.35$ mm under preload with four-point

contact. A heat transition coefficient $k_{bs,aux}$ and a replacement conductance have to be determined for the ball screw nut and the rolling elements including lubricant respectively.
If the Fourier differential equation is used, the following applies to the heat flow density:

$$\dot{q} = -\lambda \cdot \nabla T \tag{1}$$

with a thermal conductivity λ in [W m^{-1} K^{-1}] and a temperature gradient in all the three directions in space.
If there is a stationary balance, the temperature conduction equation is reduced to a temperature field that is constant the whole time. Hence, the heat transition coefficient k [W m^{-2} K^{-1}] can be calculated with:

$$k = \frac{\dot{q}}{\Delta T} \tag{2}$$

where ΔT is the temperature difference between the isothermal boundary surfaces on the warm side (exterior of ball screw nut) and the cold side of a machine element (spindle of ball screw), and $\dot{q}$ is the underlying heat flow density. As the temperatures on the ball screw spindle (S2 and S5) increase by more than ΔT_1 = 10 K and on the aluminium blocks still by ca ΔT_1 = 4, the heat transition coefficient cannot be directly calculated in an analytical way (with Equation 2).
The temperatures and the thermal resistances in the solid metal parts (ball screw nut and spindle pieces) are calculated from the sensors S3 and S6 to the sensors S2 and S5 with a thermal nodal model in Matlab. One calculation for the right side and one for the left are carried out here, and the mean of the drop in temperature is taken later on. As the heating is not finished yet in the experiment, the curves are extrapolated with mathematical approximation methods. Based on the method of least squares, the curve functions are fitted to the measurement series of the sensors in an iterative process. The Levenberg-Marquardt algorithm was used as numerical optimisation method in this evaluation. Based on the different approaches, a mean thermal replacement conductance can be calculated for the 117 rolling balls and the contained grease of $\lambda_{bs,aux}$ = 0.685 [W m^{-1} K^{-1}]. The replacement conductance determined, however, applies only to the chosen replacement geometry of the examined ball screw's rolling elements by the company NSK.

4. FE MODEL AND PARAMETER IDENTIFICATION

A simplified thermal FE model of the ball screw with spindle, replacement layer and nut is created to verify the replacement conductance of the rolling balls and the lubricant, which was determined by experiment. The method of „deductive modelling“ [2], developed at the Institute for Machine Tools, is used for this, ie the FE model is created from a CAD model by an automated procedure. The components (of the ball screw in this case) can be modelled independently in a simplified way using the Excel VBA program „crofsias“ (creation of simplified assemblies). In addition, boundary conditions such as free convection (calculated according to [3]) at the non-isolated surfaces are calculated with this Excel program and imported into the FE program ANSYS via the XML interface.

Parameter identification is not to be underestimated despite the determined replacement conductance. Among other things, material parameters of eight different materials were used in the relatively simple FE model. Since the manufacturers of the ball screw and the other test components used do usually not make the material parameters available, assumptions need partially to be made as well. Moreover simplifications in discretisation require an adaptation to the material parameters, which in turn makes it necessary to expand or change the calculation of boundary conditions or material parameters. For example, the relatively rough simplification of the ball screw nut's geometrical form requires to adjust the density by approx. $\Delta\rho$ = 30%. In addition, the calculations show that parameters depending on temperature have partially to be taken into account as well, not only when calculating free convection but also for the thermal conductivity of the insulating material. For example, the calculation also requires more than 20 connections, which have to be corrected based on empirical values and results from other experiments. Figure 3 shows the model of the thermally transient FE simulation after four hours of heating as well as a comparison between the calculated temperatures (broken line) and the values determined by experiment (continuous line) during the six hours. The maximum and mean deviation between simulation and experiment is 2.4 K and 1 K respectively.

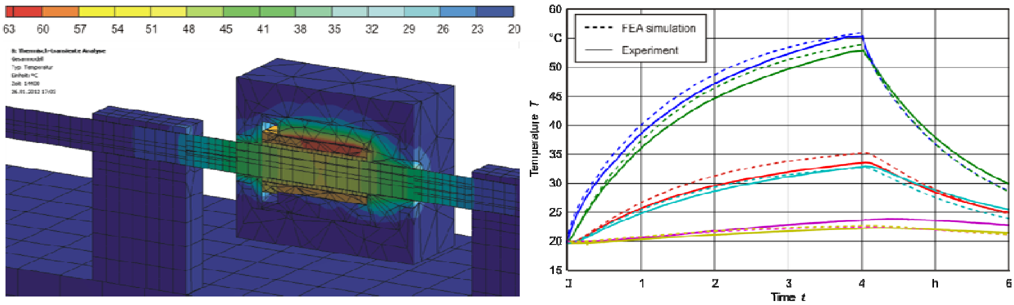

Figure 3. Final temperature of FE model (thermal-transient analysis) after four hours of heating (left) and comparison between measurement and simulation model after conducted parameter identification (right)

5. CONCLUSION

No information about thermal boundary and transition conditions such as the heat transition coefficient, described in this paper, is provided in literature or by manufacturers of machine elements. Hence, experimental analyses to establish the parameters are inevitable. The presented results of this paper show that parameter identification and model verification of a simple experiment for measuring the heat flow on a ball screw are not to be underestimated. It is nearly impossible to identify suitable parameters without taking account of boundary and transition conditions from other experiments. Mathematical methods support users in identifying parameters. Due to the complex machine element, the parameters desired can hardly be identified without an analytical calculation with a thermal nodal model. As presented here, the mean replacement conductance, taken from several values as determined by experiment, goes very well with the simulation value used in the transient FE calculation.

6. ACKNOWLEDGEMENT

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