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Uncertainties in Heat Loss Models of Rolling Bearings of Machine Tools

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Abstract

The mastering of the thermal behavior of machine tools is an important task to increase the machining accuracy. Tools that are progressively used for this task are models that simulate the thermal behavior of the machines. A main part of the models is the representation of heat loss processes. An example of these processes is the friction in rolling bearings. The model approaches available to describe the bearing friction show a high degree of uncertainty. The causes and consequences of these uncertainties are investigated on the example of the representative Palmgren friction model for rolling bearings. Thereby especially bearings on feed axes are considered. The results are quantitative statements regarding individual uncertainties. These can now be used to estimate the overall uncertainty of the model under specific operational conditions and model assumptions. This improves the understanding of heat loss modeling and will be the basis for future model enhancements.

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1. Mastering the thermal behaviour of machine tools

Mastering of the thermal behaviour of machine tools is an important task to increase its machining accuracy. This is due to the fact that a major part of the positioning errors that can cause machining accuracy are thermally induced [1].

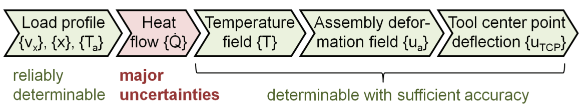

Fig. 1. Thermal causal chain of machine tools and modelling uncertainties

Causes of these errors are inner heat losses and variations of ambient temperatures. The coherences are shown in the thermal causal chain (Fig. 1). The beginning is the load profile of the machine. This is characterized by time varying axis positions $\{x\}$ and axis velocities $\{v_x\}$ as well as ambient temperatures $\{T_a\}$. The load profile initiates heat flows caused by ambient temperatures and heat losses. These heat flows change the temperature fields of the machine assemblies and lead to their thermo-elastic deformation. Due to the kinematic coupling of the assemblies a displacement between the work piece and the tool occurs and results in production deviations.

There are two measures to decrease the deviations that are different in principle. First there are compensatory measures, the aim of which is to influence the thermal behaviour in a positive way. Examples are the reduction of injected heat losses or of ambient temperature variations. Second, there are corrective measures, whose mode of operation permits the thermal processes including the assembly deformation. Thermal models are used to reproduce these processes. Based on a calculated thermal deflection, the error is corrected by applying offsets to the set values of the feed axes [2].

2. Thermal machine models and uncertainties of friction modeling

Essential for the presented measures are thermal machine models. They are used as an analysis tool for the design of compensatory measures as well as for the calculation of set values needed during controller-based correction. Thereby the

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models reproduce the complex accuracy-relevant thermal and thermo-elastic behaviour of the thermal causal chain [2]. A crucial part is the modeling of heat flows causing the temperature changes. This is typically done using empirical model approaches and shows high uncertainty (Fig 1).

Some of these heat flows are caused by inner friction of guiding elements. The model approaches for friction based heat losses show significant uncertainties. Without metrological adjustments the models can deviate 30 to 200 % from readings as investigations of rolling bearings show [3]. Due to a direct proportional correlation between the heat losses and resulting thermal deformations, the uncertainties of the calculated deformations are also significant [4]. Therefore the resulting statements in compensation and correction measures based on this type of models have also considerable uncertainties.

The aim of this paper is to enhance the understanding of uncertainty effects and its influences as a base for sufficient modeling of the thermal behavior as well as adequate interpretation of simulation results.

3. Uncertainty studies of rolling bearing models

The friction of guiding elements is studied on the example of pre-loaded and grease lubricated angular contact bearings. These bearing construction characteristics are common on machine tools. The focus is on fixed bearings of ball screw drives because these are one of typical main heat sources.

The friction modelling is based on the approach established by Palmgren [5]. It is one of the most used and investigated models for this type of bearings. Therefore a wide range of information on its application exists. The parameters are easily available in manufacturer information and in machine design data. Due to the low number of parameters there is little effort for parameterization. The accuracy of the friction prediction is not far behind and sometimes better than with other, more detailed approaches [3]. So altogether, the Palmgren approach provides a very efficient way to model and calculate friction.

4. Correlations of the Palmgren friction model

The heat loss $\dot{Q}_F$ generated by a bearing is calculated as the product of frictional torque M_F and rotational speed ω, whereby the frictional torque of rolling bearings can, according to Palmgren [5], be described by the sum of the two components M_0 and M_1 (units converted to SI-system):

$$\dot{Q}_F = M_F \cdot \omega = (M_0 + M_1) \cdot \omega \qquad (1)$$

$$M_0 = \begin{cases} 16 \cdot f_0 \cdot d_m^3 & , v \cdot \omega < 2 \cdot 10^4 \\ 4501 \cdot f_0 \cdot d_m^3 \cdot (v \cdot \omega)^{\frac{2}{3}} & , v \cdot \omega \geq 2 \cdot 10^4 \end{cases} \qquad (2)$$

$$M_1 = f_1(P_0) \cdot g_1 \cdot P_0 \cdot d_m . \qquad (3)$$

The component M_0 is a function of speed and has the following parameters: f_0 - characterizing the bearing design and lubrication mode, d_m - average diameter of the bearing and v - viscosity of the lubricant or in case of grease the viscosity of the base oil. Parameters of the load component M_1 are: f_1 – coefficient depending on bearing type and equivalent load (P_0), g_1 - actual load as a function of axial and radial forces and d_m - average bearing diameter.

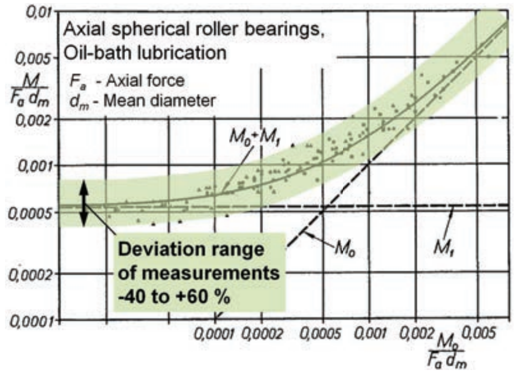

Fig. 2. Deviation of measurements based on [6]

The model is of empirical type, since it is based on correlative relations to measurement data, obtained from numerous experiments. The magnitude of uncertainty of the original Palmgen correlation is shown in Fig. 2. The typical variation of measuring points and the fitted curve of the approach is demonstrated with the example of axial spherical roller bearings. The deviations of the measuring points range from -40 to +60 % of the fitted curve. Because of missing information about the conditions of the studies, a deeper investigation of the causes of uncertainty is not possible in this particular case.

5. Model uncertainties considering operational conditions

The analysis of uncertainties outlined here addresses the friction behaviour under operational conditions on machine tool bearings. This behaviour includes the long-term effects of running-in and wear as well as the effects during machine operation because of varying outer loads and temperatures.

5.1. Influence of long-term effects

At first the effects of the long-term behaviour are investigated. There are no torque measurements known over the lifetime of grease lubricated roller bearings, measurements on preloaded profile rail guideways [7] are used instead (Fig. 3), since the friction processes are similar to roller bearings because of the balls as rolling elements. However, additional effects of ball recirculation only permit a partial transferability of the findings.

The measurements in Fig. 3 show a significant change of the frictional force in a running-in and a wear period compared to nearly no change during a relatively long period of constant friction. The magnitude of friction reduction in the running-in period can only be roughly estimated because of warming up effects in the beginning of the measurements. The wear period at the end shows a big impact. It accounts to