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IMPACT OF MEASUREMENT UNCERTAINTIES ON THE VALIDATION OF MIXED LUBRICATION SIMULATION

TRACK OR CATEGORY FLUID FILM BEARINGS II

AUTHORS AND INSTITUTIONS

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INTRODUCTION

The validation of the simulation of a journal bearing in mixed lubrication conditions with focus on friction is presented. Equality of the boundary conditions in simulation and experiment is required for validation. However, the boundary conditions cannot be measured with perfect accuracy and measurement uncertainties interfere with this requirement. Methods of the *uncertainty quantification* [1] are applied to identify and quantify the impact of the uncertainties. A probabilistic comparison of experiment and simulation is proposed to derive conclusions about the validity of the simulation models.

EXPERIMENT AND SIMULATION METHOD

The analyzed contact is shown in **Fig. 1**. The partial journal bearing is driven by an external driving shaft and lubricated with a low viscosity fluid. All contacts are immersed in a lubricant bath. The normal force, the lubricant temperature and the rotational speed of the driving shaft are controlled. The focus of the analysis lies on the friction between the roller and bushing. The friction is computed with a two-scale simulation approach [2, 3]. The impact of the roughness on the fluid flow is considered by using the flow factor theory of Patir and Cheng [4]. The flow factors are computed based on microscopic scans of the surface of the tested bushing and roller. The contact pressure curve is computed with the halfspace-theory [2]. The friction F_f in mixed lubrication is described by a solid and fluid friction component. It is computed by

$$F_f = \underbrace{\int_{\Omega} \mu_0 \, p_a(x,y) d\Omega}_{\text{solid friction}} + \underbrace{\int_{\Omega} \tau(x,y) d\Omega}_{\text{fluid friction}}$$

The fluid friction force is determined by the shearing τ of the lubricant. The solid friction is computed using the asperity pressure distribution $p_a(x,y)$ and a measured boundary friction coefficient $\mu_0(u_{sliding})$ depending on the sliding speed $u_{sliding}$.

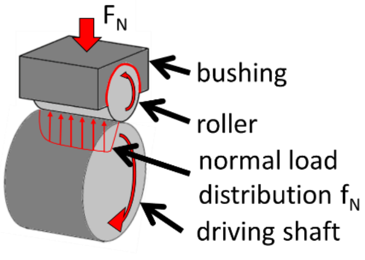

Fig.1: Experimental Setup

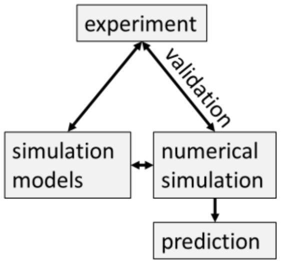

Fig.2: Scope of the uncertainty quantification [1]

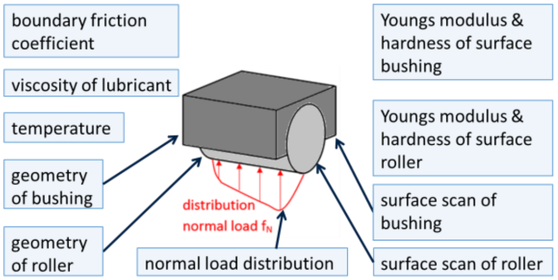

Fig.3: Measured boundary conditions of the analyzed setup

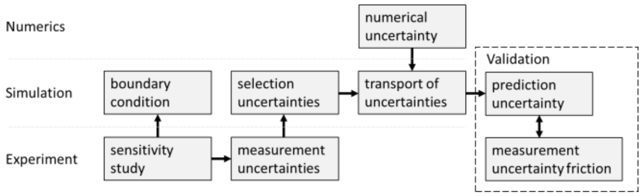

Fig.4: Workflow to identify and consider the uncertainties in the validation process

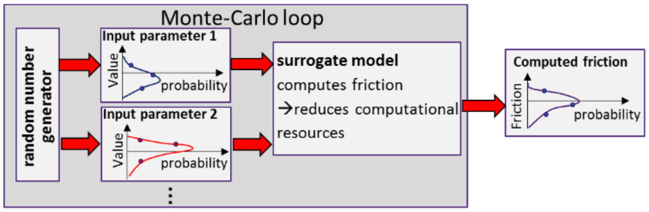

Fig.5: Computation of the transport of input uncertainties with a Monte-Carlo simulation

WHAT IS UNCERTAINTY QUANTIFICATION?

This research field deals with the impact of uncertainties in the experiment, the numerics and the models on the simulation prediction [1]. The interaction of these elements of the prediction process are illustrated in **Fig. 2**. The goal is to identify, quantify and reduce uncertainties in all three fields and to determine the overall uncertainty of the predictions. Uncertainty quantification was successfully applied to fields like meteorology, climatology, nuclear reactor design and computational fluid dynamics. To the best of the authors knowledge these methods have never been applied to tribological simulations.

HOW DO UNCERTAINTIES INTERFERE WITH VALIDATION OF MIXED LUBRICATION SIMULATION?

Numerical uncertainties arise from rounding errors, coding errors and approximation errors [1]. They lead to a divergence between the numerical approximated and the mathematical exact solution. **Experimental uncertainties** have two different effects: 1) The uncertainties of the simulation input parameters, which can typically not be measured exactly, are transported through the simulation model and lead to an uncertainly predicted friction. **Fig.3** contains the list of such input parameters. 2) The friction force itself can also be measured only with some uncertainty. This uncertainty in the measured friction force must of course also been taken into account when comparing experimental results and numerical simulation. As a consequence, the validation is inherently based on probabilities. The major goal of the validation is to identify and reduce **model uncertainties**, which lead to insufficient qualitative and quantitative predictions. Since the validation only gives a probabilistic result, the knowledge whether the simulation models represent the reality well is uncertain, too. This model uncertainty has to be considered in the prediction of friction in form of e.g. probabilistic model parameters.

APPLICATION OF THE UNCERTAINTY QUANTIFICATION ON THE MIXED LUBRICATION SIMULATION

Workflow

In **Fig. 4** the applied workflow is shown. The impact of the simulation inputs shown in **Fig. 3** on the friction was determined with an experimental sensitivity study. In this study the boundary conditions were varied and the effect on the friction was measured. The magnitude of the measurement uncertainty of the equipment used the measure the boundary conditions was determined with repeated measurements. Knowing the sensitivity of the boundary conditions and their measurement uncertainty allowed to select the parameters with the highest impact on the uncertainty of the predicted friction. To determine the probability density of the computed friction, the transport of the uncertainty of the simulation boundary conditions is computed with a Monte-Carlo-simulation (as sketched in **Fig. 5**). Finally a probabilistic comparison between the experiment and simulation for the validation is conducted.

Dealing with Numerical Uncertainties

These uncertainties are easy to identify and to reduce. Approximation errors were reduced with sufficient discretization derived from mesh convergence studies. The existence and influence of coding and rounding errors were excluded with comparisons to similar simulation software and analytical solutions. It was found that the numerical uncertainties can be neglected.

Computation of the Transport of the Input Uncertainties with Monte-Carlo-Simulation

A Monte-Carlo-simulation is used to compute the transport of the uncertainties through the model. The working principle is sketched in **Fig. 5**. A random set of input parameters is created by a random number generator. Afterwards the friction is computed based on this generated set of inputs. This procedure is repeated numerous times. The random input parameters follow a predefined probability density and the output probability density converges after a sufficient number of simulation runs. To reduce the required computational resources a surrogate model for the computation of the friction was developed. The working principle is shown in **Fig. 6** on the example

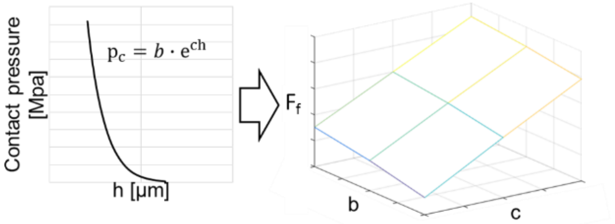

Fig.6: Principle of the surrogate model, shown on the example of the contact pressure curve

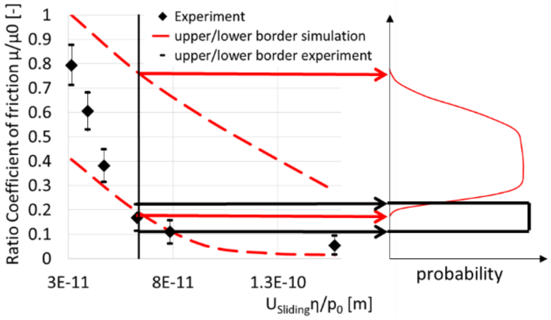

Fig.7: Simulation and experimental result: Probabilistic comparison between measurement and simulation, computed friction probability density with 1.1 million Monte-Carlo-runs

of the contact pressure curve. The computed contact pressure curves can be approximated with an exponential function in the form $b * exp(c * h)$ with b and c being curve parameters and h being the film thickness, as shown in **Fig. 6 left**. A parameter study with the numerical simulation is conducted varying the curve parameters b and c to compute a field of friction $F_f(b,c)$ (shown in **Fig. 6 right**). Analogue this concept is used for the flow factors and other parameters such as the viscosity. The surrogate model uses now the parameters b and c instead of the contact pressure curve as model input and simply interpolates the friction from the pre-computed interpolation fields. Test results show, that this surrogate model reaches a prediction accuracy of over 99% compared to the full numerical simulation.

Validation: Probabilistic Comparison between Experiment and Simulation

The measurement uncertainty of the friction was determined considering the errors of the sensors, tribological uncertainties such as wear and the reproducibility and repeatability of the test boundary conditions.

Fig.7 shows computed and measured Stribeck curves. Instead of one computed friction curve, the plots of the highest and lowest friction based on the most favorable and most unfavorable combination of the simulation inputs are shown. On the right side of **Fig. 7**, the computed probability density of the friction is shown together with the interval of the measured friction. For its computation the measurement uncertainties of the contact pressure curve, the pressure flow factor in circumferential direction, the boundary friction coefficient, the lubricant viscosity and the temperature were considered. The measured friction of the presented case is located at the lower border of the computed friction interval, which indicates an insufficient mixed lubrication model.

CONCLUSION

This contribution shows the application of methods of the uncertainty quantification on the validation of mixed lubrication simulation. The final result is the comparison between experiment and simulation shown in **Fig. 7**. The uncertainty of the computed friction due to measurement uncertainties of simulation inputs is higher than the uncertainty of the measured friction. A probabilistic comparison between experiment and simulation is required to assess the validity. The results also indicate that simulation input uncertainties have to be considered in further model improvement which uses even more input parameters derived from experiments.

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KEYWORDS

Friction Mechanisms, Fluid Mechanics Methods, Contact Mechanics