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Simulation of journal bearing friction in severe mixed lubrication – Validation and effect of surface smoothing due to running-in

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ABSTRACT

This paper focuses on the friction behavior of journal bearings operating from hydrodynamic to mixed lubrication regime where severe metal–metal contact occurs. Therefore, friction tests with two different static loads are carried out on the journal bearing test-rig from KS Gleitlager. The test results in the form of Stribeck curves provide a solid base to proof the isothermal elastohydrodynamic simulation approach. The simulation approach solves the averaged Reynolds equation introduced by Patir and Cheng and considers metal–metal contact by using the Greenwood and Tripp contact model. All necessary surface parameters are derived from surface scans. No less essential in this approach are the experimentally identified lubricant properties under high pressure and high shear rate.

The calculated friction torque matches the measurement results within the measurement uncertainty for a wide range of operation conditions. With the validated simulation approach the influence of surface smoothing due to metal–metal contact is discussed. Additionally, the limits of a constant boundary coefficient are identified and the effects of flow factors are presented.

1. Introduction

The mixed lubrication regime describes the transition between the pure hydrodynamic lubrication regime, where a fluid separates the contacting surfaces and the boundary lubrication regime, where metal–metal contact is leading. Characteristically for the mixed lubrication regime is that the fluid film cannot completely separate the adjacent surfaces and single asperities interact. Hence, the friction in mixed lubrication regime (mixed friction) is characterized by the co-existence of hydrodynamic and asperity friction [1]. The friction coefficient finds its minimum between the pure hydrodynamic lubrication and the mixed lubrication. In terms of friction reduction and efficiency it is beneficial to operate lubricated contacts in this condition. Unfortunately, wear occurs as asperities are in contact and durability problems can occur.

Especially in the automotive sector a trend to cut fuel consumption and emissions has been established which is driven by emission regulations and customer satisfaction. Downscaled turbocharged combustion engines with high power density are an achievement in modern engine development for performance improvement. The high power and small dimensions of engine components lead to highly loaded lubricated contacts such as journal bearings. Another efficiency benefit is pledged to friction reduction with low-viscous lubricants. These advancements lead to a decreasing oil film thickness in lubricated contacts. This means that journal bearings, which formerly mainly ran in pure hydrodynamic lubrication regime to ensure a long lifetime, may partly expose metal–metal contact during the dynamic operation [2–4].

For lubricated contacts, and particularly for journal bearings the Stribeck curve (see Fig. 1), named after Richard Stribeck [5,6], has become a common tool to assess friction benefits. A static load is applied to the journal bearing and the friction torque is measured for a wide speed range. With such a test configuration the different lubrication regimes can be identified. Bovington [7] describes the importance of the Stribeck curve in bearing design and discusses the effect of low-viscosity lubricant and oil additives. He conducted several tests with various engine oils which were formulated differently. More recently, the influence of surface dimple effects on journal bearing friction is experimentally studied [8] by evaluating the Stribeck curve. In the present study, a similar test setup is used for the measurements. The experimental results in the form of Stribeck curves provide a solid base to validate the simulation approach.

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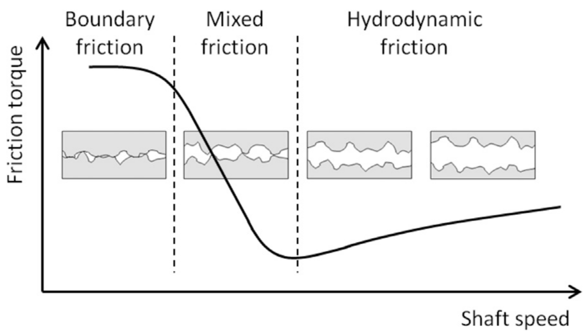

Fig. 1. Sketch of a Stribeck curve with different lubrication regimes.

Predictive simulation approaches to describe lubricated contacts in journal bearings are broadly discussed in the literature and differ in their level of detail. An overview of elastohydrodynamic lubrication analysis of conformal contacts without metal–metal contact is given by Booker et al. [9]. The extensive review focuses on the 2D Reynolds equation and discusses, among other things, bearing deformation, mass-conservative cavitation and pressure–viscosity effects. Also, the effect of surface roughness on bearing performance in elastohydrodynamic lubrication is discussed. Dobrica et al. [10] compare stochastic and deterministic models in more detail and conclude that the stochastic model correctly anticipate the trends of the deterministic models for the investigated surfaces. Both studies do not consider slip boundary conditions which is recently reviewed and discussed by Jao et al. [11]. Beyond the scope of this study is the 3D consideration of the fluid film using a computational fluid dynamics (CFD) approach [12]. Recently, Shahmohamadi et al. [13] present a thermo-hydrodynamic analysis using CFD approach including a vapor transport equation to consider cavitation. Both temperature and pressure distribution agree well with experimental data.

However, the interaction of single asperities between the contacting surfaces occurs in mixed lubrication regime and has an impact on journal bearing performance. Simulation approaches considering the asperity contact in journal bearings are covered in many text books, for instance [14–16]. Therefore, an extensive reference list is not replicated here.

Notably, only a minor number of publications discuss journal bearing friction in severe mixed lubrication and verify the calculated results with measurement results. Bartel et al. [17] present an analytical model considering metal–metal contact by using an energy approach. The calculated results were compared to measured Stribeck curves. The authors conclude that the viscosity–pressure behavior has a huge influence on the results and should not be neglected. Further, macro-deformation of shaft and bearing need to be considered for realistic friction prediction. Lu et al. [18] present a simple theoretical analysis for friction prediction in mixed and boundary lubrication regime and verified the analysis for different loads and temperatures. The tool is also used to investigate the effect of surface pattern and asperity orientation on Stribeck curves [19].

Wang et al. [20] present an analytical method to derive Stribeck curves and discuss the influence of roughness, elasticity, and thermoelasticity on friction. Especially the elastic deformation has a strong influence on the friction behavior. The influence of surface adaption caused by running-in wear on friction in dynamically loaded bearings is discussed by Bartel et al. [21]. Beside the change of surface roughness an adaption of the bearing geometry is calculated. A clear reduction of maximum contact pressure and friction is identified for the worn bearing. The influence of a worn geometry on journal bearing performance is also discussed by investigating misaligned bearings [22] and bearings subjected to numerous starts and stops [23]. Both papers conclude that a worn bearing geometry decreases the bearing temperatures. Sun et al. [24] calculate the effect of surface roughness change on misaligned journal bearings and highlight the importance of elastically deformation of the contacting bodies. However, no contact model is implemented to discuss friction due to asperity interaction.

The present study focuses on friction losses in journal bearings operating in severe mixed lubrication regime. The analytical investigation uses an isothermal mixed elastohydrodynamic simulation approach which considers the elastic deformation of shaft and bearing structure. Although the temperature is assumed to be constant within the bearing, the variation between different loads and shaft speeds is considered with introducing an equivalent bearing temperature. The equivalent bearing temperature is derived from temperature measurements at the back of the bearing shells. Additionally, the piezoviscous and non-Newtonian behavior of the lubricant are included in the approach. The equation describing the lubricant viscosity is dependent on temperature, pressure and shear rate and was previously derived by measurement. The detailed derivation of the viscosity equation was published in [25] and validated for dynamically loaded journal bearings operating in mainly hydrodynamic regime.

The influence of asperities on hydrodynamic friction is included by using the flow factors according to Patir and Cheng [26,27]. Friction due to metal–metal contact is considered by the Greenwood and Tripp contact model [28]. To derive the parameters for both, flow factors and contact model, bearing shell surface and shaft surface were scanned by white light interferometry. From the surface scans roughness parameters and asperity orientation are established. The boundary friction coefficient is the remaining unknown parameter which is chosen to be constant in this work.

Primary aim of this study is the validation of the simulation approach to calculate journal bearing friction in severe mixed lubrication regime. Further, the practicability and limits of the simple elastic Greenwood–Tripp contact model in combination with a constant boundary friction coefficient is discussed.

For a secondary aim, the influence of surface smoothing due to running-in on friction in mixed lubrication is discussed. Therefore, a ran-in journal bearing surface is analyzed and a second contact model is derived. The influence on metal–metal contact pressure, minimum radial clearance and friction is analyzed.

Further, the exclusion of the flow factors from the simulation and its effect on journal bearing friction is discussed.

Moreover, the presented study complements previous research by the authors which focused on journal bearing friction excited by dynamic loads. Allmaier et al. [29,30] presented a simulation approach using an isothermal bearing assumption. He included the viscosity–pressure relation for different single-grade lubricants and validated the friction losses over a wide range of operation conditions. Metal–metal contact was identified by simulation and also by measuring the contact voltage [31]. Later, the isothermal model was extended to a thermo-elastohydrodynamic model [32] which is able to predict the measured temperatures at the bearing shell. The results also justified the usage of an isothermal simulation approach in terms of friction prediction. Sander et al. [25] included the non-Newtonian behavior of modern multi-grade engine oils into the isothermal simulation approach. Again, the simulation results were validated for a variety of shaft speeds and dynamic loads up to 100 MPa specific load in the test bearing. After the test procedure worn areas on the bearing surface were identified which was caused by metal–metal contact. Metal–metal contact was also identified by simulation. As a consequence research on the running in process of journal bearings was conducted [33,34]. Complementary, the presented results are obtained from the same simulation approach yet discuss friction in severe mixed lubrication regime.