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MIXED AND BOUNDARY LUBRICATION IN ROLLING CONTACT: EXPERIMENT AND SIMULATION

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Abstract. *A new model of mixed lubrication is proposed in the frame of the Method of Dimensionality Reduction (MDR). In this model the dynamic lubricated rolling contact between rough surfaces is simulated based on the results from elastohydrodynamic lubrication (EHL). In order to account for the break-up of the additional boundary layer on a local micro contact area, a supplemental criterion is imposed. For comparison, a twin-disc test rig is set up to measure the electrical resistance between two lubricated rolling surfaces under different normal forces, rotation speeds and temperatures. We have investigated the probability of boundary layer breakthrough for both experiment and simulation and found good agreement.*

Key Words: *Lubricated Contact, EHL, Electrical Resistance, Mixed Lubrication, MDR*

1. INTRODUCTION

Countless examples in mechanical engineering require lubrication between components that are in relative motion. On the one hand, it is known from experience that practically no wear at all occurs when these components operate under conditions, where the surfaces and their roughness features are completely separated by a fluid film. On the other hand, current trends in engineering are at a disadvantage to the creation of a fluid film:

- Downsizing mechanical components demand for higher pressures
- Low-viscosity oil increases efficiency but decreases film thickness
- Start/stop cycles force the system through low-speed relative motion

As a consequence, it is common practice for mechanical components such as gears, bearings and cams to operate in a mixed lubrication mode. Typically the surface roughness

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of contacting bodies is of the same order as the lubricant film thickness, so that the top micro roughness features (asperities) will enter into contact and part of the load and shearing will be carried by these asperity contacts. Under this regime, a multitude of wear and damage types can occur. In experiments the contact condition for a lubricated system can be observed by measurement of electrical contact resistance R_c which is expressed as [1].

$$\frac{1}{R_c} = \frac{\sum 2a_i}{\rho} = \frac{L_{con}}{\rho} \tag{1}$$

where ρ is the resistivity of contacting materials and a_i is the radius of each single contact spot. L_{con} is the total resulting contact length and defined as the sum of contact diameters. In the case of full hydrodynamic lubrication, the rough surfaces are completely separated by the lubricant film, so the resistance measured will be very high. In contrast, when the asperity contacts carry a major part of the load, a large number of contact spots are formed, thereby decreasing the electrical resistance dramatically.

What makes the mixed lubrication problem difficult is the necessity to handle both hydrodynamic lubrication and asperity contacts. The earliest way of modeling mixed lubrication took into consideration the influence of roughness in hydrodynamic systems where the film thickness was considerably larger than the roughness [2]. In 1970s Tallian and Johnson considered both asperity contact and hydrodynamic lubrication. Tallian studied the cases where asperities deformed elastically and plastically while Johnson considered only the elastic deformation based on the Greenwood and Williamson model [3][4]. Later micro-EHL models and combined micro-EHL and asperity contact models included the interaction of surface roughness, film thickness and pressure [5]. A stochastic analysis was developed by Zhu and Cheng (1988) [6]. It combined Patir and Cheng's average flow model (1978) [7] for hydrodynamic lubrication and Greenwood and Tripp's load compliance relation (1970) [8] for asperity contacts. With the rapid development of numerical simulation techniques and faster computers, researchers were able to investigate more complicated lubrication problems. Therefore, more realistic transient, rough surface, thermal and non-Newtonian lubrication problems were studied in the past decade. A deterministic model for mixed lubrication in point contacts was developed by Jiang et al. (1999) and the contact between asperities was studied when they moved through the EHL region [9]. Wang et al. (2004) [10] developed a thermal model for mixed lubrication in point contact. In this paper we have tried a simple mixed-lubrication model and compared its results with experiment.

2. Numerical Model

We deal with the lubricated rolling contact between rough surfaces of cylinders where a boundary layer is present on the two surfaces. Most non-conforming lubricated contacts such as roller bearings, journal bearings, cam and followers or gear teeth can be viewed as such systems.

We will impose a new model for the micromechanical contact between asperities including the physically or chemically absorbed boundary layer (Fig. 1) and apply it to the conditions found in lubricated rolling contacts.

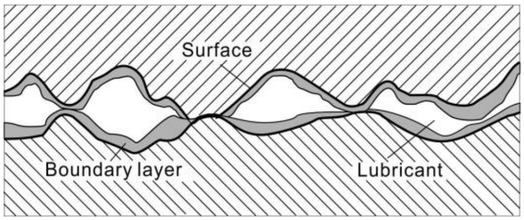

Fig. 1 Schematic contact between two cylinders and its view of contact area in micro scale. Surfaces may either have a positive gap width when separated by a boundary layer or they can be in intimate contact. The contact conductance only has a considerable value, when there is intimate contact, or the boundary layer has decreased to molecular scale

The contact between two elastic cylinders is known for having equivalent in the contact between a rigid plane and an elastic cylinder with equivalent modulus of elasticity $\frac{1}{E^*}=\frac{1-\upsilon_1^2}{E_1}+\frac{1-\upsilon_2^2}{E_2}$ and radius $\frac{1}{R^*}=\frac{1}{R_1}+\frac{1}{R_2}$, where E_1 and E_2 are moduli of elasticity, υ_1 and υ_2 are Poisson's ratios, R_1 and R_2 are radiuses of both cylinders. According to Hertzian contact theory, the contact width *2a* under load F_N is equal to

$$a=\sqrt{\frac{4F_N R^*}{\pi L' E^*}} \tag{2}$$

where L' is length of cylinder. For elastohydrodynamic lubricated rolling contact the bodies are separated by an oil film and its thickness over whole contact area *2a* is almost uniform, except for the trailing edge where a small decrease in the film thickness occurs. A common formula of central film thickness is given by Hamrock from numerical studies [13]

$$h_0=\frac{2.992\alpha^{0.470}(\eta_0 v)^{0.692}R^{*0.474}}{(F_N/L')^{0.166}(2E^*)^{0.056}} \tag{3}$$

where v is mean surface velocity $v=(v_1+v_2)/2$. The values of η_0 (viscosity at atmosphere pressure) and α (pressure-viscosity coefficient) are properties of the lubricating medium and are usually temperature-dependent. Thus in a case of a known operation scenario, the film thickness excluding roughness can be calculated.

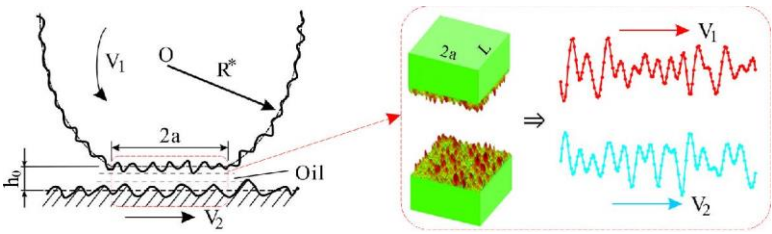

Fig. 2 Reduced model for lubricated contact. The original 3D problem consists of two rough opposing bodies with a clearance stemming from the lubricant film. Surfaces constantly move tangentially, so that new asperity contacts may form. The problem is transformed with the MDR onto two one-dimensional rough lines

The lubricated contact area in three dimensional (Fig. 2) consists of two moving rectangles with width $2a$ and length L that are separated by an oil film with average distance h_0 where some asperity contacts may take place.

We treat the contact problem in this zone by using the dimensionality reduction method proposed in 2007 by Popov and Geike [11]. It has some major advantages in computational complexity compared to other methods that can simulate asperity contact. It maps three-dimensional contact problems onto one dimension and eliminates the elastic coupling, so that the computing time is dramatically reduced. In the past few years it has been developed for many contact problems, such as elastic and viscoelastic contact, normal and tangential contact including rough contact [12].

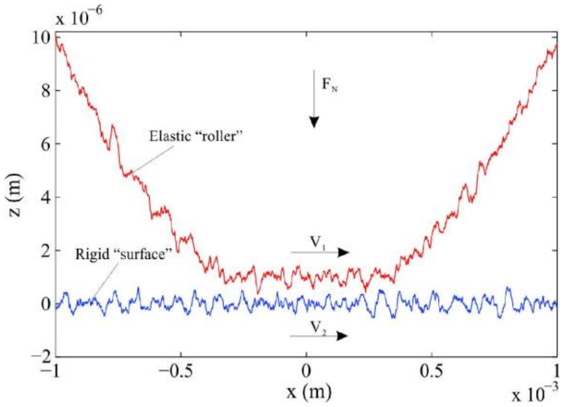

Fig. 3 One-dimensional contact between an elastic 'roller' and a rigid body. The mean gap width between both is obtained by the EHL theory, the resulting micro contacts are analyzed by means of the MDR

Coordinates x and z are seen in Fig. 3. The average of the rough rigid profile is assumed to be zero and the rough roller is a superposition of a parabolic line and roughness. The roughness has power spectral density $C_{1D} \propto q^{-2H-1}$, where q is the wave vector and H is the Hurst exponent. In this paper, the lines are generated with 10^6 points, corresponding to the perimeter of the roller used in experiments. The spectral density is defined from $q_{\min} = 2\pi / 2a_{\max}$ to $q_{\max} = 2\pi / 10\Delta x$, where $a_{\max}$ is half the contact width and $H = 0.7$. From the results of EHL, the macroscopic shape of the 'parabolic line' in the interval $[-a, a]$ is assumed to be flattened out and the average distance between the elastic 'roller' and the rigid profile is equal to the thickness of oil film h_0. With applied normal force F and rotation speed v_1 and v_2 (and also temperature), the value of contact width $2a$ and film thickness h_0 can be calculated according to Eq. (2) and Eq. (3). Therefore, the initial contacting profiles at $t = 0$ are determined. Then, the points on the lines enter and transit through the contact width with different velocities v_1 and v_2. At each time step we check the contact condition. It can be easily observed that some points are in geometrical contact (Fig. 4), but in this paper we consider the boundary layer between two contacting bodies; therefore, based on this geometrical contact, the failure of boundary layer must be calculated.

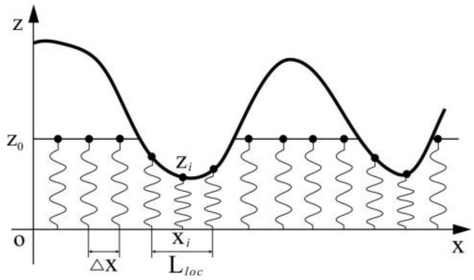

Fig. 4 One-dimensional model for the deformation of an elastic body. The 3D surface topography is transformed to give an equivalent line. The indentation of the rough line must be done with densely packed, independent springs

For the break-up of the boundary layer, we consider the model of a perfectly plastic material. It is known [14] that if two plates with radius R are pressed together under normal force F_N and separated by a layer of material with low limiting shear stress τ_0, a film remains with thickness

$$h = \frac{2\pi}{3}\frac{\tau_0 R^3}{F_N}. \tag{4}$$

According to the rules of MDR [12], the elastic body is modeled as a series of parallel springs with the normal stiffness $\Delta c = E^* \Delta x$, where Δx is the discrete step (Fig. 4). The force on each 'spring' is defined as

$$f(x_i) = E^* \cdot \Delta x \cdot \Delta z(x_i). \tag{5}$$

Here Δz is the displacement of indentation. In the reduced model Eq. (4) is written as

$$h_l = \frac{\pi\tau_0}{12}\frac{D_l^3}{F_l}. \tag{6}$$

Here D_l is the local contact length and equal to Δx times the number of contacting points and F_l is the normal force on this local area and equal to $F_l = E^* \Delta x \Sigma \Delta z_i$ from Eq. (5). For each "geometrical contact" if value h_l calculated according to Eq. (6) is smaller than the critical thickness of boundary layer h_c, the layer is defined as broken up while asperities are in intimate contact. The boundary layer thickness due to adsorption and chemical reactions is about 1...10 nm [15]. In the simulation we considered h_c = 5nm and $\tau_0 = 10^6$ Pa.

In a single operation case, the change of total contact length on time is recorded as Fig. 5 (a). It is seen that at some moments there is no asperity in contact at all. Based on it a general contact condition in this operation case can be obtained from it, which is named the probability of boundary layer breakthrough in the paper and calculated as time percentage when real contact occurs. In a well lubricated condition, the probability is close to zero.

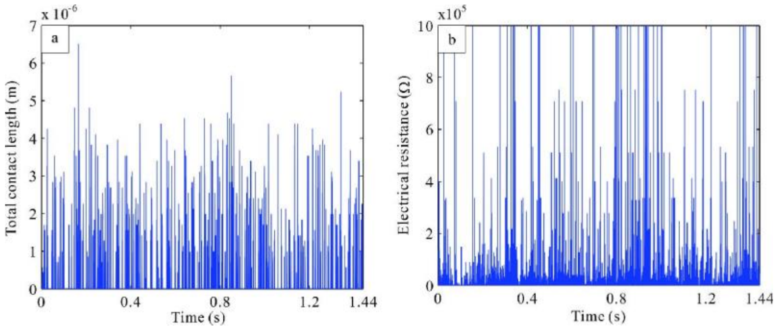

Fig. 5 (a) Contact length over time, data extracted from MDR simulation; (b) electrical resistance over time from experiment data. Parameters: $800\ \mathrm{N}$, $100\ \mathrm{r/min}$ and $40\ ^\circ\mathrm{C}$

3. EXPERIMENT MEASUREMENT

A twin-disc test rig is used (Fig. 6) is used for validating the results obtained from simulation. Two identical cylinders (radius $R = 0.05$ m, width $L' = 0.01$ m, roughness $\sigma = 0.2\ \mu$m) are pressed together and rotated at identical speeds so that pure rolling occurs. A synthetic lubricant is constantly fed into the contact zone; Mobilgear SHC XMP 320 is used because of its wide usage in highly loaded wind turbine gear boxes. The whole test setup can be heated to give stationary temperature for the rollers and the injected oil.

We have measured electrical resistance between the two rollers for a range of operating parameters: The normal force is varied from 100 to 1600 N, rotation speeds from 86 to 200 r/min and temperatures from 40 to 80 $^{\circ}$C.

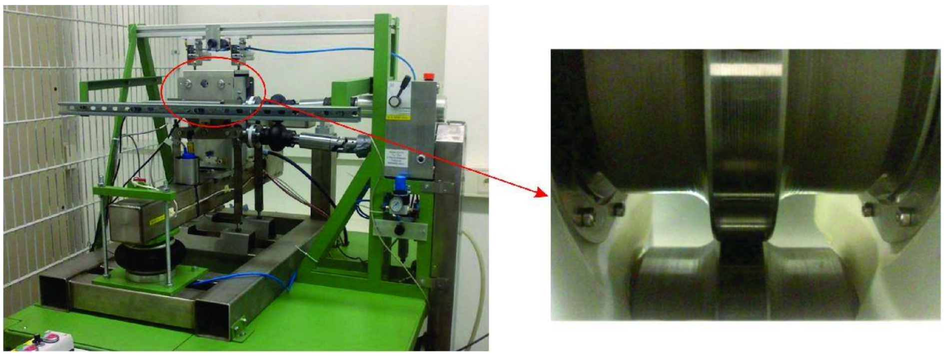

Fig. 6 Experimental setup. The left hand side shows the overall test rig. Inside the aluminum block, there are two rollers, driven by external drive shafts. The lower block can be lifted pneumatically to exert a normal force. The right hand side shows a picture of the two rollers in contact without lubricant

Fig. 5 (b) shows a typical sample of the time-dependent resistance measurement. It can be seen that the contact condition rapidly changes from states of good conductivity to very high resistance.

In order to compare the results quantitatively, we have used the classical approach of contact probability [16]. We calculate the percentage of time, for which the electrical resistance is measured to be below 100 Ω. Whenever this is the case, we consider the surfaces to be in contact and the electrical current can flow through the contact spots; otherwise they are separated by a lubricant film. We compare this probability of contact to the simulated one of the boundary layer breakthrough from the 1D model.

4. RESULTS

There are totally 125 operation cases in both simulation and measurement. Fig. 7 (a) shows the simulated breakthrough probability as a function of the temperature. In Fig. 7 (b) the experimental contact time probability for the same scenarios are shown. For reason of clarity, not all the cases are included. It can be seen that the contact probability increases

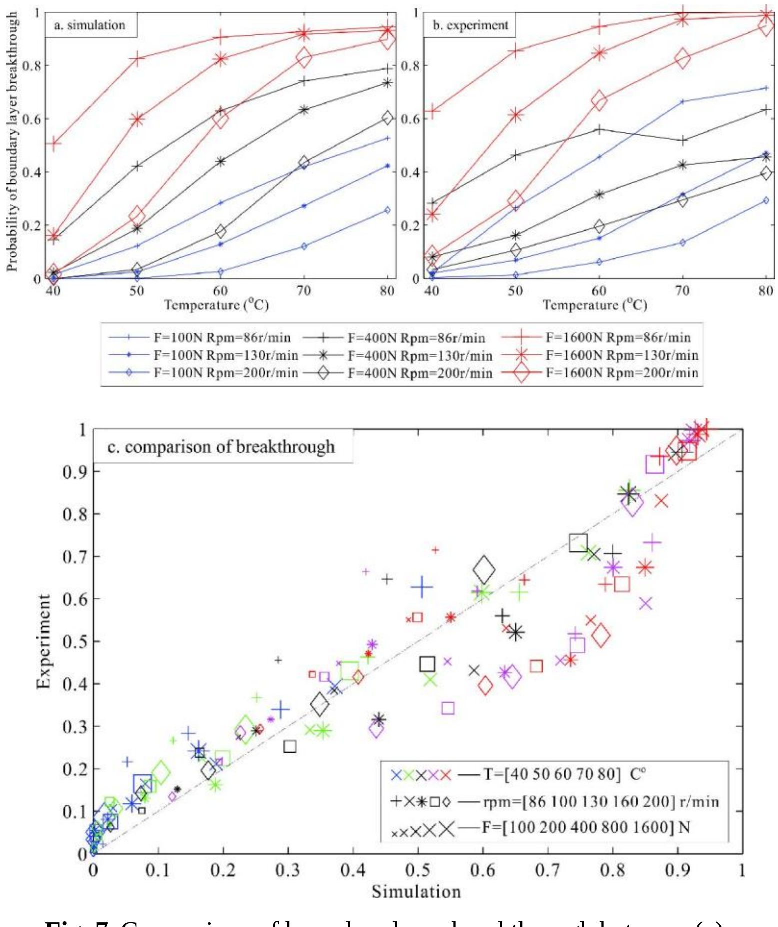

Fig. 7 Comparison of boundary layer breakthrough between (a) simulation and (b) experiment (c) with all data.

with temperature and load but decreases with rotation speed in both investigations. Fig. 7 (c) gives a direct comparison for the probability of boundary layer breakthrough between simulation and measurement. Good agreement can be found qualitatively and quantitatively in most cases.

5. CONCLUSIONS

The method of dimensionality reduction is used to simulate the process of lubricated rolling contact between rough surfaces. A novel criterion for the breakthrough of the chemical or physical boundary layer is introduced, based on the assumption of perfectly plastic material behavior. Using this criterion, the breakthrough probability under different working conditions is predicted and compared to experimental findings. The obtained results show good agreement.

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MEŠOVITO I GRANIČNO PODMAZIVANJE PRI KONTAKTU VALJANJA: EKSPERIMENT I SIMULACIJA

Predlaže se jedan novi model mešovitog podmazivanja u okviru metode redukcije dimenzionalnosti ili MDR-a. Kod njega se dinamički podmazani kontakt valjanja između grubih površina simulira na osnovu rezultata elastohidrodinamičkog podmazivanja (EHL-a). Da bismo objasnili prekid dodatnog graničnog sloja na lokalnoj mikrokontaktnoj površi uvodimo i dopunski kriterijum. Upoređenja radi, postavlja se testirna oprema od dva diska radi merenja električnog otpora između dve podmazane valjane površine pod različitim normalnim silama, rotacionim brzinama i temperaturama. Ispitali smo verovatnoću proboja graničnog sloja i za eksperiment i za simulaciju i utvrdili dobro slaganje.

Ključne reči: *podmazani kontakt, EHL, električni otpor, mešovito podmazivanje, MDR*