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The Beneficial Effect of Hydrophobic Coating on the Hydrodynamically Lubricated Bearing Performance

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Abstract

In lubricated sliding contact such as bearing containing moving components, there is a need to achieve low friction and high load support by lubrication. However, many researches were focused only on how to improve the lubrication by texturing surfaces of the lubricating siding contact. Only few works dedicated to the application of the slip on the surface resulted from the hydrophobic coating. In this study, the modification of surface in the lubricated sliding contact by applying the hydrophobic coating is of particular interest. The numerical simulations based on a modified Reynolds equation are performed. It is found that the hydrophobic coating has a significant effect in altering the tribological performance of the bearing. It is also confirmed that in a lubricated system, if one of the lubricated surfaces is introduced with an optimal hydrophobic configuration, a higher load support as well as the flow rate with a reduced friction force can be achieved.

Keyword: flow rate, friction, hydrophobic, load support, lubrication, wall slip

INTRODUCTION

Bearings are widely used, and nowadays, bearings have become more sophisticated and more stringent design and longevity requirement. In such devices, the temperature and stress are stretched to the material limit. Bearings contain rotating and/or sliding elements. Hence, the requirement for protection of moving surfaces in bearings became more than a casual interest. The use of a lubricant could avoid direct contact between the surfaces, so the friction and wear can be reduced.

In classical liquid lubrication, it is assumed that surfaces are fully wetted and no-slip occurs between the fluid and the solid boundary. In bearings, this wetting is actually an unwanted process because it can encourage the occurrence of stiction (static friction) and as a result parts of the bearing cannot be moved [1]. Currently, many workers attempted to solve the stiction problem by introducing the hydrophobic coating on the opposing surfaces. When one or both surfaces are not wetted by the fluid, wall slip may occur due to weak bonding between the fluid and the solid surface, which reduces the shear stresses in the fluid adjacent to the non-wetted surface. There was a considerable study in micro bearing with the aim to utilize a hydrophobic coating in order to reduce viscous drag. However, the next main concern is how the hydrophobic coating can affect the lubrication performance, such as the friction force and the load support when there are some low loads applied externally. Spikes [2-3] proposed a possible means of reducing the friction in liquid-lubricated bearings by making one nearing surface hydrophobic while the other hydrophilic, so that the liquid slips against the former under shear but adheres to the latter. Hild et al. [4] examined the influence of wettability on the friction force. It was shown that the Newtonian friction law breaks down for hydrophobic surfaces. The friction force becomes significantly smaller in the hydrophilic-hydrophobic interaction than in the same property interaction. The same result was shown by Choo et al. [5]. Their experiments were conducted using a tribometer to show the effect of wettability on the friction coefficient between two shearing surfaces lubricated by an aqueous glycerol solution. The results obtained with two hydrophilic contacting surfaces were found to be consistent with hydrodynamic theory. It means that no-slip occur at these surfaces. From the experimental validation, they found that a reduction in the friction force occurs when one surface was made hydrophobic and the other was hydrophilic. It should be pointed out that these studies mainly focused only on one parameter, i.e. the friction force. Only little attention was paid to the effect of hydrophobic to the load support [6-8]. In engineering application, there is very high possibility that hydrophobic coating causes a friction force reduction, although at the same time the hydrophobic coating may produce a small hydrodynamic response. In lubricated bearing, low friction force and high load support are the goals which want to be achieved.

In the present study, the effect of hydrophobic coating on the hydrodynamic performance (i.e. load support, friction force, and flow rate) in bearings will be examined by means of

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numerical analysis. As a note, according to the published works, for example [9-11], the configuration zone of the hydrophobic coating has a significant role in improving the performance. Therefore, in the present study, hydrophobic coating will be placed in optimal position which in previous works [8-11] revealed a reduction in friction force due to the presence of slip resulted by hydrophobic property. The optimal position here means that one of the contacting surfaces will have one region with hydrophobic coating and another region without hydrophobic coating. The hydrodynamic load support, the flow rate and the friction force of the hydrophobic bearing will be compared from the analysis with conventional bearing.

MODIFIED REYNOLDS EQUATION

Suppose a lubricated sliding contact on micro-scale as shown in Fig. 1. On the surface 2, which has a rectangular area, hydrophobic coating is applied as a partial condition. Surface 1 is conditioned as no-slip boundary. The height of the fluid film separating the two surfaces is assumed to be a linear function of *x*.

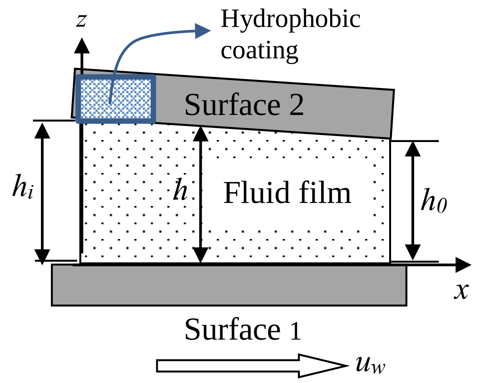

Figure 1: Schematic of a lubricated sliding contact with wall slip

The great challenge for a hydrophobic surface from the perspective of a numerical simulation is choosing a model for the boundary slip. For nearly two hundred years ago, Navier [12] proposed that the slip velocity is proportional to the shear rate at the wall with a slip length, β , being a constant.

$$u_S = \beta\eta \frac{\partial u}{\partial z} \tag{1}$$

where u_s is the slip velocity, η the dynamic viscosity and $\partial u / \partial z$ the shear rate.

The derivation of the classical Reynolds equation with a Newtonian lubricant is based on the assumption of no slip between the lubricant and the surfaces. The model of lubrication presented here is based on the fact that slip at the interface between lubricant and surface will exist. The proposed wall-slip model leads to a modified Reynolds equation. In the present work, the proposed model as well as the steps of derivation of such mathematical model is similar to the lubrication model published by Tauviqirrahman et al. [10]. Such a lubrication system can be described with the modified Reynolds equation as follows:

$$\frac{\partial}{\partial x}\left(h^3 \frac{h^2 + 4h\eta\left(\alpha_a + \alpha_b\right) + 12\eta^2\alpha_a\alpha_b}{h\left(h + \eta\left(\alpha_a + \alpha_b\right)\right)} \frac{\partial p}{\partial x} \right) = 6\eta U \frac{\partial}{\partial x}\left(\frac{h^2 + 2h\alpha_a\eta}{h + \eta\left(\alpha_a + \alpha_b\right)} \right)$$

$$-6\eta\tau_{ca} \frac{\partial}{\partial x}\left(\frac{\alpha_a h(h + 2\alpha_b\eta)}{h + \eta\left(\alpha_a + \alpha_b\right)} \right) + 6\eta\tau_{cb} \frac{\partial}{\partial x}\left(\frac{\alpha_b h(h + 2\alpha_a\mu)}{h + \eta\left(\alpha_a + \alpha_b\right)} \right) - 12\eta U \frac{\alpha_a\eta}{h + \eta\left(\alpha_a + \alpha_b\right)} \frac{\partial h}{\partial x}$$

$$\frac{\partial}{\partial x}\left(h^3 \frac{h^2 + 4h\eta\left(\alpha_a + \alpha_b\right) + 12\eta^2\alpha_a\alpha_b}{h\left(h + \eta\left(\alpha_a + \alpha_b\right)\right)} \frac{\partial p}{\partial x} \right) = 6\eta U \frac{\partial}{\partial x}\left(\frac{h^2 + 2h\alpha_a\eta}{h + \eta\left(\alpha_a + \alpha_b\right)} \right)$$

(2)

The modified Reynolds equation (Eq. (2)) is discretized over the flow using the finite volume method, and is solved using tridiagonal matrix algorithm (TDMA). By employing the discretization scheme, the computed domain is divided into a number of control volumes using a grid with uniform mesh size. The grid independency is validated by various numbers of mesh sizes. An assumption is made that the boundary pressures are null at both sides of the contact. However, the Reynolds cavitation model is adopted.

The simulation results will be presented in dimensionless form, i.e.

$$W = wh_i^2 / (U_1\mu L^2) \tag{3}$$

$$F = fh_i / \mu U_1 L \tag{4}$$

$$QY = q / hU_1 \tag{5}$$

W is denoted for dimensionless load support in which *w* is the load per unit length, and μ = the lubricant viscosity. The load support is determined by integrating the calculated hydrodynamic pressure. F is denoted for dimensionless friction force (where f is the unit width friction force). In this case, the shear stress at the stationary surface is integrated to determine the friction force. Finally, Q is denoted for dimensionless volume flow where q is the unit width volume flow.

RESULTS AND DISCUSSIONS

Figure 2 shows the influence of the sliding velocity on the load support W for two conditions, i.e. slip and no slip. It can be seen that increasing the velocity increases the load support. The simulation results show that the application of hydrophobic coating gives a positive effect in improving the load support for all value of the sliding velocities. This is as expected because the hydrophobic coating which induces the wall slip changes the pressure gradient to be larger.

Figure 3 depicts the effect of the sliding velocity of the flow rate Q_Y. It can be observed that the hydrophobic coating accelerates the flow rate of the lubricant entering the inlet of the lubricated sliding contact. Consequently, the lubricant increases the pressure hydrodynamic and thus loads support. This phenomenon is not found if the surface has a classical surface, that is, no slip coating.

Figure 4 reflects the effect of the sliding velocity of the friction F. The friction supported by the surface with wall slip shows a lower load than those without slip. It achieves a friction that is 0.5 times that of the surface with no-slip boundary. Therefore, for the lubricated sliding contact on micro-scale, if surface is conditioned as a partial slip boundary, the positive effect can be found. Similar to the load support, the wall slip decreases the friction force. The reduction of this friction is an advantage effect for bearing lubrication. The friction force increases linearly with the sliding velocity. Friction is found to be lower for the contact with slip than those without. This finding is consistent with the previous result which stated that fully slip reduces both the hydrodynamic pressure and the friction force on the surface contact over the entire velocity range.

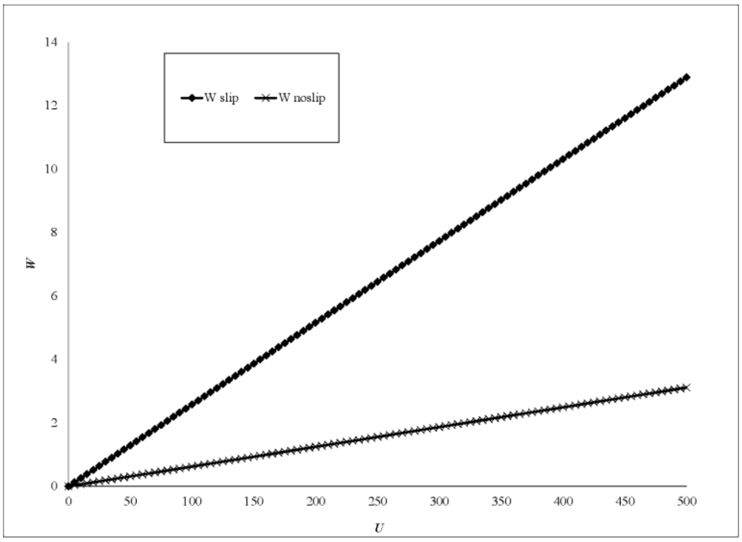

Figure 2. Effect of the sliding velocity, U, on the load support, W

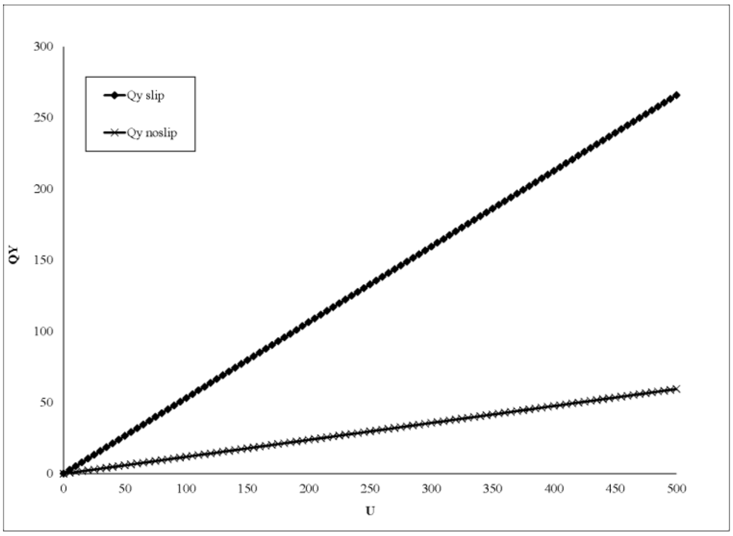

Figure 3. Effect of the sliding velocity, U, on the flow rate QY

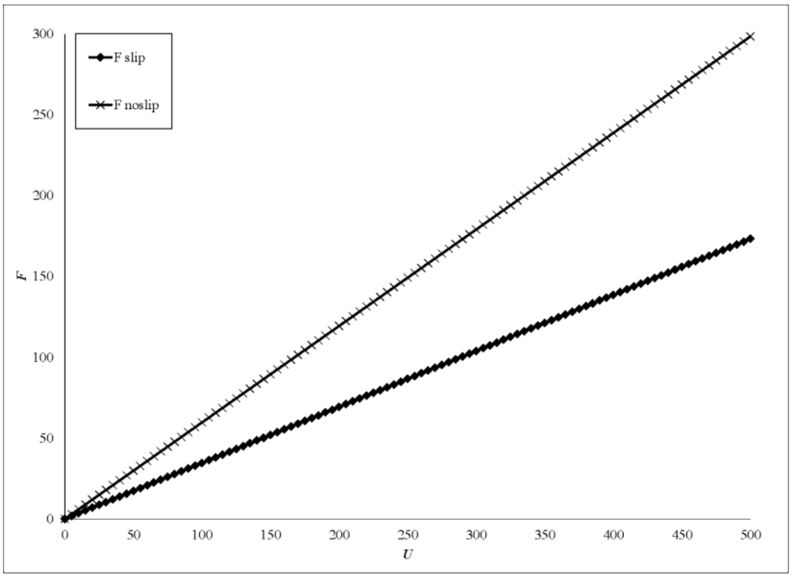

Figure 4. Effect of the sliding velocity, *U*, on the friction force *F*

CONCLUSIONS

This study demonstrates the effect of hydrophobic coating on friction force, flow rate and the load support. Numerical results obtained and reported in this paper show that the hydrodynamics of a lubrication film confined between a no-slip surface and a slip surface differs significantly from that of a film confined between two no-slip surfaces. It is found that it is very advantage to make one of the contacting surfaces in bearing with hydrophobic coating for achieving ideal lubrication performance, i.e. reduced friction, increased load support, and flow rate.

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