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Full and partial boundary slippage effect on squeeze film bearings

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ABSTRACT

Simple experiments were carried out to illustrate the effect of the boundary slippage on the load capacity of a squeeze film. The surface energy of the bearing surface was modified using laser excimer (UV laser). It was found that the load capacity can be reduced if the surfaces are modified to be hydrophobic. The boundary slippage effect on squeeze film was further studied theoretically to get more insight. The paper presents a mathematical model with a critical shear-stress criterion of slippage to describe the squeeze film effect. Three types of slippage, i.e. single zone partial slippage, single zone full slippage, and double zone partial slippage, are modeled. The analytical solution shows that the pressure distribution is a piecewise parabolic curve, where the pressure gradient can be discontinuous at the border of the slip and no-slip regions. Parametric studies illustrate the variations of the pressure and the boundary slippage under different conditions. It is demonstrated that with the increase of the length of the hydrophobic region, the maximum pressure does not increase continuously. Similar to the classical squeeze film bearing, the pressure decreases with the increase in the film thickness or the decrease in the approach velocity. The influences of the critical shear stress are also explored, and are found to significantly affect the squeeze behavior.

1. Introduction

The velocity or no-slippage boundary condition, which specifies no relative motion between a solid surface and a liquid immediate adjacent to it, is a core concept in fluid mechanics. It has been employed almost universally in macroscopic analyses in the fluid mechanics [1]. However, for more than a century, evidence has been presented to show that the no-slippage assumption may not always hold. For non-Newtonian polymer melts of high molecular weights, boundary slippage has been well verified through a variety of experiments, and the extent of slippage is proposed to be stress dependent. A detailed review can be found in [2]. For simple Newtonian fluids, early studies were most concerned with the capillary flow measurement of liquids and showed that the rate of liquid flow can exceed that predicted by conventional hydrodynamic theory if the wall of a capillary of a small diameter is repellent to liquids [3,4]. However, the wall slippage of simple Newtonian liquid did not seem to be recognized at this early stage. The recent development of investigating flow behavior at small scales in a quantitative manner has enabled the identification of the boundary slippage of simple liquids. Several molecular simulations have shown that when a solid/liquid interface has weak interaction, enhanced mobility or the slippage of liquid molecules against solid surfaces can be found [5,6]. Direct experimental evidence, as given by total internal reflection–fluorescence recovery after photo-bleaching (TIR-FRAP), shows that simple Newtonian liquids can develop slippage at the wall [7]. Atomic force microscopy (AFM) and surface force apparatus (SFA) have recently been employed to disclose the slippage by detecting the deviations of the squeeze force confined within a micro-gap as compared to that predicted by conventional hydrodynamics [8,9].

The wall slippage of simple Newtonian fluids is related to liquid flow and transportation at a micro/nano scale. Hence, it is reasonable to anticipate promising utilization of wall slippage in micro-devices such as micro-electromechanical systems (MEMs). In fact, efforts are being made to design new lubricating devices based on wall slippage and to explore their potential applications. The feasibility of non-wetted bearings with surfaces that are hydrophobic to liquid droplets has been experimentally investigated [10,11]. Experiments were carried out to study the hydrodynamic interactions of surfaces [12], and they indicated the important role of wettability in the hydrodynamic effect. To improve lubrication performance by boundary slippage, theoretical work has also been initiated. The concept of the half-wetted bearing is among the pioneer efforts [13,14], in which it is analytically demonstrated that such a bearing has a satisfactory combination of fair load support and low-friction behavior. Numerical analysis of a sliding bearing with a slip/no-slip surface has also been reported [15], showing that generic slider bearing

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Nomenclature

H	film thickness, m
H	dimensionless film thickness, $H=h/h_0$
h_0	reference film thickness for nondimensionalization, m
L	length of slider, m
p	film pressure, Pa
P	dimensionless film pressure, $P=p/\frac{\eta l^2 v_0}{h_0^3}$
V	approach velocity, m s^{-1}
v_0	reference velocity for nondimensionalization, m s^{-1}
V	dimensionless velocity, $V=v/v_0$
X	coordinate, m
x_m	position of the maximum pressure, m
x_s	slippage region parameter, m
x_t	length of non-wetting region, m
X	dimensionless coordinate, $X=x/l$
X_{m}, X_s, X_t	dimensionless parameters, $X_{m,s,t,}=x_{m,s,t}/l$
z	coordinate across the film, m
Z	dimensionless coordinate, z/h_0
η	viscosity, Pa s
τ	shear stress, Pa
$\overline{\tau}$	dimensionless shear stress, $\tau/\frac{\eta l v_0}{h_0^2}$
τ_C	critical shear stress, Pa
$\overline{\tau}_C$	dimensionless critical shear stress, $\overline{\tau}_C=\tau_C/\frac{\eta l v_0}{h_0^2}$

performance can be enhanced by a prescribed slip/no-slip surface. Recently, it has been analytically proven that two parallel plates in relative motions (without the geometrical wedge) can be separated by an effective lubricating film using the concept of partial boundary slippage [16].

A particular stimulus for this work is the potential use of the boundary or partial boundary slippage effect on lubrication. Whilst it is recognized that viable realization of this largely relies on the understanding of the mechanism, experimental and mathematical models for squeeze film bearings with/without boundary or partial boundary slippage were studied.

2. Experimental details

Surface free energy of a glass plate specimen was modified by ultraviolet (UV) irradiation. Two identical glass plates which are optical flats of a quarter wave accuracies were chosen for comparative tests. One was UV irradiated and the other one was not. Tiny quantities of a mineral oil (LVI 260) were dropped onto the two specimen glass planes and their contact angles were measured to be 18.7° and 32.4° for glass surfaces without and with UV irradiation, respectively, as shown in Fig. 1. The higher the contact angle, the smaller the surface energy is [17]. Hence, the UV exposure reduced the surface energy of the glass specimen surface. The squeeze film was realized by attaching the specimen glass plate to an actuator head and moving it slowly towards another untreated glass plate at the bottom. Fig. 2 shows schematically the set-up. The downward speed was only a few millimeters per second. Slow speed employed aimed at steady flow and without any cavitations. The initial gap size between the two glass plates was about 7.5 mm and both of them were submerged in an oil bath. The oil bath rested on a stage whose inclined angle can be adjusted. The parallelism of the two glass plates could be adjusted to not greater than 0.02°, which led to the uncertainty of load measurements less than 0.5%. The top specimen glass plate approached toward the lower glass plate with a constant speed and stopped at a final gap of 0.5 mm. The resistant force of the squeeze film was monitored by a load cell attached to the actuator. The forces achieved when it came down to the final gap for tests of different approaching speeds are plotted in Fig. 3. The UV irradiated glass surface generated much less resistance to the squeeze flow. The lubricant is thus easier to slip on the glass surface. The comparison was based on the same speed. The differences in the load-carrying capacity could only be attributed to the surface modification by UV irradiation, which made the specimen glass more hydrophobic to the lubricant, as shown by its increased contact angle by UV irradiation.

3. Mathematical model and its solution

A partial boundary slippage can be applied to bearings without geometrical wedge i.e. parallel bearings [16]. Flow resistance for lubricants in the inlet where the surfaces slip is lower than that in the outlet where no-slip occurs, thus hydrodynamic effect is

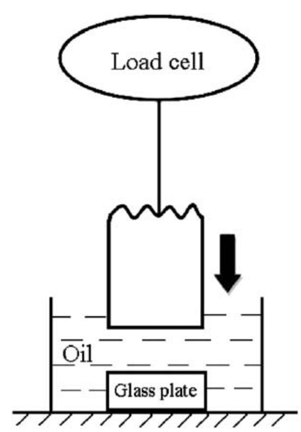

Fig. 2. Schematic set-up.

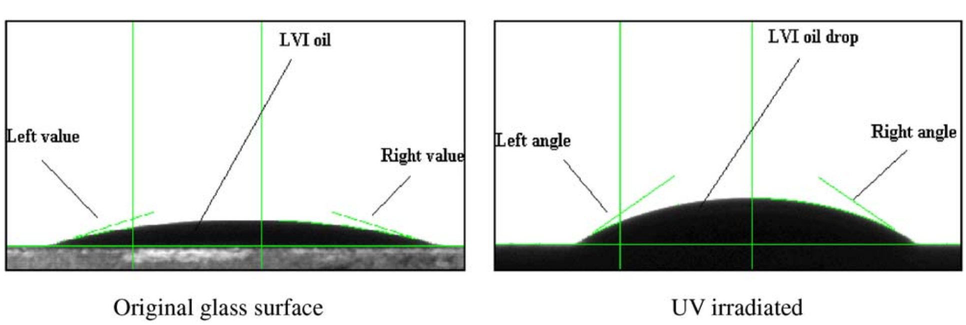

Fig. 1. Contact angle of original and UV treated glass planes.