Tribology International 90 (2015) 324–331

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

The role of micro-cavitation on EHL: A study using a multiscale mass conserving approach

Leiming Gao [a,*], Gregory de Boer [b], Rob Hewson [a]

[a] Department of Aeronautics, Imperial College London, London SW7 2AZ, UK
[b] School of Mechanical Engineering, University of Leeds, Leeds LS2 9JT, UK

ARTICLE INFO

Article history:
Received 29 October 2014
Received in revised form
11 March 2015
Accepted 3 April 2015
Available online 14 April 2015

Keywords:
Cavitation
Multiscale
Textured Surface
Elastohydrodynamic Lubrication (EHL)

ABSTRACT

The role of micro-cavitation in Elastohydrodynamic Lubrication is numerically investigated using a multiscale approach whereby both the small scale topographical features and the micro-cavitation of the lubricant due to the features are resolved. Micro-cavitation and the fluid's shear-thinning property are modelled at the small scale of topological feature. The effects of topographical features on the film thickness of the line contact bearings and friction coefficient are presented with a focus on the role of micro-cavitation. This highlights how a mass conserving small scale model can be used to model both micro-cavitation and cavitation occurring at the bearing scale, and how topological features can be designed to reduce friction while maintaining bearing load.

1. Introduction

In this paper the role of cavitation in an Elastohydrodynamic Lubrication (EHL) converging–diverging line contact is investigated. The bearing surfaces are a smooth moving roller surface relative to a stationary, textured flat surface. Topographical changes to a lubricated surface of industrial components have been experimentally and numerically shown to improve their tribological performance in three main aspects, the load carrying capacity, the friction coefficient and the lubricant fluid film [1,2]. Such applications include piston rings [3,4], mechanical seals [5,6], journal bearings [7,8], pad bearings [9–12] and roller bearings in line contacts [13–17] and point contacts [18,19].

A number of numerical approaches have been proposed to represent lubrication of surfaces with topographical features [7,17,18,20,21]. One of the challenges of numerically describing these problems is the order of magnitudes difference in the size of bearing surface topography and the bearing itself. This has led to a number of multiscale methodologies to analyse the problem and overcome the limitation in terms of computing costs [22–26]. Among the multiscale models, many of them employ an adapted Reynolds equation based on Patir and Cheng's average flow model [27] to solve the large scale fluid pressure, and the Stokes or Navier–Stokes equations to solve the small scale fluid flow [22,24,26]. Recently, the homogeneous multiscale approach has been developed, in which the large scale fluid flow was governed by a homogeneous pressure-gradient function whose coefficient was obtained from the small scale simulations. These include the work of Nyemeck et al. [25] on the hydrodynamic lubrication with rigid bearing surfaces of seals, and the authors' work [11,12] on the EHL simulation of micro-textured pad bearings.

The role of micro-cavitation on lubrication has been studied by a number of investigators arising from experimental observation of cavitation occurring in the vicinity of surface roughness [20,28]. The role of cavitation raises further questions regarding the validity of using a form of the lubrication equation, where cavitation effects may not be uniform across the film thickness due to the underlying topography; this cannot be captured by the lubrication approximation where a constant pressure is assumed across the film thickness. Olver et al. [29] proposed an 'inlet suction' effect due to fluid flow driven by cavitation pressures located in the inlet region of the pad bearing surface. Ausas et al. [30] and Qiu and Khonsari [31] studied micro-cavitation in textured bearing lubrication using a mass conserving model and compared different boundary conditions of cavitation; the half-Sommerfield condition, Swift–Steiber (Reynolds) condition and the Floberg–Jakobsson–Olsson (JFO) condition. It was found that the Reynolds condition largely underestimated the cavitation area and predicted a higher load-carrying capacity than the JFO results. Other studies of micro-cavitation have used Navier–Stokes based Computational Fluid Dynamics (CFD) simulations to solve the fluid flow, for example, Shi and Ni [32], Wahl et al. [33] and Meng and Yang [34]. However, these studies of micro-cavitation were all modelled at a single scale, where the topographical features were described over the entire lubrication domain. The number of simulated micro dimples or grooves in these studies was limited to up to 10 due to the very fine mesh required to resolve the small scale

* Corresponding author. Tel.: +44 20 7594 1976.
E-mail address: leiming.gao@gmail.com (L. Gao).

http://dx.doi.org/10.1016/j.triboint.2015.04.005
0301-679X/

Nomenclature

d	Cell depth [m]
E	Young's modulus [Pa]
E'	Equivalent Young's modulus [Pa]
e	Rigid displacement [m]
h	Large scale film thickness [m]
g	locally film gap [m]
$\boldsymbol{K}$	Displacement influence coefficient matrix [m^3/N]
$\boldsymbol{K_G}$	Non-diagonal terms in $\mathbf{K}$ (with respect to the global deformation) [m^3/N]
k_L	Diagonal element in $\boldsymbol{K}$ (with respect to the local deformation) [m^3/N]
L	Cell length [m]
n	Number of large-scale mesh grid
p	Pressure [Pa]
$\hat{p}$	Homogenised pressure at the large scale [Pa]
p^*	Small scale average pressure [Pa]
p_c	Threshold cavitation pressure [Pa]
P	Dimensionless small scale pressure
$\hat{P}$	Dimensionless homogenised pressure
$\dot{m}$	Mass flow rate per unit length [kg/m/s]
r	Radius of cylinder [m]
t'	Equivalent small-scale cell height [m]
U_0	Sliding speed of the roller [m/s]
$\boldsymbol{u}$	Fluid velocity vector [m/s]
w	One-dimensional load per unit length [N/m]
x	Coordinate in direction of fluid flow [m]
X	Dimensionless coordinate of x
α	Pressure–viscosity coefficient
$\dot{\gamma}$	Shear rate [1/s]
δ	Elastic deformation [m]
ε	Strain
η_0	Viscosity at zero shear rate [Pa s]
η_∞	Viscosity at infinite shear rate [Pa s]
η^*	Generalised viscosity in Carreau model [Pa s]
θ	Density fraction in cavitation model
μ	Friction coefficient
σ	Normal stress [Pa]
τ	Shear stress [Pa]
ν	Poission's ratio
ρ_0	Ambient fluid density [kg/m^3]
ρ	Generalised fluid density [kg/m^3]
ω	Rotation velocity of cylinder [rad/s]

features and cavitation. In real engineering applications the number of micro dimples (and roughness) could be much larger on a real textured bearing's surface, and a multiscale method is especially relevant to solve such problem.

In this paper the Heterogeneous Multiscale Method (HMM) [35] is applied to EHL as derived by the authors [11,12,36] and extended to include cavitation effects, via the application of a mass-conserving approach at both small and large scales. This enables the model to capture cavitation at both scales. The pressure gradient-mass flow rate relationship is obtained from a homogenised local scale solution. This relationship is subsequently used at the global scale as a governing equation of fluid flow, and solved along with the conservation of mass. In this work cavitation is considered at the local scale via a predefined threshold cavitation pressure. The effects of the micro-texture's geometrical parameters on the bearings' lubrication film thickness and friction coefficient are presented. The piezo-viscous and shear-thinning effects are discussed and the importance of the role of micro-cavitation at the small scale is highlighted.

2. Numerical methodology

2.1. Geometry and materials

In this study, the global geometry of the lubrication model is a two-dimensional cylindrical line contact. The smooth cylinder rotates relative to a textured stationary surface, as shown in Fig. 1. The material of the plane is PTFE with an elastic modulus (E) of 0.5 GPa and Poisson's ratio (υ) of 0.4. The cylinder is assumed to be rigid compared to the soft PTFE bearing surface. The radius of the cylinder (r) is 25 mm and the rotation speed (ω) is 80 rad/s, and equivalent to a sliding speed (U_0) of 2 m/s. The micro-pocket length (L) ranges from 20 μm to 100 μm and the depth (d) from 0 μm to 30 μm. The geometrical and material parameters are listed in Table 1.

2.2. Large scale simulation

The large scale simulation describes the fluid–structure interaction in the global lubrication domain, where the fluid pressure is solved simultaneously with the elastic deformation of the bearing surfaces. The difference between the current study and classical EHL analysis is that the governing equation for the hydrodynamic pressure is a homogenised equation from the small scale simulations, rather than the Reynolds equation, expressed as

$$\frac{d\hat{p}}{dx} = f(g, \hat{p}, \dot{m}) \tag{1}$$

together with the mass conservation equation

$$\frac{d\dot{m}}{dx} = 0 \tag{2}$$

The pressure gradient ($d\hat{p}/dx$) is a homogenised function of the pressure ($\hat{p}$), mass flow rate ($\dot{m}$) and film gap (g), interpolated from a series of small scale solutions. The large scale boundary conditions used to solve Eqs. (1) and (2) are that the pressure at the bearing inlet and outlet boundaries is equal to zero:

$$\hat{p}_{in} = \hat{p}_{out} = 0 \tag{3}$$

The line contact bearing load is balanced by an integral of the average small scale pressure (i.e., load per unit length p^*), along the line contact domain. The average small scale pressure (p^*) was defined in Eq. (17) in Section 2.3.2 ‘Small Scale Simulations’.

$$w = \int_{xin}^{xout} p^* \, dx \tag{4}$$

The geometry equation is expressed as a sum of the rigid displacement (e, an unknown constant determined by load w), rigid gap geometry and the surface deformation (δ):

$$h = e + \frac{x^2}{2r} + \delta \tag{5}$$

$$\delta = \boldsymbol{K} \times p^* \tag{6}$$

where the displacement influence coefficient matrix $\boldsymbol{K}$ was obtained using Green’s function [37] for linear elastic contact model.

2.3. Small scale simulations

The small scale problem is described by the flow equations and those governing the elastic deformation of the small scale features.