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Modelling three-dimensional soft elastohydrodynamic lubrication contact of heterogeneous materials

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ABSTRACT

This paper presents an approach for modelling three-dimensional soft elastohydrodynamic lubrication (EHL) contact of heterogeneous materials. In this approach, a hydrodynamic interface element is developed to achieve the coupling of elastic deformation of heterogeneous contacting bodies and the steady-state hydrodynamic lubrication at the contact interface. The deformation behaviors are simulated by the finite element method, while the hydrodynamic lubrication is dealt with by solving the Reynolds equation. This approach can enable the simulation of soft EHL contact between bodies with heterogeneous materials and complicated geometric configurations. Predicted lubrication performances of soft EHL contacts show good agreement with the experimental measurements reported in literature. Analysis and discussion are also conducted on various cases of soft EHL contact between an elastic ball and a coating-substrate system with or without inhomogeneities.

1. Introduction

In the last decade, there is growing interest in soft elastohydrodynamic lubrication (EHL) contact in which large deformation occurs because one or two contacting bodies are compliant (small elastic modulus). Soft EHL contact is typical for many biological systems such as synovial joints, contact lens, eye–eyelid contact, and human skin contact [1–4]. It is challenging to tackle soft EHL contact problems because most of the contacting bodies involved are heterogeneous materials that may contain surface coatings, reinforcements, or microdefects such as cracks or inclusions. Therefore, a simulation approach for soft EHL contact of heterogeneous materials is of great significance to achieving a well-designed soft EHL system.

Hard EHL contact occurs when both contacting bodies are stiff, and hard EHL contact of materials with coating and inclusions has been widely studied over the past decade. Elsharkawy et al. [5] proposed a numerical solution for the micro-EHL problem of two coated elastic bodies in line contact. Xue et al. [6] presented a numerical routine to simulate the contact of elastomer-layered cylinders lubricated by isoviscous liquids. Liu et al. [7,8] developed an EHL model for coated surfaces in point contact by combining the elastic deformation formulation for the coated surfaces with an EHL model. Wang et al. [9,10] developed a numerical model for the EHL contact of heterogeneous materials, and several types of inhomogeneities, such as cuboid, sphere, and functional graded coating, were considered. Zhou and Dong [11] presented a numerical solution for heterogeneous materials with multiple inclusions under EHL contact. Then, they investigated EHL contact of coated materials with multiple subsurface inhomogeneities and cracks [12,13]. The effects of coatings and subsurface defects, surface roughness of heterogeneous structures, and heterogeneous elastoplastic materials on the lubrication performance and elastic fields were also analyzed [14–17].

Contrary to hard EHL problems, soft EHL contact produces large deformation of the contacting bodies due to their highly compliant materials. In the classical EHL theory, as done in hard EHL problems, the deformable material is assumed to be linear elastic and the elastic deformation is usually calculated with an elastic half-space approximation. In fact, due to the material and geometrical non-linearities associated with the large deformation of the heterogeneous contacting bodies in soft contact problems, both linear elastic deformation and elastic half-space approximation assumed in the classical EHL theory are not suitable for the soft-EHL problems.

In recent years, soft EHL contact has been modeled with different methods. Stupkiewicz et al. [18,19] proposed a fully-coupled nonlinear framework for a 2D soft EHL contact in a reciprocating elastomeric seal. Then, Lengiewicz et al. [20,21] extended the above approach to a three-dimensional (3D) case considering the mass-conserving cavitation lubrication model. Gao et al. [22] proposed an approach for modelling a

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transient soft EHL contact in 2D seals. Some factors of soft EHL in 2D seals have also been investigated, such as the shear stress of lubricant [18,19,23], the material nonlinearity of the contacting bodies [18,19,24,25], and the roughnesses of the matching surfaces [26–28].

Soft EHL problems have also been experimentally investigated. Myant et al. [29] investigated the influence of load and elastic properties on the rolling and sliding friction of lubricated compliant contact. de Vicente et al. [4,30] measured friction in the contact between a steel ball and an elastomer flat, and obtained Stribeck curves showing the variation of friction coefficient with the product of entrainment speed and lubricant viscosity. Nigel et al. [31] measured the oil film thickness using optical interferometry. By means of photoelasticity, Fang et al. [32] investigated the oil film pressure at the lubricating interface and the stress distribution in contacting bodies. The effects of the roughness of contacting surfaces on the lubrication performances were also investigated [4,33].

However, few investigations have been reported on the 3D soft EHL problem involving heterogeneous materials. In practice, most of contacting bodies involved in soft EHL contact are heterogeneous materials containing surface coatings and inclusions. Taking the field of biology for example, the cartilage covering bony ends of the diarthrodial joint is a coating with low-friction and wear-resistant characteristics, and bone inhomogeneity affects mechanical response of the joint during physiological loading [34].

This study proposed a fully-coupled finite element framework for modelling 3D soft EHL contact of heterogeneous materials. The framework involves descriptions of the deformation of heterogeneous bodies, the hydrodynamic lubrication at the contact interface, and elastohydrodynamic coupling. The deformation behaviors of contacting bodies are simulated with the FE software package ABAQUS 6.17. A hydrodynamic lubrication element is built via a user subroutine UEL (User-defined element) to solve the Reynolds equation, as well as to achieve the elastohydrodynamic coupling of the surface lubrication and deformation of contacting bodies. An elastic ball in soft EHL contact with a heterogeneous coating-substrate system is modeled, and the effects of coatings and inhomogeneities with various material properties on both mechanical and lubrication performances are analyzed.

2. Hydrodynamic lubrication model

2.1. Reynolds equation with the mass-conserving cavitation model

The hydrodynamic lubrication theory is concerned with modelling the fluid flow in a thin film between two surfaces in relative motion. In this study, the mass-conserving cavitation model is adopted to solve the lubrication problem. According to the cavitation model, the cavitation appears when the fluid pressure p is lower than the cavitation pressure p_{cav}, with the lubrication domain Ω being split into the full film zone Ω_f and the cavitation zone Ω_c by the cavitation boundary Σ as shown in Fig. 1. In the cavitation zone, the cavitation fluid is a mixture of the liquid, gas and vapour, and its density is lower than that of the intact fluid. Therefore, the pressure and the saturation of the fluid can be expressed as [35,36].

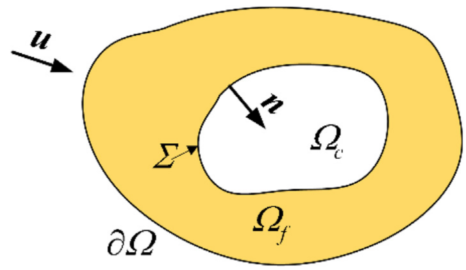

Fig. 1. Schematic representation of the lubrication domain.

$$\begin{cases} p > p_{\text{cav}}, & \theta = 1 \quad \text{in } \Omega_f \\ p = p_{\text{cav}}, & \theta < 1 \quad \text{in } \Omega_c \end{cases}, \tag{1}$$

where $\theta = \rho_0/\rho$ is the saturation of the fluid; ρ and ρ_0 are the densities of the cavitation and intact fluids, respectively. In this work, the cavitation pressure p_{cav} is assumed to be zero for the sake of simplicity. For the soft EHL problem, the hydrodynamic pressure is relatively low and the lubricant can be regarded as incompressible in the full film region.

By assuming the flow to be laminar and isothermal, and neglecting the inertia of the lubricant, the steady state mass-conserving cavitation model can be expressed as [37].

$$\frac{d}{dx}\left(\frac{h^3}{12\eta}\frac{\partial p}{\partial x}\right) + \frac{d}{dy}\left(\frac{h^3}{12\eta}\frac{\partial p}{\partial y}\right) = u\frac{\partial(\theta h)}{\partial x} \qquad \text{in } \Omega_f \cup \ \Omega_c, \tag{2}$$

with the mass-flux continuity condition on the cavitation boundary [37,38]:

$$\begin{cases} p = 0, & \frac{\partial p}{\partial \boldsymbol{n}} = 0 \qquad \text{Film rupture boundary} \\ p = 0, & \frac{h^2}{12\eta}\frac{\partial p}{\partial \boldsymbol{n}} - \frac{(1-\theta)}{2}u_{\boldsymbol{n}} = 0 \qquad \text{Film reformation boundary} \end{cases} \\ , \tag{3}$$

where h denotes the oil film thickness, and η is the dynamic viscosity. The variable $\boldsymbol{n}$ is a unit vector normal to Σ and towards Ω_c; u is the entrainment speed and $u_{\boldsymbol{n}}$ is the speed in the direction of $\boldsymbol{n}$. The cavitation boundary is divided into film rupture boundary and film reformation boundary according to whether the fluid starts to cavitate or reform. This boundary condition can also be called Jakobsson-–Floberg–Olsson (JFO) boundary conditions [39]. If the reformation boundary is assumed to be the same formula as the rupture boundary, the boundary is called the “Reynolds boundary”. In many cases, JFO and Reynolds boundaries can yield very similar results, but the mass conservation is crucial in cases with textured surfaces or strong transient effects [35,40].

In addition, the Dirichlet boundary condition is employed on the boundary $\partial\Omega$ of the lubrication domain as

$$P = 0 \qquad \text{on } \partial\Omega \tag{4}$$

The film thickness distribution is expressed as

$$h(x, y) = h_0(x, y) + \Delta h + e(x, y), \tag{5}$$

where h_0 is the initial separation between two lubricated surfaces; Δh and e are the total rigid relative motion and total normal deformations of the contacting surfaces in the normal direction, respectively. In the classic EHL theory, deformation of the lubricated surface is calculated from the Boussinesq integration for a half space. However, the deformation in this approach is derived from an FE simulation for the contacting bodies, which is stated in detail in Section 3.

Under low pressure, the dependence of the lubricant viscosity on pressure (i.e., the piezo-viscous effect) is not pronounced. However, for completeness, the dependence of the lubricant viscosity on pressure is considered with the Barus equation [41].

$$\eta = \eta_0 \exp(\alpha p), \tag{6}$$

where η_0 is the viscosity at zero pressure and α the viscosity-pressure coefficient.

Apart from the hydrodynamic pressure, the friction resulting from lubricant shear also acts on the lubricated surfaces. In the classical EHL theory, the effect of friction on the deformation of the connecting bodies is neglected [18,41]. However, in soft EHL contact, friction is not negligible and should be fully considered. The shear stress induced by lubricant shear is calculated by

$$\tau = -\frac{\eta}{h}\boldsymbol{u} - \frac{h}{2}\nabla p = -\frac{\eta u}{h} - \frac{h}{2}\frac{\partial p}{\partial x} \tag{7}$$

Once the sliding velocity and oil film distribution are determined,