Tribology International 103 (2016) 516–528

Contents lists available at ScienceDirect

Tribology International

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

Short communication

Mixed lubrication problems in the presence of textures: An efficient solution to the cavitation problem with consideration of roughness effects

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ARTICLE INFO

Article history:
Received 21 April 2016
Received in revised form
27 July 2016
Accepted 5 August 2016
Available online 6 August 2016

Keywords:
Mass-conserving algorithm
Roughness effects
Mixed lubrication
Surface texturing

ABSTRACT

In order to consider the effect of the local surface properties, such as textures and roughness, a mass-conserving model is specifically developed based on the Elrod–Adams model. The classic flow factor methodology is incorporated in this model to deal with the roughness scale. Meanwhile, by reformulating the cavitation conditions according the Fischer–Burmeisster equations, the system of discretized equations for this model is changed to be unconstrained. The computational efficiency of the developed model is similar to that when cavitation is not considered. Finally, this model is evaluated in the predicting the performance of the textured ring/liner system under the start-up process.

1. Introduction

In recent years, much attention has been devoted to the study of the performance enhancement of the textured lubricated system, such as mechanical seals [1,2], journal bearings [3–5], and ring-liner conjunction [6–10]. The development and effect of surface texturing in general applications have been summarized in many review papers [11–14]. The technology of surface texturing is regarded as a means of controlling friction and wear in engines. It can expand the behavior under the hydrodynamic lubrication regime instead of the mixed or boundary lubrication regimes [13–15].

According to the survey provided by Gropper et al. [14], hundreds of studies, whose topics are focused on the influence of rough/textured contacts on the tribological performance, have been published since 1966. Among them, the purely theoretical researches account for more than 50%, which are based on different forms of the Stokes equations, Navier–Stokes equations or Reynolds equation. Regarding the numerical simulation of the textured system, since the lubricant film would experience the rupture and reformation multiple times, it is generally accepted that a mass-conserving treatment of cavitation is required for conducting an accurate performance prediction [16]. The developed mass-conserving models are generally based on the JFO cavitation boundary conditions [17,18]. The JFO cavitation boundary conditions are experimentally validated and widely accepted. Many mass-conserving models have been successfully implemented in the study of textured surfaces. However, there is a long-standing problem in solving these mass-conserving models. The non-linear boundary conditions may bring the difficulties in the numerical solution, as well as numerical instabilities [14]. An efficient and stable search of the pressure and cavitation distributions is needed.

Besides, the friction pair is often under various lubrication conditions. Different kinds of lubrication regimes would be experienced. For example, in ring-liner contact, the mixed lubrication regimes are inevitable, particularly at the moment near the dead centers. In fact, the mixed and boundary lubrication conditions have become increasingly prevalent, owing to the trend of using the lower viscosity lubricants [19]. When the mixed or boundary lubrication regimes are experienced, the clearance between two contact surfaces is limited. Along with the reducing clearance, the roughness effects are more and more obvious due to the presence of asperity contacts [20,21]. It seems logical to consider the role of surface roughness in the textured system [15].

The aim of this work is to build a fast mass-conserving model that takes the effect of the local surface properties into account. In the proposed model, the texture-induced cavitation is treated in the mass-conserving manner, and the influence of surface

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http://dx.doi.org/10.1016/j.triboint.2016.08.005
0301-679X/

roughness is considered by incorporating a number of correction factors. These correction factors are called the flow factors, which are defined by Patir and Cheng [20]. Moreover, based on the Fischer–Burmeister equations, the system of discretized equations for this model is turned into an unconstrained system of nonlinear algebraic equations. It can provide an additional opportunity to reduce the computation time. As an application, the developed model is adopted to evaluate the performance of the textured system under the start-up process, as the previous experimental studies have shown that a large portion of engine-out emissions are produced during cold start-up [22] and in the first 75 engine cycles [23]. Through this simulation, a better in-sight of the effect of surface texturing under the start-up operation is given.

2. Mathematical model

The computational model consists of four coupled components: a fluid mechanics analysis of the lubricant film, a contact mechanics analysis of the asperities, a dynamic analysis of the ring, and a rheological analysis of lubricant. They would be presented as follows:

2.1. Fluid mechanics

In this paper, the ring-liner conjunction is studied. The cavitation would take place along with the movement of the ring. Assuming that the fluid can be characterized as Newtonian, the hydrodynamic pressure of oil film is predicted on the basis of the JFO and its implementation by Elrod and Adams [24]. The corresponding equations are given as follows:

$$\frac{\partial}{\partial x}\left(\frac{\rho h^3}{\mu}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\rho h^3}{\mu}\frac{\partial p}{\partial y}\right)=6U\frac{\partial((1-\theta)h)}{\partial x}+12\frac{\partial((1-\theta)h)}{\partial t} \tag{1}$$

with

$$\begin{cases} p>0 \Longrightarrow \theta=0 \\ \theta>0 \Longrightarrow p=0 \\ 0\le\theta\le 1 \end{cases} \tag{2}$$

where ρ is the lubricant density; h is the oil film thickness, in other words, the term h means the clearance between the ring and the liner; μ is the lubricant viscosity; U is the ring velocity; p is the hydrodynamic pressure and θ is the cavity fraction. It is noteworthy that the cavity fraction θ is related to the cavitation. The term θ is influenced by the pressure p. As shown in Eq. (2), the term θ is set to 0, when the hydrodynamic pressure p is greater than the cavitation pressure (A value of 0 is used as the cavitation pressure in this study). When the cavitation takes place, the hydrodynamic pressure p is equal to the cavitation pressure, the term θ is greater than zero and meets the condition $\theta>0$.

Fig. 1 shows three different scales in the rough textured surfaces. They are global scale, texture scale and roughness scale, respectively. There is a large difference in scale between the global contact dimensions and local surface properties. Local surface properties, including textures or roughness, also play an important role in the efficiency of lubricated contacts. In term of the size of surface textures, it can range from tens to hundreds of microns, while, the surface roughness of engineered surfaces is also on the order of one tenth of a micron. Therefore, considering the effect of surface roughness on the lubricant flow in the simulation is necessary.

Similar to the approach provided by Qiu et al. [25], Eq. (1) can then be rewritten in the suitable form by implementing a number of correction factors to consider the effect of surface irregularities. These correction factors are called flow factors, which are defined by Patir and Cheng [20]. In this manner, the time dependent two-dimensional Reynolds equation with the effect of roughness in consideration reads:

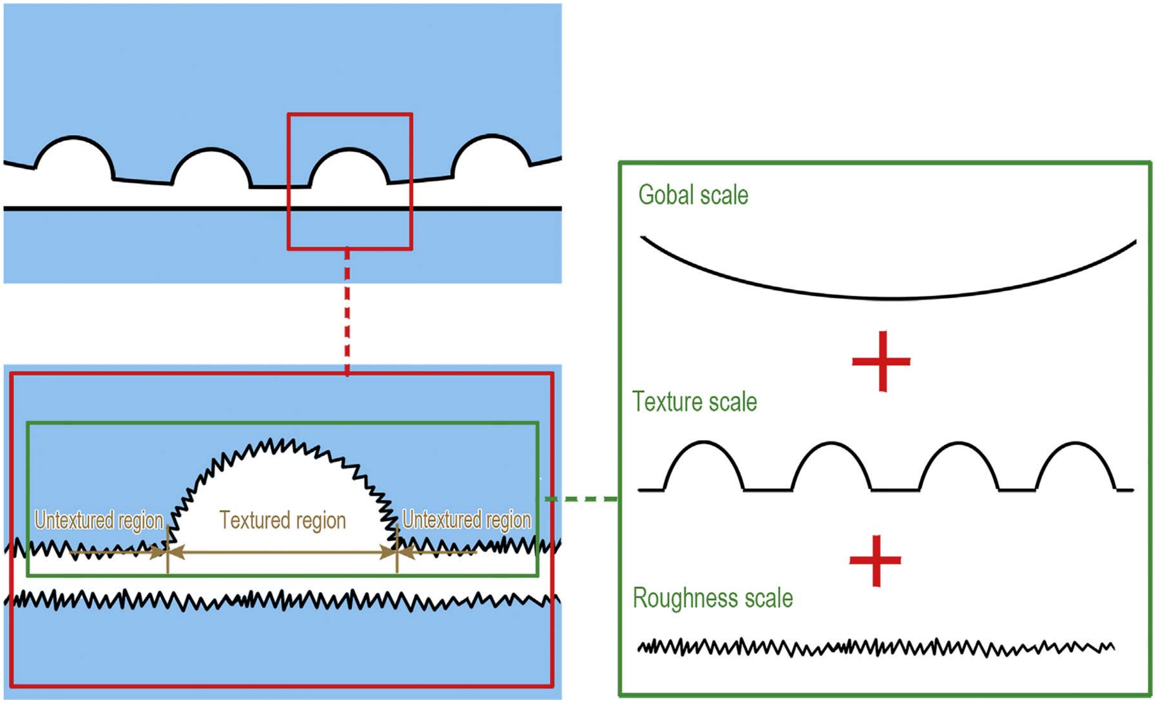

Fig. 1. Different scales of the rough textured surfaces.