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A deterministic multiscale computation method for rough surface lubrication

Shiyuan Pei [a,*], Hua Xu [a,b], Fanghui Shi [a,c]

[a] Key Laboratory of Education Ministry for Modern Design and Rotor-Bearing System, Xi'an Jiaotong University, Xi'an 710049, China
[b] School of Mechanical Engineering, Xinjiang University, Urumqi 830046, China
[c] General Motors Company, Warren, MI 48090, US

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ABSTRACT

A multiscale computational method (finite cell method, FCM) for heterogeneous lubrication problems is developed in this paper. The theoretical basis and key implementation steps are systematically introduced. Several representative numerical examples, including both periodic and non-periodic roughness, are presented to demonstrate the accuracy and efficiency of proposed method. Parallel performance of developed method are also investigated. The results show that FCM can be used in two ways. One is to obtain the average effect using the coarse mesh, but with deterministic small-scale effect included. The other is that deterministic small-scale effect can be recovered accurately when necessary. If combined, these two steps can provide same accuracy as the complete deterministic modeling, yet require significantly less computation time and storage.

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1. Introduction

Modern design of lubricated components require it is in compact size and is capable of endure high power density. Surface topography and roughness significantly influence the performance of machine elements especially operating in a thin film or mixed lubrication regime, because the size of topography and the film thickness are of a comparable order.

Hence, these requirements impose a demand of understanding tribological surfaces not only at the macroscopic level (designed geometry) but also at the microscopic level (surface roughness) or the sub-macroscopic level (machined surface features) in engineering applications. There are mainly three types of theoretical models used when describing the rough surface lubrication problem: stochastic, homogeneous and deterministic.

Early studies mainly employed stochastic models, using a few statistical parameters to describe the surface and lubrication characteristics. Among various models published, the average Reynolds equation [1,2], which rewrites the Reynolds equation, descripting of smooth surface lubrication flow, in terms of the averaged flow factors, has enjoyed wide recognition and led to numerous publications [3–7]. However, the stochastic models deal only with the global effect of surface roughness, and predict average parameter values of the rough surface [8]. The local information, such as pressure/thickness distributions, which may often be critical in the design of the tribological components, are obviously lost. In addition, there exists ambiguities in determining the flow factors in this approach, as demonstrated by Harp and Salant in [5,6]. In addition, since there is a large variety of engineering surfaces, it is impossible to describe their characteristics satisfactorily with any simple mathematical expression using only a few stochastic parameters [9].

More recently, homogenization techniques [10–16] have attracted a great deal of attention to treat the surface roughness. One advantage of these methods is that the flow factors can be computed for an arbitrary periodic roughness, permitting the use of measured surface topographies of real surfaces. Moreover, the computations of the flow factors have rigorous mathematical foundation and complete unambiguity [17]. However, it is important to note that the homogenization models can only deal with the problems with scale separation [18] and periodic roughness [17,19]. In addition, although detailed local pressure and film thickness distribution of a single cell can be obtained by expansion of homogenous results, it needs too much computational effort to extract the entire solution on large-scale.

Deterministic models, on the other hand, divide the computational domain into extremely small elements. Classical lubrication and contact theory is subsequently applied on this highly fined mesh, thus providing information on what happens at the roughness level. A literature review shows that there are only very few deterministic models [19,20] for lubricated conformal contacts dealing with the surface roughness. Due to roughness level

* Corresponding author.
E-mail address: peishiyuan@mail.xjtu.edu.cn (S. Pei).

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meshing, these models requires prohibitive memory and computing time, which is difficult even with modern computers. Thus, it is desirable to find a way to reduce the memory consumption and computing time, and still includes the effects from the surface roughness.

In previous work [21], we proposed the finite cell method (FCM) and demonstrated the efficiency of FCM to solve the two-scale surface texture problems, the results showed that both the computing time and storage required by FCM are significantly reduced compared with FEM for the periodic surface texture lubrication problem. In the present study, the FCM is further developed to analyze the non-periodic conformal contacted lubrication problems with multiscale roughness. The implementation procedures of the FCM are illustrated in detail with the emphasis on the new interpolation scheme for the construction of the cell stiffness matrix. Parallel implementation and performance of the developed method are also investigated in this paper.

2. Mathematical model

2.1. Governing equation

The two-dimensional, steady-state form of the Reynolds equation for an incompressible Newtonian fluid in a laminar flow is given by:

$$\frac{\partial}{\partial x}\left(h^3\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(h^3\frac{\partial p}{\partial y}\right)=6\eta U\frac{\partial h}{\partial x} \tag{1}$$

where x and y are the Cartesian coordinates, parallel and normal to the sliding direction. h and p are the local film thickness and the pressure at a specific point within the domain. U is the relative slide velocity of the conformal contacted surfaces, and η is the viscosity of the lubricant.

2.2. Film thickness

Note that for all the cases in the present study, we assume that the film thickness $h(x,y)$ at a specific point within the domain consists of two parts: one function describing the geometry of the bearing $h_0(x,y)$ and the other function describing the surface roughness $h_1(x,y)$. Mathematically, the following representation of the two parts (h_0 and h_1) of the film thickness was used:

$$h(x,y)=h_0(x,y)+h_1(x,y) \tag{2}$$

2.3. Load capacity

While obtaining the pressure distribution p by utilizing a certain numerical method, integrate this pressure over the lubrication area yields the load carrying capacity w:

$$w=\iint_\Omega p dA \tag{3}$$

Where A is lubrication area.

2.4. Error estimate

Two kinds norm (L_2 and L_w) are defined to estimate the relative errors between FCM results and reference results:

$$L_2=\frac{\|\mathbf{p}-\mathbf{p_{ref}}\|_2}{\|\mathbf{p_{ref}}\|_2} \tag{4}$$

and

$$L_w=\frac{|w-w_{ref}|}{w_{ref}} \tag{5}$$

where $\mathbf{p_{ref}}$ is the reference film pressure and w_{ref} is the reference film load capacity.

3. Finite cell method and its implementation

The goal of this paper is to develop the multiscale deterministic approach [21] to solve lubrication problems with multiple scales, which are intractable using traditional numerical methods. The framework of the FCM that formulates a procedure the structure of which follows the classical finite element implementation at the macro level. First, the whole domain is meshed by coarse cell of which dimension is much larger than the smallest roughness features. To account for the micro-scale features, each cell is further meshed using finer grids, and a local problem is constructed to obtain the cell stiffness matrix. The solution procedure then only needs to be carried out on the coarse cell meshes. After the macro responses of the domain are got, a straightforward recovery step is performed to get the fine-scale solutions. In general, the FCM consists of the following three phases [21]: construction of the cell stiffness matrix, solution of coarse-scale pressure and recovery of fine-scale pressure. We note that the key difference of present study and our previous work [21] is the construction of the cell stiffness matrix, and the rest, which are still included, are almost the same in order to give the full picture of the developed method. A simplified lubrication model, as shown in Fig. 1, is adopted for illustration in order to detailed explanation to the theoretical basis and the key steps of FCM.

3.1. Construction of the cell stiffness matrix and load vector

The domain is firstly meshed by $n\times n$ coarse cells, where n equals 2 in Fig. 1. We use condensation and interpolation procedures to obtain each cell equivalent stiffness matrix and load vector, here taking the upper left cell of Fig. 1 for illustration.

3.1.1. Condensation of coarse element internal pressure

To account for the fine-scale features inside of the cell, the cell is further meshed by $m\times m$ traditional bilinear quadrilateral elements, as shown in Fig. 2a. The conventional FEM is then utilized to discretise the Eq. (1), and the coarse cell equilibrium equation in fine-scale meshes can be assembled as:

$$\mathbf{k_f}\ \mathbf{p_f}=\mathbf{f_f} \tag{6}$$

where the subscript f denotes for fine-scale meshes. We define the pressure at the cell boundary nodes as $\mathbf{p_b}$, whereas the pressure at

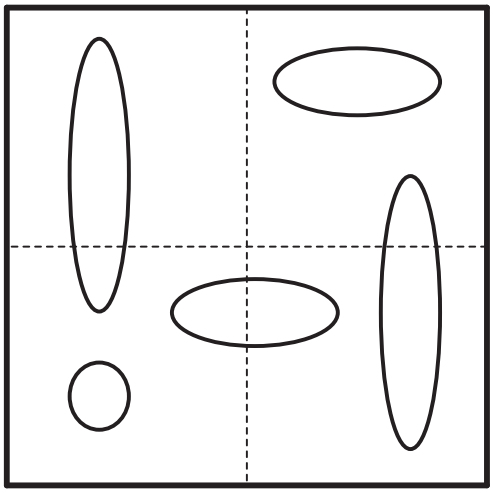

Fig. 1. schematic of the computational domain.

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