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A MULTISCALE APPROACH OF MIXED LUBRICATION – APPLICATION TO MECHANICAL SEALS

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Abstract

The lubricating fluid film developed between the faces of mechanical seals is a fraction of micron in thickness leading to a mixed lubrication regime. However, over a velocity threshold the fluid film can completely separate the faces because of the hydrodynamic effect due to the surface roughness even if the mean surfaces are parallel. To study this phenomenon a deterministic model is preferable because the stochastic theory based on flow factors is unable to reproduce this effect. Unfortunately the deterministic approach needs a prohibitive amount of nodes and computation time. This is why a multi-scale model is proposed. It is composed of a micro-deterministic model working on small area coupled with a macro model giving the pressure distribution on a macro-mesh. The results of the multi-scale model are compared to a pure deterministic model in terms of accuracy and computation time when the areas of the macro-cells are varied.

Introduction

Modeling the regime of mixed lubrication where hydrodynamic lubrication and asperity contact act simultaneously, calls more scientist investigation. A deterministic model of mixed lubrication has been recently developed and proved to be robust, accurate and efficient [1]. The results highlight the influence of surface roughness on hydrodynamic lift generation. However, the main difficulty of this approach is the tremendous amount of computer memory and CPU time required that can easily exceed the limit of today's computing resources. This situation can be relieved to some degree by parallel computing. The load is simply shared by more processors with more memory.

Different techniques have been developed for similar problems but, the common idea to all these methods is the multiscale treatment. The central goal of this approach is to obtain the macroscopic scale solution accurately and efficiently while including micro scale behavior.

The multiscale basic idea goes back to earlier work by Babuška and Osborn [2]. But the first multiscale finite element method was introduced by Hou and Wu [3], and then followed by Jenny et al [4] with the multiscale finite volume. This method is based on the construction of special finite element base functions that are adaptive to the local property of the differential operator, and was introduced as a tool to solve elliptic partial differential equation with multiple-scale solution. Although multiscale finite element method generates solutions that reflect the important fine-scale characteristics of the elliptic coefficients, these solutions are globally but not locally mass-conserving.

This paper presents a multiscale model for numerical calculations of the pressure distribution. The idea behind this approach is to express pressure on macro-cells by using a mass-conservative law whose coefficients are computed on a micro-scale mesh.

1. Theoretical considerations

The multiscale approach is developed in a small radial band of the seal interface. The aim of this approach is to obtain the pressure distribution at the macro-scale while taking into account the micro-scale behavior.

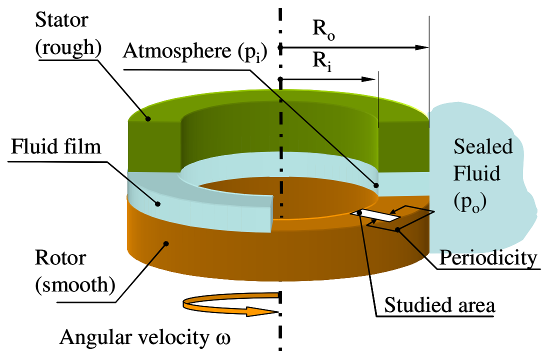

Figure 1: Mechanical seal configuration

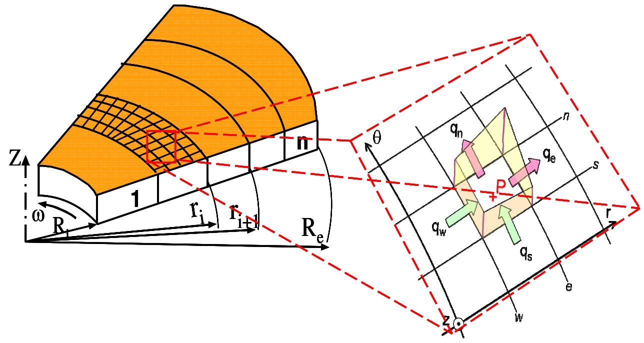

Figure 2: Studied area with macro and micro descriptions

1.1 Macro-scale model description

The macro-scale model idea is to subdivide the studied area into macro-cells (Fig.2). We assume that, the problem is stationary and axisymetric. The radial flow rate across one cell can be express as a non-linear function of pressure applied at the cell boundaries, i.e.

$$q^{(i)} = q_r{}^{(i)}(p_i, p_{i+1}) \qquad (1)$$

By using Taylor transformation, the flow rate approximation is given as follows:

$$q^{(i)}(p_i+\Delta p_i, p_{i+1}+\Delta p_{i+1}) = q^{(i)}_{r(p_i,p_{i+1})} + a^{(i)}\Delta p_i + b^{(i)}\Delta p_{i+1} \qquad (2)$$

If the coefficients ($a^{(i)}$, $b^{(i)}$) of eq. (2) are known, it is possible to compute the pressure ensuring the flow rate balance. The coefficients are computed on the micro-scale mesh. Since the coefficients of each cell can be calculated independently, the code is easily parallelizable.

The mean distance between the rings is adjusted so that the hydrodynamic lift and contact force from each macro cell balance the closing force applied on the floating ring.

1.2 Fine-scale model description

The model used in this part is dragged from [1]. The fine-scale calculation is performed on each macro-cell as shown in figure 2. A periodicity condition is imposed on the lateral boundaries whereas a constant pressure, coming from the macro-scale model, is applied on the radial boundaries. The Reynolds equation used in that case can be written as:

$$F\frac{\partial}{\partial r}\left(\frac{rh^3}{\mu}\frac{\partial D}{\partial r}\right)+F\frac{\partial}{\partial\theta}\left(\frac{h^3}{\mu r}\frac{\partial D}{\partial\theta}\right)=6V_2^{\theta}\left[\frac{\partial h}{\partial\theta}+(1-F)\frac{\partial}{\partial\theta}(hD)\right] \qquad (3)$$

where D is a universal variable and F a switch function for active and cavitated areas i.e.

$$F=0 \quad D=\frac{\rho}{\rho_0}-1 \quad p=p_{cav}$$
$$F=1 \quad D=p-p_{cav} \quad \rho=\rho_0 \qquad (4)$$

The behavior of each asperity that goes in contact with rotating surface is treated with the Hertz theory [1].

2. Results

The study has been done with the mechanical seal described in table 1.

Table 1: Operating and design parameters of the mechanical seal.

Inner radius R_i	0.029 m
Outer radius Ro	0.033 m
Balance ratio	0.64
Rotation speed ω	10 – 900 rad/s
Outer pressure p_o	1 Mpa
Inner pressure	0
Fluid viscosity μ	10^{-3} Pa.s
Fluid dentsity ρ_0	1000 kg/m^3
Cavitation pressure p_{cav}	-0.01 MPa
Dry Contact friction coeff.	0.2

The surface characteristics as shown in table 2, indicate that it's not Gaussian. It was little be modified because of periodic boundaries. In the case studies, 4000 cells in the radial direction, and 200 in the circumferential direction are well suited to be efficient.

Table 2: Characteristics of the rough surface and of the mesh.

Roughness height σ	0.1 µm
Skewness coefficient S_k	- 2,7
Kurtosis coefficient Ku	35,4
Number of cells in radial dir.	4000
Number of cells in circ. dir.	200

The simulation has been carried out on a computer with a dual processor system so, the real CPU time is shared between them. This allows simulating multiscale by parallel computation. The results from numerical solution are presented below. The Stribeck curve is an overall view of friction variation in the entire range of lubrication (hydrodynamic, mixed and boundary). Figure 3 presents a numerically obtained Stribeck curve with a decreasing friction zone corresponding to mixed

lubrication and an increasing friction zone at higher speeds typical of hydrodynamic regime. It shows that, for different macro-cell numbers, the Stribeck curves obtained with the multiscale model are correlated with the one obtained by a deterministic model. However, we remark a little difference in the mixed lubrication regime. These results show the accuracy of the present approach, in spite of the multiscale hypothesis.
In figure 4, it can be seen that the computation time decreases when the number of macro-cells rises. The amount of time saved is enhanced by parallel computation. However, the relative average errors (compared to the deterministic model) of friction coefficient and cavitation area increase with the number of macro-cells as shown in figure 5.

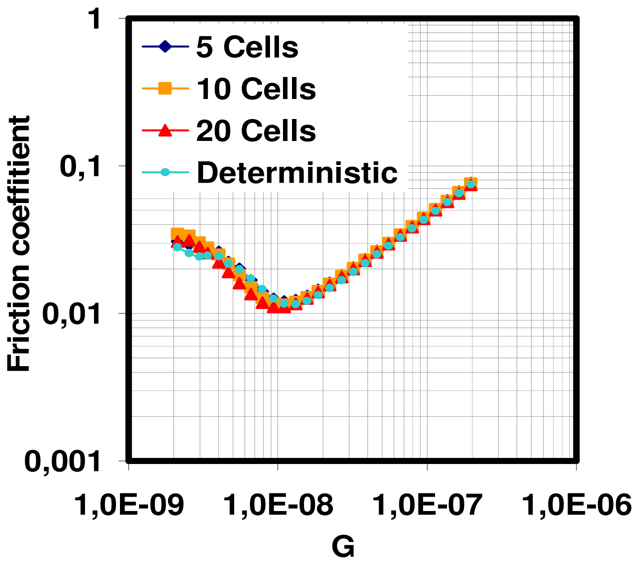

Figure 3: Comparison of the Stribeck curves obtained with the multiscale and deterministic models

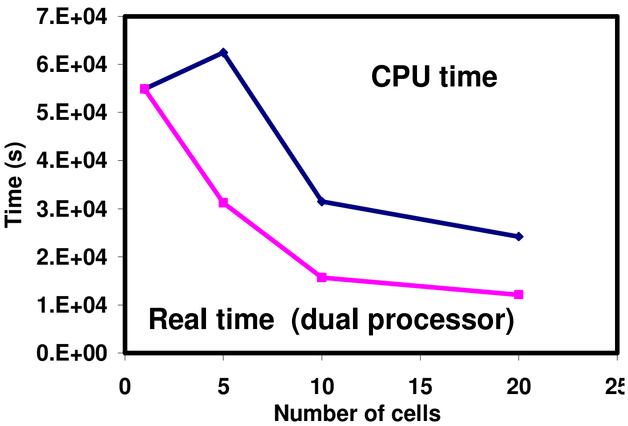

Figure 4: Comparison of computation time

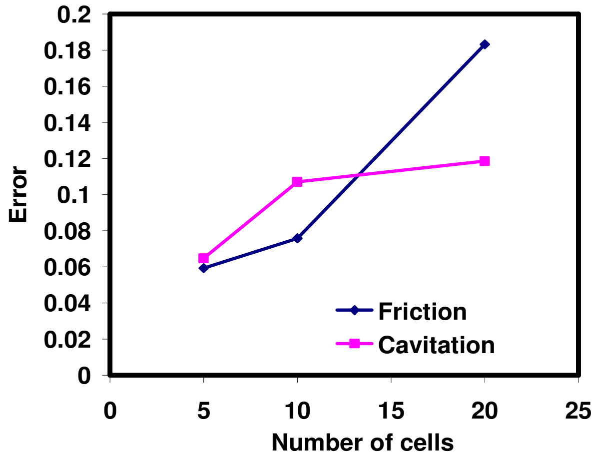

Figure 5: Friction coefficient and cavitation average errors

3. Conclusion

A multiscale approach for mixed lubrication is presented. It is based on micro-deterministic model working on small area coupled with a macro-scale model giving the pressure distribution on a macro-mesh. According to the results, this approach allows to significantly reduce the computation time while maintaining a reasonable accuracy compared to a full deterministic approach. The presented multiscale approach can be extended to a three dimensional configuration.

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