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Numerical analysis of a surface-textured mechanical seal operating in mixed lubrication regime

Noël Brunetière *, Bernard Tournerie

Institut Pprime CNRS, Université de Poitiers, ENSMA, UPR 3346, Département Génie Mécanique et Systèmes Complexes, SP2MI Téléport 2, Boulevard Marie et Pierre Curie, BP 30179, F86962 FUTUROSCOPE CHASSENEUIL, Cedex, France

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ABSTRACT

This paper presents a numerical study of the behavior of a mechanical seal with textured surfaces. It is used to analyze the mechanisms underlying the enhancement of the hydrodynamic lift associated with surface texture in mechanical seals. The model solves the Reynolds equation coupled with a mass-conservative cavitation algorithm and takes into account asperity contact. It is shown that, unlike rough-textured surfaces, smooth-textured surfaces are unable to generate a load. The performance of two rough surfaces are compared with those of the same surfaces equipped with dimples. The effect of texture density and aspect ratio are studied as well.

1. Introduction

Mechanical face seals are basically composed of two flat rings, one of them rotating, separating a pressurized fluid from the atmosphere. The usual theory of lubrication is unable to predict any hydrodynamic load generation between two flat seal faces. However, it has been known for a number of years that hydrodynamic pressure is generated in the interface, leading to separation of the surfaces from a given value of the duty parameter G [1]. In 1964, Nau [2] analyzed several surface defects involved in breaking down surface parallelism, such as misalignment, waviness and roughness. These could be at the origin of hydrodynamic lift-off. Two years later, Hamilton et al. [3] experimentally demonstrated that surface roughness, by causing local cavitation zones in the fluid film, can provide a net hydrodynamic force. To analyze more accurately the effect of roughness they created regular patterns of microasperities, consisting of a regular array of small cylinders, using a photoetching technique. The asperities, whose diameters vary from 45 to 120 μm with heights in the 2–3 μm range, occupy 5 to 21% of the total area of the stator of the seal. These generated asperities appear to be very efficient in load-generation. The latter is associated with appearance of cavitation areas at the trailing edge of the cylinders. The study was extended by Anno et al. [4] by analyzing larger asperities. According to the authors, another mechanism should enhance hydrodynamic force, this being a wedge at the top of the asperities. Two years later, the same authors [5] analyzed the leakage of these textured surfaces, this being a key parameter in mechanical seals. Since micro-asperities tend to increase the leakage path, the authors proposed to use a surface with negative micro-asperities or small cavities. Indeed, in the latter case, the gap between the surfaces can be completely closed when the two surfaces which are nominally flat are put in contact. The surface with micro cavities demonstrated an equivalent ability to generate load, while the leakage is drastically reduced in comparison with surfaces with positive asperities. The use of micro-textured surfaces in lubrication had been dormant for about three decades until Etsion et al. [6] presented experimental results obtained with a textured mechanical seal. Using a laser, the authors generated spherical holes in a steel ring that was afterwards polished to a roughness of 0.01–0.02 μm. In this first study, the pores have a diameter of about 90 μm and a depth varying from 2 to 20 μm. They occupy about 25% of the sealing area. In operating conditions, the texture allows the film thickness to be increased relative to untextured surfaces. Thus a higher load can be attained before seizure occurs. A number of papers have been published recently dealing with textured surface in all types of lubricated contacts. Since mechanical seals are quite different from other machine components their faces being nominally flat, the authors will address papers dealing with mechanical seals.

In 2002, Wang et al. [7] studied a water-lubricated silicon carbide (SiC) sliding flat ring against a laser-textured SiC disk. The authors tested different values of pore diameter, depth and density and showed that the critical load can be increased by a

* Corresponding author. Tel.: +33 5 49 49 65 31; fax: +33 5 49 49 65 04.
E-mail address: noel.brunetiere@univ-poitiers.fr (N. Brunetière).

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factor of two compared to untextured surfaces. The critical load corresponds to the load above which the friction coefficient drastically increases because of asperity contact. For some values of the texture parameters considered, Wang et al. found that the improvement can be only very weak.

The same year, Yu et al. [8] carried out a similar study but with a carbon ring versus a textured SiC ring in oil. They showed that the textured surface leads to a doubling or tripling of the reduction in friction, depending on the load, compared to an untextured surface. Their results were probably obtained in the mixed lubrication regime because of the high values of the friction coefficient. The latter, moreover, exhibits a decreasing trend with velocity. Etsion and Halperin [9] set out to partially texture the seal ring near the inlet radius, thus affording a kind of effective surface taper. This partial texturing is expected to increase the hydrostatic pressure between the surfaces. Their experimental results showed that a drastic decrease in both friction and temperature are obtained compared to the corresponding values for an untextured seal face.

In 2003, Wang and Kato [10] explored a wider range of pore diameters for SiC on SiC lubrication in water. In line with the observations of Etsion et al. [6], they showed that texture significantly reduces the friction fluctuation that is usually obtained with non-textured surfaces. The friction coefficient is stabilized at a lower value and the duty parameter value, at which the transition from mixed to hydrodynamic lubrication takes place, is reduced as well.

In a recent paper, Yan et al. [11] experimentally analyzed a cast-iron ring sliding on a textured cast-iron ring with oil. They showed that the more significant parameter is pore density. The texture can reduce friction, but in some situations an increase in friction is obtained, when compared to values using untextured surfaces.

Even though the improvement provided by surface-texturing has been experimentally shown, the trends displayed in the presented papers vary and, in some situations, the texture may actually have a negative effect.

There have been several theoretical attempts to explain the operation of textured surfaces in mechanical seals. Hamilton et al. [3] developed an analytical solution of the Reynolds equation, eliminating negative pressure from their solution. This rudimentary cavitation model (known as the half-Sommerfeld model) was also used by Etsion and Burstein [12], who demonstrated that a pore density of 20% is desirable for optimizing load generation. Three years later, Etsion et al. [13] improved the model using the Reynolds cavitation model. However, the theoretical model predicts lower pressure generation and film thickness values than were found by Etsion et al. [6]. This cavitation model, which does not ensure mass conservation, is not able to accurately predict the film reformation boundary. In 2009, Qiu and Khonsari [14] made a thorough comparison of these two cavitation models with the mass-conservative JFO model in the case of parallel smooth surfaces with spherical dimples. They clearly show that Reynolds and half-Sommerfeld models should not be used for textured surfaces as these lead to unrealistic cavitation areas. They also analyzed the load generated by dimples with the Reynolds and JFO cavitation models. While the former model predicts a generated pressure as high as ten times the feeding pressure, the pressure generated when an accurate cavitation model is used, barely reaches 1% of the supplying pressure.

According to the last-mentioned theoretical work, a textured smooth mechanical seal face cannot generate load. Thus another mechanism must be considered. In a recent work, Minet et al. [15], successfully demonstrated with a deterministic numerical model of mixed lubrication that the roughness of seal faces can generate a sufficient load to completely separate the seal surfaces. As suggested by Hamilton et al. [3], micro-cavitation is necessary for a load to be generated. In the present paper this model has been modified to include spherical dimples in the rough surface, as was done in experiments where the surfaces are not perfectly smooth. It is then used to analyze the effect of dimples on the lubrication regime by showing numerically-obtained Stribeck curves for textured and untextured surfaces. The effect of the texture density and aspect ratio is also analyzed.

2. Theoretical model

Even though the numerical model used in this study has been previously presented [15], it is described again for convenience.

First, it is assumed that the problem is stationary. To this end the seal faces are aligned and only the stator is rough, the rotor being perfectly smooth. Because of the very thin spatial sampling (about 1 μm in the following simulations), it is impossible to analyze the entire contact surface. Thus, the studied area is a small radial band from the outer radius R_o to the inner radius R_i, as shown in Fig. 1. It is been necessary to impose a periodicity condition on the lateral boundaries. To achieve this, a numerically-generated rough surface which is periodic in the sliding direction, is used [16].

The fluid flow problem is discretized by a control volume method. The continuity equation on the control volume of Fig. 2 is

$$q_w - q_e + q_s - q_n = 0 \tag{1}$$

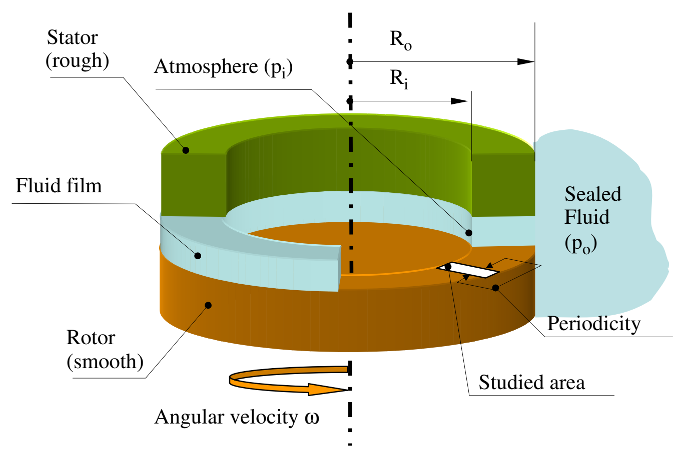

Fig. 1. Configuration of the problem.

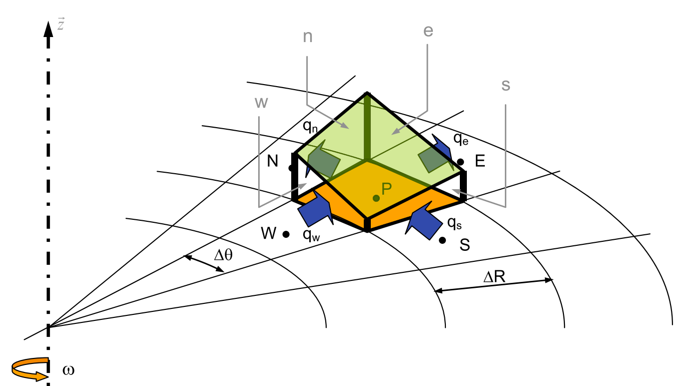

Fig. 2. Description of the fluid flow model.