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Modelling of leakage on metal-to-metal seals

Francesc Pérez-Ràfols*, Roland Larsson, Andreas Almqvist

Division of Machine Elements, Luleå University of Technology, Luleå, Sweden

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ABSTRACT

Surfaces in a typical seal exhibit both waviness and roughness. The influence of the interaction between these two scales on the leakage behaviour is expected to be relevant. Therefore, a model, which can study it, is developed here. The model is composed of state-of-the-art models for the contact mechanics between rough metal surfaces and for the liquid flow through the rough aperture in-between them. Correlation between percentage real contact area and actual contact topology and leak rate was confirmed through numerical analysis. Small changes in relative position between the contacting surfaces showed large deviation in leak rate. The validity of the model was justified by comparing results from numerical simulations using the model and experimental results found in literature qualitatively.

1. Introduction

Static metal-to-metal seals are typically installed whenever the conditions in terms of temperature and pressure are so severe that the commonly used rubber seals cannot be used. This includes space industry, cryogenic applications and nuclear power among others [1]. Despite the importance of these applications, little work is found regarding these seals; both because of the intrinsic complexity of the components and because more focus was placed on rubber seals [2].

The complexity of metal-to-metal seals comes from its topography, which usually has a structure as given by a turning process; this is, with a spiral groove covering the whole seal face surface and roughness in smaller scales [3]. Such topography is depicted schematically in Fig. 1. Making an analogy with a 2-D profile, the bottom part of the groove can be referred as valleys and its upper parts as peaks. If such a surface is placed into contact with a flat smooth surface, the contact will occur solely on the peaks and the contact will form a spiral pattern. Because of the roughness at smaller scales, this pattern will not be continuous, but rather the contact will be supported only by the asperities present on the peaks. This second contact distribution was experimentally observed by Nitta et al. [4] and allows connecting the valleys in radial direction. One could actually see the contact as occurring in two separated scales: a first scale on the top of the peaks and a smaller one on the top of the asperities. It is also important to consider that the turning process does not leave a regular groove, but rather an irregular distribution of peaks and valleys and errors of form. It has already been shown that these deviations are relevant in the prediction of leak rate [5].

The previously defined topography imposes a very particular flow pattern in form of meanders, as was observed by Nakamura and Funabashi [6]. The pressure gradient leading the flow is in radial direction, perpendicular to the spiral groove, and, therefore, this will be a preferred direction for the flow. However, due to the contact distribution, the flow has less restriction to flow in circumferential direction, following the spiral groove. Therefore, whenever the path in the radial direction becomes too constricted, the flow will advance in the circumferential direction until a sufficiently large opening in radial direction is encountered. However, the preferred direction of the flow will still be radial, since it is the direction of the pressure drop, and the flow will only advance in the circumferential direction when the radial flow is too restricted, as pointed out by Robbe-Valloire and Prat [7]. This is also the explanation for the meandering flow pattern observed experimentally in [6].

Therefore, whenever the path in radial direction becomes too tough, the flow will advance in the circumferential direction until an easier path in radial direction is found. However, the preferred direction of the flow will still be radial, since it is the direction of the pressure drop, and the flow will only advance in circumferential direction when the radial flow is not allowed [7]. The described flow pattern creates, indeed, the meanders observed experimentally.

Capturing the behaviour defined previously in a numerical model is complicated because it might require, in general, a large and dense grid. Therefore, the studies found in the literature attempting to model metal-to-metal seals are scarce and tend to simplify greatly the surface topography. Since the complexity appears because of the combination of the spiral groove and the roughness on top of it, one usually finds works where either the roughness or the groove are not

* Corresponding author.
E-mail addresses: francesc.perez.rafols@ltu.se (F. Pérez-Ràfols), Roland.Larsson@ltu.se (R. Larsson), Andreas.Almqvist@ltu.se (A. Almqvist).

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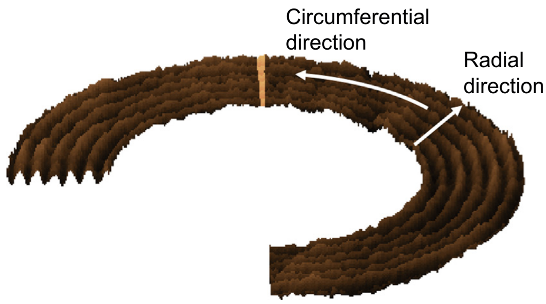

Fig. 1. Schematic of a typical topography encountered in a metal-to-metal seal, with the two main directions indicated. In bright, a width of about 0.5 mm is marked, assuming a seal diameter of 30 mm. The area marked also show the relative size of the domain utilized in this work (see Fig. 3) in comparison with the full size of the seal.

fully considered. In the first type of approach, the works of Geoffroy and Prat [3] and of Robbe-Valloire and Prat [7] are relevant because they could distinguish the flow mode according to its main direction and give insight in the order of magnitude of the leakage of each mode. Ledoux et al. [5] also used a simple representation of the groove to state that the low-frequency surface defects can affect the leakage performance significantly. From the second type of analysis work is found which is not restricted to metal-to-metal seals, as the particular structure of the topography is no longer relevant. Also, these models are have reached a more detailed description of reality. As an example, Vallet et al. [8] computed the deformation of a fractal surfaces when elastically compressed under a certain load and computed the flow through the resultant aperture by means of the Reynolds equation. Also, Sahlin et al. [9,10] presented a model where the contact was treated as elastic-perfectly plastic and the flow was computed in a smaller cell using the homogenization technique. That model showed good agreement with experimental results. A different approach was taken by Persson and Yang [11], who exploited the fractal nature and isotropy of many surfaces to develop a semi-analytical model for such surfaces. According to their multi-scale representation of roughness, the channels in radial direction (and thus the leakage) should never disappear. In practice, however, those must be of a certain size to allow significant percolation. Also, at some point the circumferential flow will be more significant than the one through the small channels in axial direction.

In order to achieve a deeper understanding of the seals, however, both the groove and the roughness must be accounted for at the same time, as it can be deduced from the experimental work done by Nakamura and Funabashi [6] and Nitta et al. [4] that the interaction between the two is relevant to determine the flow. The work by Marie et al. [12] is an early attempt to fully consider the problem, but the roughness representation was not sufficient to study its effects fully. More over, the consideration of two equally rough counter surfaces introduces new features that must be understood.

The purpose of this work is, therefore, to develop a model capable of predicting the leak rate accounting for both spiral groove and roughness. The topography is therefore defined by measurements taken of both counter-surfaces, which allows including a realistic representation of all scales (down to a manageable one). This is accomplished by adapting pre-existing models, see [9,10], that can account for roughness so that they can be utilized to study also the effects imposed by the groove. Notice here that no pre-existent knowledge is pre-imposed in the model definition; this information is rather used to qualitatively validate the model results.

In Section 2 the model developed is presented and in Section 3 the model is utilized to describe the flow through two equally rough surfaces. This includes both a comparison of the results given by the model with previous experimental work and introduction of new insights.

2. Leakage model

The model presented follows a structure similar to previous works, e.g. [9,12]. This structure solves the problem in two stages. First the two surfaces are placed in contact under certain load and the contact mechanics theory is used to compute their deformation and obtain the gap left between them. In a second step, the flow through this gap is computed to obtain the leakage. These two problems are decoupled in this structure. This decoupling is justified by the small typical values of fluid pressure (up to few MPa) as compared to the contact pressures (up to few GPa), which allows neglecting the surface deformation due to fluid pressure.

Before going in detail with the solution, however, the solution domain is defined.

2.1. Specification of the solution domain

The criteria used to define the solution domain is to be the smallest possible such that it can account for the structure of the topography. This is necessary for computational reasons.

A significant length in radial direction is required in order to account properly for the irregularities in peaks and valleys, as they appear at very long wavelength and a relatively large amount of peaks shall be considered at the same time. The reason that prevents the decoupling of different peaks is that the amount of contact carried by a certain peak depends on the neighbour peaks. Indeed, if one peak is between two higher ones, it will be difficult for it to engage in contact with the other surface. Moreover, this kind of seals can have a radius of curvature to concentrate the contact region. Therefore, the full length of the seal usually needs to be considered.

In order to choose the length in circumferential direction, it is assumed that the flow is mainly radial. Of course, at very low leak rates, the circumferential flow should be taken in account. But one must considerer that, while the pressure drop in the seal occurs in few millimetres in radial direction, it would occur along few meters in circumferential direction, making it negligible for most applications. More care must be taken to capture the meanders, which can become significantly large as flow in radial direction is more and more restricted. In this study, this length has been enforced by computational limitation. It is realized that, at the smallest leak-rates, meanders might not be accounted for properly.

Because of the usage of periodic boundary conditions in circumferential behaviour, the surface has been mirrored in that direction. The reason for that is that an unrealistic topography would be created on the boundary otherwise and, as it will be seen later on, this could have a significant effect.

The narrow cell selected allows presenting the domain in Cartesian coordinates instead of polar ones, this is

$$\Omega = \{(x,y) \in \mathbb{R}^2 | 0 \le x \le L_x,\ 0 \le y \le L_y\}, \qquad (1)$$

where x stands for radial direction and y stands for circumferential direction. Also, the spiral groove appears as a (irregular) sinusoidal wave with alternating peaks and valleys instead of a connected grove.

2.2. Contact mechanics

The deformation of the topography is computed following the model presented by Sahlin et al. [9]. A summary is given in this section for the sake of completeness. The reader is referred to their article for more details and an algorithm for implementation.

The deformed aperture, h, in the seal is defined as the gap between the two surfaces when they are compressed under a certain load. Therefore, it determines the volume and the geometry through which the fluid can percolate. It can be expressed