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A multi-scale finite element contact model using measured surface roughness for a radial lip seal

Jonathan F. Wenk [a,*], L. Scott Stephens [a,c], Scott B. Lattime [b], David Weatherly [a]

[a] Department of Mechanical Engineering, University of Kentucky, Lexington, KY, USA
[b] The Timken Company, Canton, OH, USA
[c] Bearing and Seals Laboratory, University of Kentucky, Lexington, KY, USA

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ABSTRACT

Historically, large computational requirements have left contact modeling approaches unable to combine multiple-length scale effects (comprised by the macro-scale geometry of the component and sub-micron geometry of the surface roughness) into a single deterministic analysis. This work presents a three-dimensional, multi-scale, finite element contact and deformation model for a worn-in radial lip seal. The model includes elastomer bulk geometry and apex surface roughness measured from an experimentally tested elastomer seal. The work describes the modeling method used to simulate the compressed state of the seal. A statistical parameter analysis of both the compressed and uncompressed surface roughness was performed. Results are presented and discussed with respect to their potential impact on modeling efforts and the operating conditions of the seal.

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1. Introduction

1.1. Surface roughness contact models on bulk geometry

Contact between bodies in relative motion is a key factor in the performance of many mechanical devices. One such device is a radial lip seal (Fig. 1), in which the contact provides the basis for the sealing mechanism – yet contributes to the degradation of the device through frictional heat generation and wear. During dynamic operation, a thin liquid (lubricant) film usually develops at the sealing zone interface. Therefore, the complete modeling of a radial lip seal is a complex, coupled fluid–structure interaction problem with a number of complicated sub-models that span several dimensional scales. In particular, the bulk deformation of the elastomeric lip and how it interacts with the shaft is a primary factor in determining the sealing apparent area.

In juxtaposition stands the detailed surface roughness for the shaft and the elastomer, with dimensional scales on the order of microns – also determining factors in the performance of the seal. Unfortunately, present contact model approaches have been unable to combine the multiple-length scale effects into a single deterministic analysis. The most promising approach has been the finite element (FE) method, but it has not been used successfully in realistic radial lip seal applications where the surface roughness is included due to the computational burden.

The current work presents a multi-scale contact model using the FE method that encompasses all important dimensional scales for radial lip seal-shaft contact, including the bulk deformation of the elastomer and the micro-deformation of the elastomer surface roughness. This work describes the FE modeling method in detail, provides a statistical parameter analysis of both the compressed and uncompressed surface roughness, and discusses the results in the context of lip seal performance.

In general, contact models for surface roughness have included statistical, fractal, multi-scale and FE approaches. Statistical methods include works by Greenwood and Williamson [1] with modifications by Onions and Archard [2], among others. The former work treated each asperity as an identical hemisphere but distributed the heights statistically. The rough surface was then compressed into an opposing smooth, rigid surface. A Hertzian contact model was then used as each sphere contacted the opposing surface. The latter work modified [1] to allow for a statistical variation in the radius of each sphere, making the model one step closer to reality. However, surface roughness is an inherently multi-scale problem where asperities are on top of, and connected to, other asperities – each with characteristic geometry (heights and effective radii) that may range from angstroms to micrometers. Depending upon a given application, any or all of these characteristic lengths may be important.

Fractal [3–6] and multi-scale [7,8] contact models were subsequently developed to capture this span of characteristic lengths

* Correspondence to: Department of Mechanical Engineering, University of Kentucky, 269 Ralph G. Anderson Building Lexington, KY 40506-0503. Tel.: +1 859 218 0658; fax: +1 859 257 3304.
E-mail address: wenk@engr.uky.edu (J.F. Wenk).

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Nomenclature

A_{ij}	Area of Actual Contact (μm^2)
L_x	Length of FE Contact Domain in Axial Direction (μm)
L_y	Length of FE Contact Domain in Circumferential Direction (μm)
S_{al}	Fastest Decay Auto-Correlation Length (μm)
S_{bi}	Bearing Index
S_{ci}	Core Index
S_{dr}	Developed Interfacial Area Ratio (%)
S_{ds}	Summit Density ($1/mm^2$)
S_{dv}	Valley Density ($1/mm^2$)
S_{ku}	Kurtosis
S_q	RMS Roughness (μm)
$S_{q\ air}$	RMS Roughness on Air Side of Contact Domain (μm)
$S_{q\ oil}$	RMS Roughness on Oil Side of Contact Domain (μm)
$S_{\Delta q}$	Root Mean Square Slope (μm/μm)
S_{sc}	Average Summit Curvature (μm)
S_{sk}	Skewness
S_{sr}	Average Summit Radius (1/μm)
S_{td}	Texture Direction (deg)
S_{tr}	Texture Aspect Ratio
S_{vi}	Valley Index
S_z	10 Pt. Height (μm)
x_i	Axial Location (μm)
y_j	Circumferential Location (μm)
β	Angle of Texture Direction from Axial Direction (deg)
η_{pi}	Surface Peak Height (μm)
η	Surface Height (μm)
η_{vi}	Surface Valley Height (μm)

within the contact zone. These models were used in combination with other approaches that capture the macro-scale deformation within the system, in which the surface roughness is part of a larger component. This results in additional layers of multi-scale effects where the geometry of the component may also play a significant role in overall performance. The component macro-geometry may be on the order of millimeters, centimeters or meters in many cases. Therefore, in the seemingly worst-case scenario, a complete component model that includes surface roughness effects could span nine orders of magnitude or more. To address this difficulty multi-scale component models that include surface roughness have used decoupled approaches where the macro-performance of the bulk component resides in a separate model from the detailed surface roughness model. The two models are then coupled through any number of methods. An example of this is found in [9] for rough electrical connectors: The FE method is used to capture the bulk deformation and a separate multi-scale model is used to capture the localized deformations and contact area of the surface roughness.

The FE method is a powerful and prominent tool in the modeling of the component macro-geometry and micro-geometry, but has lagged behind when combining the two scales. The reasons for this were studied in two papers by Thompson [10,11], who demonstrated through a comprehensive review of the literature that the present conventional wisdom is that the FE method cannot be applied to contact analysis of 3D integrated macro-geometries with detailed surface roughness due to the associated computational burden. Two examples of such work are those found in [12,13] where the authors limit their FE models to consider only two-dimensional roughness or single, hemispherical asperities.

Thompson [11] opines that this is now a false limitation, given the recent advances in computational speed, and further points out that models that span a large degree of “multi-scalism” are commonly found in other fields such as biomedicine, where the investigators must fit point clouds of irregular micro-geometry onto large, irregularly shaped macro-components and analyze the integrated system in a single 3D FE model. An example of such work is provided in [14], where the method is applied to generate models for the mitral valve of a heart.

For a thorough review of the different contact modeling approaches, one is referred to the review paper by Bhushan [15], who points out that asperities that comprise surface roughness are not definite objects but instead digitally sampled entities. Thus, measured surface roughness is an extrinsic property, which implies that the proper selection of sampling intervals for a given surface roughness measurement is defined by the complete set of contact conditions in the application itself. Another way of stating this is that the degree of “multi-scalism” required to be modeled within any given problem depends upon the contact conditions. For instance, in hard, lightly loaded contacts such as those found in atomic force microscope tips, the nano-scale and atomic scale effects are very important. By contrast, tribological devices that make use of a soft material that is heavily compressed may need to include only the surface roughness micro-scale geometry.

Such is the case with radial lip seals that operate in the elastic or hyperelastic region of an elastomeric material (typically nitrile butadiene rubber (NBR) or fluorocarbon rubber (FKM)) that is compressed into significant contact with a relatively smooth, relatively rigid metal shaft. These devices are used to contain one medium from another (e.g., to seal lubricant within a bearing housing or prevent the ingress of contaminants into a bearing housing). In these applications, the amount of deformation due to an interference fit and perhaps other mechanical loading (e.g., garter spring) and the apparent area of contact are very large compared to the elastomer surface roughness.

1.2. Rough contact in radial lip seal models

Decoupled multi-scale modeling approaches have been the norm for radial lip seal analysis. A complete lip seal analysis includes a coupled fluid–structure interaction model that computes the soft elastohydrodynamic lubrication parameters at a given operating condition. For a review on lip seal lubrication parameters, one is referred to [16]. These parameters include film pressure distribution, average film thickness, radial and tangential elastomer deformation, power loss, cavitation and flow rate. Several papers detail the modeling approaches [17–21]. Inherent in these models are two central ideas related to surface roughness: (1) a thin film develops in the contact zone between the shaft and elastomer and interacts with the elastomer surface roughness micro-asperities to generate hydrodynamic lift, thus separating the lip from the relatively smooth shaft [22]; and (2) lip seals have a reverse pumping action where fluid, when injected on the air side of the seal, will be pumped upstream toward the (lightly) pressurized oil sump (this is the so-called “fully flooded” condition). This action was observed experimentally and described in [23–26], among others. These observations led to the generally accepted visco-seal concept [25] that explains the reverse pumping mechanism in radial lip seals.

The visco-seal theory depends upon the asymmetrical contact pressure distribution between the elastomer and the shaft in the axial direction, with the peak contact pressure closer to the oil side of the seal. Such a contact pressure distribution is illustrated in

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