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REVIEW OF FUNCTIONAL THEORIES AND NUMERICAL APPROACHES IN ELASTOHYDRODYNAMIC LUBRICATION OF RADIAL SHAFT SEALS

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Abstract

This review explores different functional principles and numerical models of radial shaft seals, with a strong emphasis on the significance of thermo-elastohydrodynamic lubrication (TEHL). The analysis of radial lip seals has evolved from experimental observations to highly complex numerical simulations that consider thermal conditions, micro-surface contact, and the dynamic behavior of seals. Key studies and findings from pioneering researchers are highlighted, providing a comprehensive overview of advancements in this field. Particular attention is given to the quantitative aspects of elastohydrodynamic lubrication (EHL), the influence of surface roughness on back-pumping and other performance factors, as well as the challenges associated with sealing lubricating fluids. This review is based on a wide range of studies and developments in radial lip seal technology.

Keywords: *radial shaft seal, EHL, back-pumping.*

INTRODUCTION

Radial shaft seals play a critical role in preventing contaminants from entering rotating machinery, ensuring operational reliability and extended service life [1]. These seals are indispensable across a diverse range of industrial applications, from automotive transmissions to heavy-duty hydraulic systems, as they establish a dynamic contact between a rotating shaft and a stationary sealing lip [2]. The performance of radial shaft seals is essential for maintaining the efficiency and integrity of lubricated systems, where leakage prevention is a primary concern [3].

Radial shaft seals consist of a spring energized sealing edge connected to a metal reinforced static body via a flexible membrane, as shown in ***Fig. 1 (a)***. The oil side contact angle between the sealing edge and the shaft is greater than air side angle. Additionally, the spring energizer features a lever arm relative to the sealing edge, creating an asymmetric pressure distribution between the seal and the shaft.

To achieve optimal sealing performance, a thin lubricating film must form between the sealing lip and the shaft surface [3]. While this lubricating film reduces friction and wear, it also creates a potential pathway for leakage, which must be carefully controlled [4]. The formation and behavior of this lubricating film is influenced by numerous interacting parameters, including the properties of the sealing material, lubricant rheology, surface topography of seal and shaft, operating conditions (pressure, speed, temperature), and seal geometry. By definition, the combination of hydrodynamic lubrication, elastic deformation of the contacting surfaces, and thermal effects constitutes the subject of TEHL. Understanding the complex interactions among these factors is crucial for designing effective sealing

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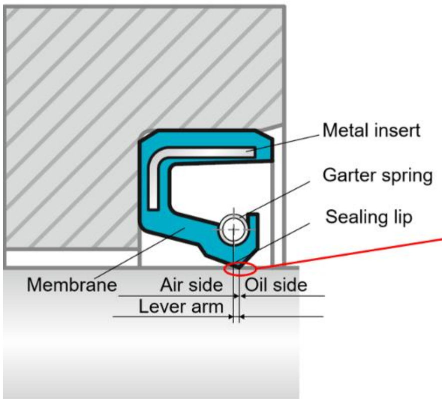

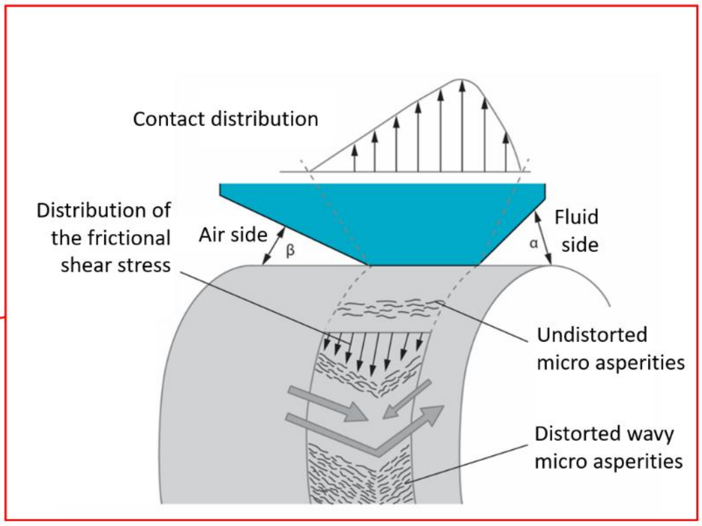

Fig. 1. (a.) *Components of the radial shaft seal* ***(b.)*** *Sealing edge distortion*

solutions and predicting seal performance under varying operating conditions [4].

EXPOSITION

The research into the tribological behavior of rotary shaft seals has been ongoing for decades, yet a comprehensive understanding remains elusive. This complexity arises from the multitude of interacting parameters that govern the EHL regime at the seal-shaft interface. The primary challenge lies in accurately modeling the thin lubricant film that exists between the sealing lip and the rotating shaft, with a thickness typically ranging from sub-micrometer to several micrometers. For context, the surface roughness of the shaft is often comparable in magnitude to the fluid film itself. Consequently, proper modeling of the fluid film necessitates accounting for shaft roughness.

Additionally, under dynamic operation, radial shaft seals exhibit an active sealing mechanism that prevents fluid leakage from the oil to the air. This mechanism operates by continuously pumping fluid from the air side to the oil side. The principle behind this fluid transport is explained by several pumping hypotheses, all of which are based on the asymmetric contact pressure distribution between the sealing lip and the shaft. The four major hypotheses describing this mechanism are:

- Distortion Hypothesis
- Side Flow Hypothesis
- Oscillation Hypothesis
- Viscoelastic EHL hypothesis

Initially proposed by Kammüller [7], the distortion hypothesis suggests that axial wear patterns in the sealing lip undergo circumferential deformation due to the rotating shaft and non-uniform pressure distribution ***Fig. 1 (b)***. This deformation creates grooves and ridges that divert fluid flow axially, causing dynamic pressure to increase just upstream of the area of maximum contact pressure. When this dynamic pressure exceeds the mean sealing pressure, the sealing lip is lifted slightly, allowing fluid to transfer across the high-pressure area. The inherent asymmetry in pressure promotes net fluid flow from the air side to the oil side.

The side flow hypothesis, presented by Müller [8], states that active sealing can occur even in the absence of axial wear structures. According to this theory, randomly scattered micro-asperities on the sealing edge generate microscopic pressure fluctuations as the shaft rotates. These localized pressure peaks and valleys cause the surrounding fluid to divert or be drawn through the sealing interface. The lower pressure gradient typically present on the air side facilitates net fluid transport toward the oil side.

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Additionally, cavitation zones may form, further drawing fluid into the sealing gap.

The oscillation hypothesis, proposed by Jenisch [9], assumes that if the sealing edge is mounted or axially misaligned with slight eccentricity relative to the shaft axis, it undergoes axial oscillations. This back-and-forth "wiping motion," combined with the asymmetric pressure distribution, enables fluid transfer from the air side to the oil side, similar to the behavior of a hydraulic rod seal.

The viscoelastic EHL hypothesis, introduced by Stakenborg [10], highlights the role of the viscoelastic properties of the seal material in fluid film formation. This lubrication mechanism arises from the dynamic excitation of the sealing lip, caused by factors such as shaft unroundness or radial movements of the shaft center. The viscoelastic properties of the sealing material play a crucial role; if the sealing material was purely elastic and without inertia, no separation between the seal and shaft would occur, and no fluid film lubrication would be the outcome. However, the viscoelastic and inertial characteristics of the seal material create fluid-filled clearances with non-uniform geometry, enabling visco-elastohydrodynamic lubrictation (VEHL). This mechanism generates a positive load-carrying capacity similar to that of a journal bearing. Entrainment and squeeze effects further contribute to the load-carrying capacity of the fluid film.

The literature indicates [11] that these hypotheses represent complementary pumping effects that collectively define the active sealing behavior of radial shaft seals. Due to challenges associated with experimentally analyzing micrometer-thick fluid films in radial shaft seals, there has been sustained interest in numerically solving the complex EHL problem. The following sections provide an overview of relevant numerical studies on the lubricating fluid film and functional sealing mechanism of radial shaft seals.

Early elastohydrodynamic lubrication models, that incorporated surface roughness effects, treated asperities as sine functions. In the study by Hajjam and Salant, roughness was modeled as the sum of two sinusoidal functions. Salant [12] further advanced the theoretical understanding of elastomeric seal lubrication. Early EHL models relied on analytical or simplified numerical solutions to the non-mass-conserving Reynolds equation, as well the radial deformation and tangential distortion of the sealing edge. Subsequent research emphasized the need to account for mixed lubrication regimes, where both hydrodynamic and asperity contact contribute to load support. Shi and Salant [13] developed a mixed, soft elastohydrodynamic lubrication model that included interasperity cavitation, surface shear deformation, and micro-EHL effects. Their numerical solution involved solving a modified Reynolds equation that accounted for cavitation and surface deformation. The study concludes that interasperity cavitation is significant even at low speeds, asperity flattening is essential, and shear deformation plays a critical role in preventing leakage.

Later models expanded upon this foundation by incorporating thermal effects into the sealing contact. Kang and Sadeghi [14] used Salant's hydrodynamic model to investigate local TEHL behavior. Day and Salant extended these studies to conduct comprehensive TEHL analyses [14]. Maoui, Hajjam, and Bonneau presented a numerical analysis on the thermal effects on the elastohydrodynamic behavior of elastomer radial shaft seals [15]. Their approach coupled thermal solutions between the shaft and fluid film, demonstrating that local temperature significantly increases with shaft speed, influencing film thickness and power loss.

Recognizing the limitations of axisymmetric finite element analysis (FEA) assumptions, researchers began incorporating three-dimensional (3D) lip deformations into their models. Maoui, Hajjam, and Bonneau [16] compared axisymmetric and 3D

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elastic methods, showing that accounting for 3D lip deformation influences deformation distribution significantly affects deformation distribution and pumping rate values. The impact of shaft surface finish on seal performance also became a focus of interest. Jia et al. [17] developed a simulation model, verified through experiments, to predict pumping by shafts with varying surface finishes, coupling fluid mechanics analysis with seal deformation analysis.

Wennehorst [18] employed experimental and theoretical approaches, including hybrid finite element formulations, to investigate lubrication and friction in soft, rough, conformal sliding contacts.

Yang et al. [19-21] introduced direct numerical simulation of rotary lip seals, marking a significant step forward in transitioning from experimental testing to analytical modeling techniques. Ribbed helix lip seals, critical for preventing leakage in automotive applications, owe their success to strategically designed ribbed helix features that actively pump lubricant back into the sealed space. Key performance factors include the number of ribs, their height, and the helix angle. Numerical tools such as FEA and computational fluid dynamics (CFD) have been used by Wen et al. [22] to optimize design, with increasing emphasis on fluid-structure interaction for accurate predictions of oil pumping behavior and film thickness. Dakov [23] highlighted the role of such simulations in expanding the high-pressure zone of the convergent area between the rib on the air side and the lip, enabling high pumping rates and enhanced sealing effectiveness. Numerical models validated with experimental data are essential for developing high-performance, custom-tailored lip seals that meet the sophisticated requirements of modern mechanical systems. A triangular pressure contour between the rib and the sealing edge, referred to as the pressure valley, is an important factor. Hydrodynamic pressure for a specified lubricating fluid film is analyzed using the Reynolds partial differential equation. Recent design developments aim to optimize the sealing aid for equal applicability in both shaft rotation directions.

Wenk et al. [24] presented a 3D, multiscale FEA contact model of a worn-in radial lip seal, incorporating measured surface roughness data into the bulk geometry. The work utilized micro-scale surface roughness measurements from five points around the circumference of a worn seal. It compared compressed and uncompressed surface roughness through statistical parameters. The surface roughness exposed to the lubricant and shaft in a lip seal exists in an extremely compressed state. A multi-scale FEA contact model was created by matching measured surface roughness data to a worn lip seal's bulk geometry and then compressing the lip seal surface onto a smooth, rigid shaft.

Grün et al. [4] extended the 3D multiscale FEA model to simulate of the microscopic distortions within the contact area between the shaft surface and sealing edge. The principle of sealing edge distortion relies on the microscopic effects within the sealing contact; therefore the roughness of the sealing edge must be considered. A numerical approach was applied to generate rough sealing edge surfaces. FEA was employed to simulate structural mechanics problems. Tangential distortions of the sealing edge surface in the circumferential direction were confirmed, and the relationship between the pressure distribution and the local tangential deformation in the sealing contact was determined for both ideally smooth and rough surfaces. This work numerically verified the sealing edge distortion principle postulated by Kammüller. Later, the research group [25] extended the analyses by employing actual measured surface data instead of numerically generated rough surfaces. Rough sealing edge surfaces with varied roughness parameters were considered. The study presented in situ observations of the lubrication and sealing behavior of rotary shaft seals based on the alignment of hydrodynamically active roughness topographies.

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The research by Grün et al. [26] on surface roughness focused on the hydrodynamic action of rough elastomer sealing edge surfaces, assuming the shaft surface to be ideally smooth. Data from deformed rough sealing edge surface was introduced directly from earlier finite element simulations into the computational domain, and the method also enabled the incorporation of surface measurement data. The numerical method used to calculate transient multiphase flows in the lubricant film was CFD. This approach comprised a mixture model for three fluid phases (oil, oil vapor, and air) in a three-dimensional micro-scale computational domain, solving conservation equations for mass and momentum using the finite volume method for discretization and the implicit method for pressure-linked equations. These numerical efforts achieved significant milestones, such as demonstrating the existence of a stable phase boundary between the liquid oil and gaseous air phases when unsteady flow processes and the multiphase flow in the sealing gap were considered. The validity of the model was confirmed by high concurrence between calculated mass flow rates and experimental data, providing valuable insights into sealing and lubrication mechanisms. Key conclusions indicated that the dynamic sealing gap is non-uniform circumferentially, featuring a prevailing tangential flow. The method offers ample opportunities for future research, such as incorporating heat transfer and elastic deformations.

CONCLUSION

The study of radial shaft seals highlights the intricate interplay of mechanical, tribological, and fluid dynamic phenomena that govern their sealing performance. From the foundational understanding of EHL to the more advanced TEHL models, research has progressively unraveled the mechanisms behind active sealing behavior. The four major hypotheses – distortion, side flow, oscillation, and viscoelastic EHL – emphasize the multifaceted nature of fluid transport across the sealing interface.

Numerical modeling has proven to be a powerful tool in addressing the limitations of experimental analysis, enabling detailed simulations of fluid film behavior, surface roughness effects, and thermal influences. The integration of FEA and CFD, particularly in multi-scale and 3D contexts, has significantly enhanced the predictive capabilities for seal performance under diverse operating conditions.

Recent advancements in ribbed helix lip seal design and multiphase flow modeling underscore the critical role of combining experimental validation with simulation to optimize sealing efficiency. As mechanical systems continue to evolve, the demand for high-performance, custom-tailored sealing solutions will only increase. Future research should prioritize the incorporation of real-time deformation, heat transfer, and material behavior to further refine the understanding and design of radial shaft seals.

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