VDMA
Fluid Power Association

23rd ISC

International Sealing Conference

Stuttgart, Germany
Sept.30 - Oct.1, 2026

Sealing the future –
Facing the challenges of tomorrow

UNI STUTTGART

Fachverband Fluidtechnik im VDMA e. V. Lyoner Str. 18
50628 Frankfurt am Main
Germany

Phone +49 69 6603-1513
E-Mail maximilian.baxmann@vdma.eu

Internet www.vdma.eu/fluid

A bi-directional shaft seal concept for high-speed rotary applications

Peter Bauer, Nino Dakov, Martin Franz

This study presents a novel bi-directional shaft-seal concept designed for high-speed rotary applications, utilizing a phase-shifted wave technology to achieve the required sealing performance. The essence of this technology lies in its unique groove configuration: multiple grooves, each featuring single-sided waviness, are arranged so that the minimal cross-section of one groove aligns with the maximal cross-section of a neighboring groove. This deliberate phase shift creates a dynamic, bi-directional back-pumping effect along the sealing interface, realizing the basic idea of a double-helical hydrodynamic feature while avoiding the drawbacks associated with intersecting open helical grooves. As a result, the seal establishes a robust fluid barrier that functions efficiently in both rotational directions. This approach inherently minimizes direct contact between the sealing surfaces, leading to extremely low friction and negligible wear, as verified through extensive laboratory testing. The test results demonstrate that, even under rigorous high-speed conditions, wear rates remain below detectable thresholds and friction levels are substantially lower than those of conventional shaft seals. Collectively, these outcomes highlight the phase-shifted wave technology as an effective and durable solution for advanced rotary systems, promoting both superior operational efficiency and extended service life.

1 Introduction

Radial shaft seals are widely used in mechanical systems to separate a lubricated region from the surrounding environment while accommodating a rotating shaft. Their functionality relies on a delicate balance between contact, lubrication and hydrodynamic effects occurring within the sealing interface. Although a nominally closed contact line forms between the sealing lip and the shaft, it is well established that a thin lubricant film exists during operation, which fundamentally governs sealing performance [1], [2].
The presence of this thin film implies that sealing is not a purely static phenomenon, but rather the result of dynamic interactions in the micrometer-scale contact region. In particular, a continuous leakage tendency exists due to pressure differences and shear-driven transport mechanisms. To maintain leak-tightness, an effective counter-mechanism must transport fluid from the air side back toward the oil side. This process is commonly referred to as back-pumping.
The effectiveness of a shaft seal is therefore strongly linked to its ability to generate and sustain such a back-pumping effect. Ideally, this effect should be continuous, robust against variations in operating conditions and, increasingly important, independent of the direction of shaft rotation. The latter requirement has gained significant relevance in modern applications, where rotational direction may change frequently.
Applications such as electric drive systems impose particularly demanding requirements on shaft seals. These include high surface speeds, wide temperature ranges,

varying lubrication regimes and bi-directional operation. Under these conditions, classical sealing solutions often reach their functional limits, especially with respect to frictional losses and wear.
Consequently, there is a clear need for new sealing concepts that combine efficient hydrodynamic back-pumping with reduced contact forces and improved robustness. In the following sections, we discuss the limitations of existing solutions and introduce a novel phase-shifted wave concept as a means of achieving truly bi-directional hydrodynamic sealing under high-speed conditions.

2 State of the art

2.1 Back-pumping strategies for shaft seals

2.1.1 Conventional radial shaft seals with line contact

Traditional radial shaft seals, with and without hydrodynamic features, all use a sealing lip that forms a narrow circumferential line contact with the shaft. The contact is maintained through elastic deformation and often a garter spring, resulting in a closed sealing line that is statically capable of preventing leakage. However, purely static sealing would not suffice in dynamic applications, as even minute imperfections lead to leakage paths.

The dynamic sealing performance of such seals is therefore governed by hydrodynamic effects that develop within the contact interface. These effects arise from a combination of surface roughness, material properties and deformation of the sealing edge. During operation, these factors lead to the formation of microstructures, such as wear-induced grooves [3], which contribute to a pumping action toward the oil side.

This hydrodynamic pumping is inherently dependent on the direction of shaft rotation and on the history of operation [4]. As a result, the sealing performance of conventional designs may differ significantly depending on the direction of initial conditioning. This directional sensitivity represents a fundamental limitation in applications requiring frequent reversals.

2.1.2 Wide-contact sealing concepts for high-speed rotary applications

At higher surface speeds, the frictional losses associated with line-contact seals become increasingly critical. To mitigate excessive heat generation and wear, alternative sealing concepts based on wider contact areas have been developed. These designs typically use PTFE or advanced elastomeric compounds and rely more strongly on engineered hydrodynamic features [5].

Such seals operate with reduced contact pressure and enhanced lubrication conditions. Their performance is therefore less dependent on elastic deformation and more strongly influenced by surface structuring and fluid dynamics. Various approaches have been proposed to improve hydrodynamic behavior, particularly with respect to back-pumping.

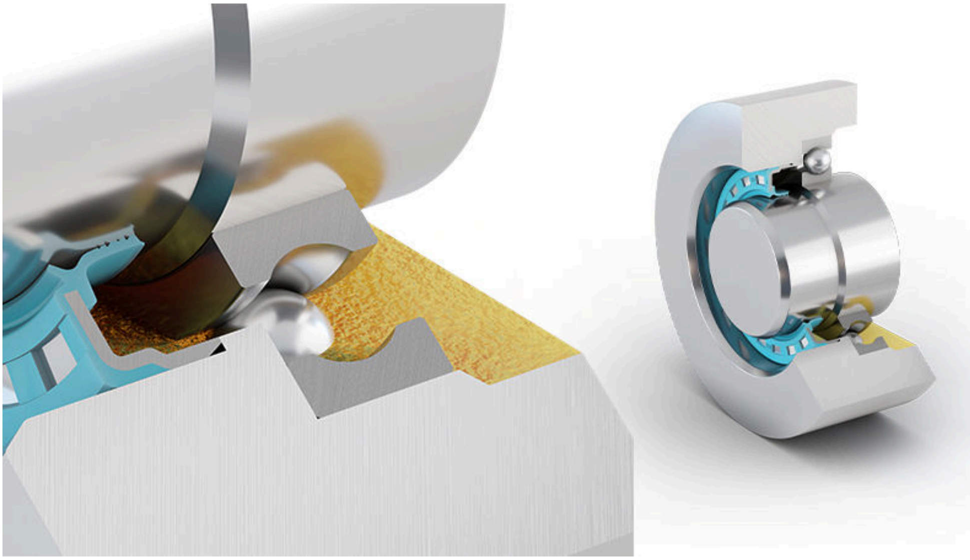


Figure 1: Elastomer lip seal with a wide-contact hydrodynamic feature design for high-speed rotary applications

A. Unidirectional pumping via spiral grooves

One of the most effective hydrodynamic features is the use of spiral grooves [6]. These grooves act analogously to an Archimedes screw, continuously transporting fluid in a defined axial direction. When properly designed, they provide a strong and stable pumping effect.

However, spiral grooves are inherently unidirectional. Reversing the direction of shaft rotation reverses the pumping direction, potentially leading to leakage. This limitation restricts their applicability in systems requiring bi-directional operation.

B. Concentric groove structures

To address the issue of directional sensitivity, concentric groove structures have been introduced. These designs eliminate preferential flow directions and therefore behave symmetrically with respect to rotation. However, this symmetry comes at the expense of active pumping capability.

Instead of generating a back-pumping effect, concentric grooves act primarily as a flow restriction. The sealing function is therefore based on limiting leakage rather than actively returning fluid to the oil side. As a consequence, their performance is confined to a relatively narrow range of operating conditions.

C. Undulated sealing edges

Another approach to bi-directional sealing is based on undulated sealing edges. These structures introduce an alternating geometry along the contact line, which can create localized pressure gradients and induce a pumping effect in both rotational directions.

In practice, however, this mechanism is discontinuous. The sealing edge acts similarly to a scraping element, intermittently transporting fluid from the side with a lower axial contact stress gradient to the side with a higher one. Because there is no perfectly sealed interface, some fluid always passes underneath the sealing lip. At higher speeds, this fluid may escape entirely from the contact region, particularly on the air side, leading to leakage.

D. Grooves with single-sided waviness

A particularly promising concept is the use of grooves with single-sided waviness. These grooves create a consistent pressure gradient along their geometry, enabling continuous fluid transport in a defined direction. Within the contact region, this leads to effective back-pumping.

Nevertheless, this concept exhibits a fundamental restriction. It is primarily effective within the contact zone and does not actively entrain fluid from outside this region. In other words, if lubricant reaches the air side beyond the contact interface, it is not necessarily transported back to the oil side.

2.2 Requirement for optimal back-pumping

From the analysis of these approaches, a generalized requirement for effective bi-directional hydrodynamic sealing can be formulated.

> *“An oil droplet entrained within the sealing interface should be continuously guided toward the oil side, irrespective of its circumferential position or the direction of rotation.”*

This implies that the fluid must always encounter geometrical features that redirect its motion in the desired direction. Discontinuities or dead zones, where fluid transport is not actively controlled, must be avoided. The challenge therefore lies in designing a surface structure that ensures continuous, direction-independent fluid transport across the entire sealing interface.

3 Phase-shifted wave design

The proposed phase-shifted wave design builds upon the principle of single-sided waviness and extends it in a manner that addresses its inherent limitations. The central idea is to distribute multiple grooves across the contact width and to establish a controlled interaction between them. Each groove retains the characteristic single-sided waviness that induces a local pumping effect. However, instead of acting independently, the grooves are arranged so that fluid can transferred from one groove to the next.

The key innovation lies in the relative positioning of adjacent grooves (Figure 2). The geometry is designed so that the location of maximum groove cross-section in one groove coincides with the minimum cross-section of the neighboring groove. This phase shift minimizes the distance that fluid must travel when transitioning between adjacent grooves. As a consequence, fluid is not confined to individual grooves but is continuously transferred from one groove to another. This results in a coherent flow network that spans the entire contact region (Figure 2 and Figure 3).

The hydrodynamic behavior of this structure can be understood as a superposition of local pumping effects and inter-groove transfer mechanisms. Within each groove, the asymmetric geometry generates a pressure gradient that drives fluid toward the oil side. At the same time, the phase shift ensures that fluid exiting one groove is immediately entrained into the neighboring groove. This continuous transfer prevents stagnation and ensures that any fluid within the interface is actively transported. Importantly, the mechanism functions independently of the direction of rotation, since the underlying geometric relationships remain unchanged.

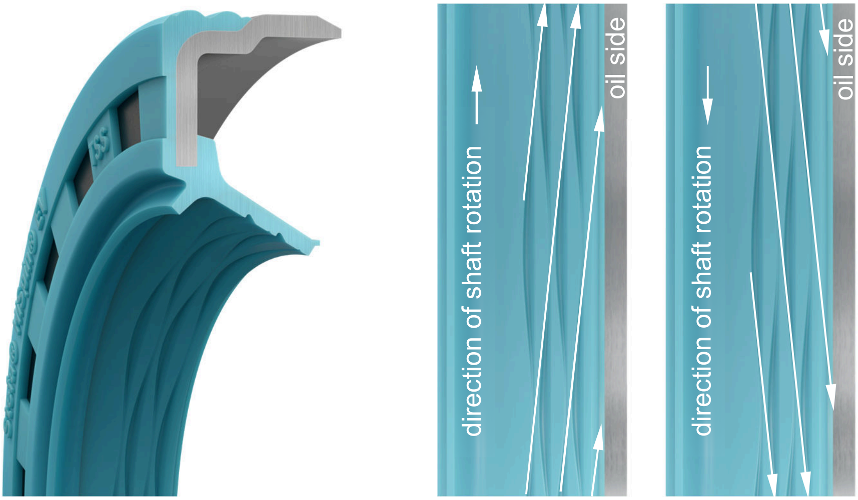


Figure 2: Phase-shifted arrangement of neighboring grooves with resulting fluid flow paths across the sealing interface

The resulting flow pattern resembles that of a theoretical double-helical groove system, in which fluid is transported along intersecting helical paths. However, double-helical designs are not used in practice because of the open, intersecting channels, which may compromise leak-tightness.

In contrast, the phase-shifted wave design achieves a similar functional effect without introducing open channels. The surface remains closed in the circumferential direction, preserving static sealing capability while enabling dynamic fluid transport.

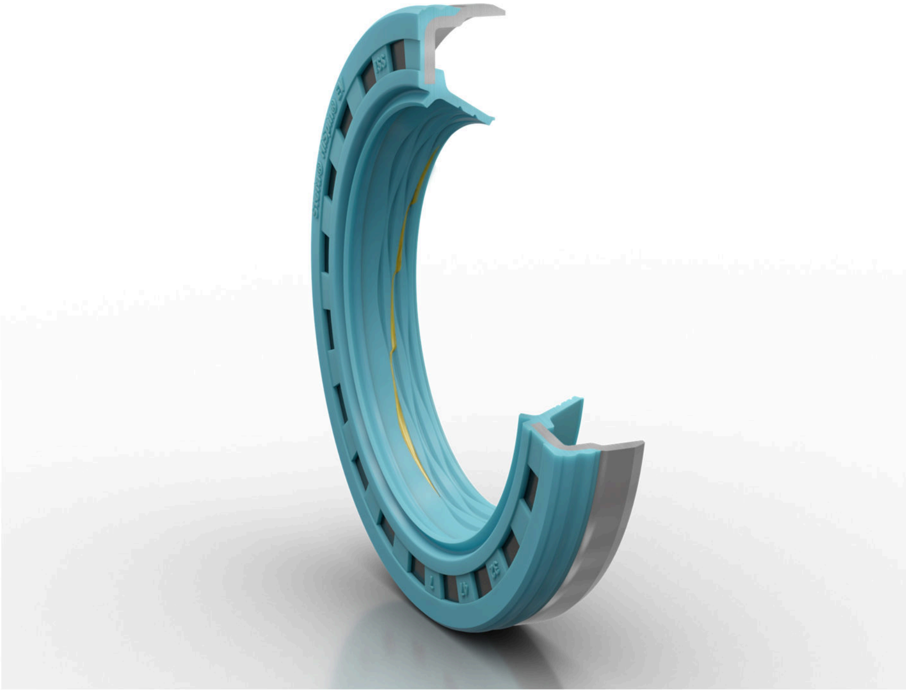


Figure 3: Oil flow across the sealing interface at bi-directional hydrodynamic (phase-shifted wave) design

By ensuring continuous and direction-independent fluid transport, the phase-shifted wave design fulfills the previously defined criterion for optimal back-pumping. The resulting hydrodynamic support reduces the effective contact load between the seal and the shaft, leading to lower friction and reduced wear. At the same time, the robust fluid barrier prevents leakage even under demanding conditions, making the design suitable for high-speed applications with bi-directional operation.

4 Test results

To validate the performance of the proposed design, a series of laboratory tests was conducted using seals manufactured from a high-performance FKM material suitable for high-speed operation. A 38 x 52 x 7 mm seal was used. The tests were carried out on a rotary test rig designed to simulate realistic operating conditions, including elevated speeds, controlled oil supply and temperature stabilization.

The shaft surfaces used in the tests were prepared with standardized roughness and hardness to ensure reproducibility. The lubrication system was configured to provide a controlled oil supply, representing conditions ranging from oil mist to flooded environments.

The experimental program focused on evaluating three key performance criteria: friction, back-pumping capability and leak-tightness. The seals were subjected to continuous operation over extended periods, including cycles with alternating rotational direction.

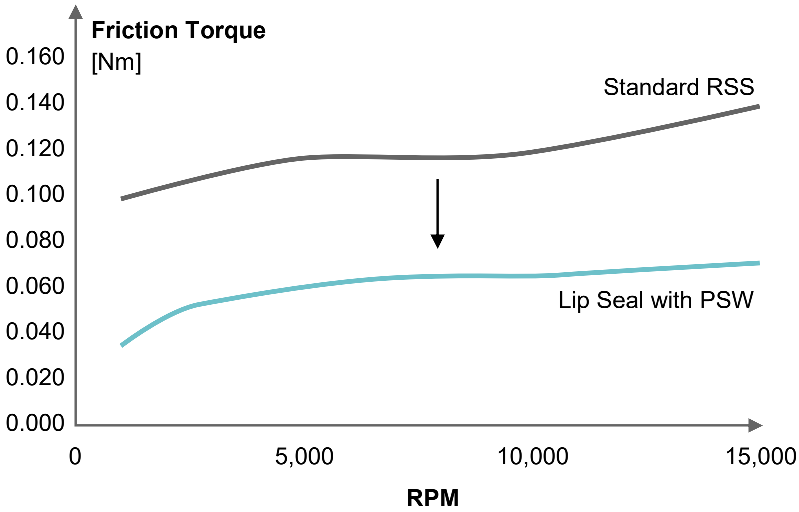


Figure 4: Friction torque as a function of shaft speed for a shaft diameter of 38 mm

During testing, friction torque was recorded continuously, and leakage was monitored by collecting and measuring any escaping fluid. After completion of the tests, the sealing surfaces were inspected for wear.

The measured friction torque values indicate a substantial reduction compared to conventional radial shaft seals (Figure 4). This reduction can be attributed to the presence of hydrodynamically supported contact, in which the fluid film partially separates the sealing surfaces. The reduced contact load results in lower shear stresses and consequently lower friction losses. This effect becomes more pronounced at higher speeds, where hydrodynamic pressures increase.

The experimental observations confirm the presence of a continuous back-pumping effect in both directions of rotation. No direction-dependent behavior was observed, indicating that the phase-shifted geometry successfully eliminates directional sensitivity. Moreover, the pumping rate was found to be significantly higher than that of a conventional helix groove on the sealing lip (Figure 5).

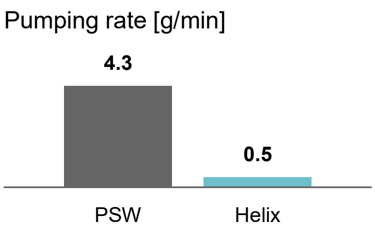


Figure 5: Back-pumping behavior of inversely mounted seals at 7,000 rpm

A durability test with a total duration of 1,000 h was conducted at 100 °C and 1/8 fluid-fill level at the seal-shaft interface (Figure 6). The test cycle is shown in Figure 6. The fluid transport mechanism proved stable across the tested operating range, with no evidence of performance degradation under reversed rotation. All tested specimens remained leak-tight throughout the test duration, demonstrating the effectiveness of the hydrodynamic barrier. Wear analysis revealed no significant material removal or damage to the sealing edge (Figure 7). The wear patterns were negligible and did not exhibit characteristic features associated with abrasive or adhesive wear. This finding is consistent with the reduced contact stresses and improved lubrication conditions.

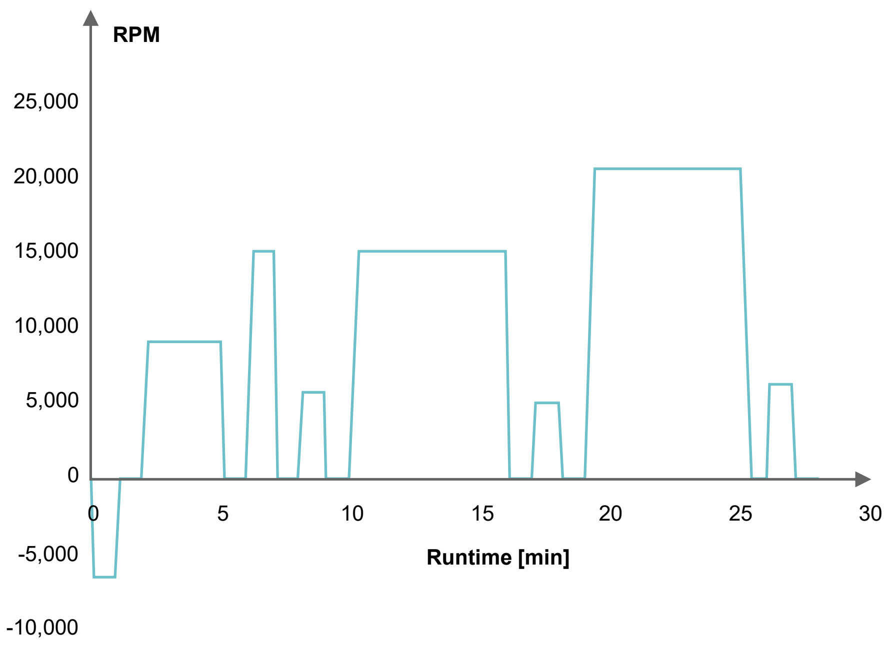
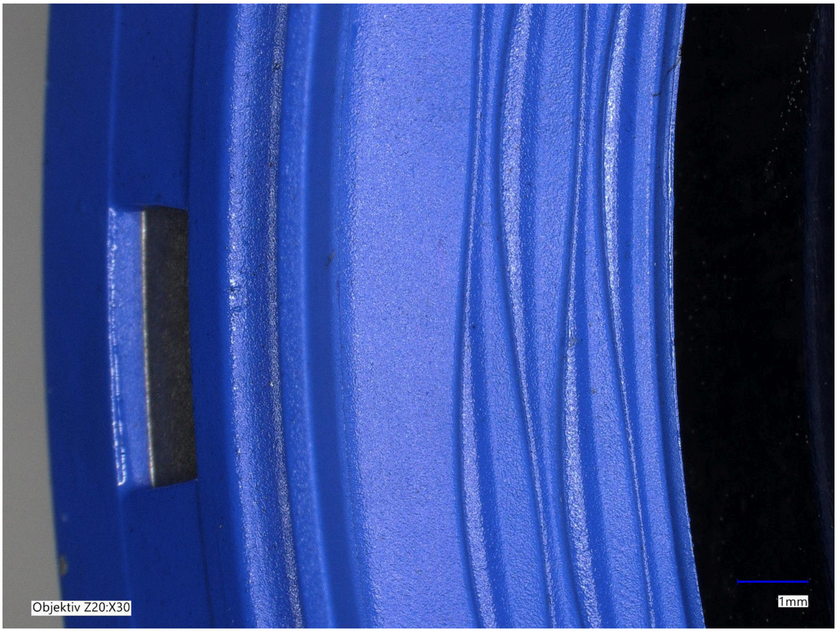
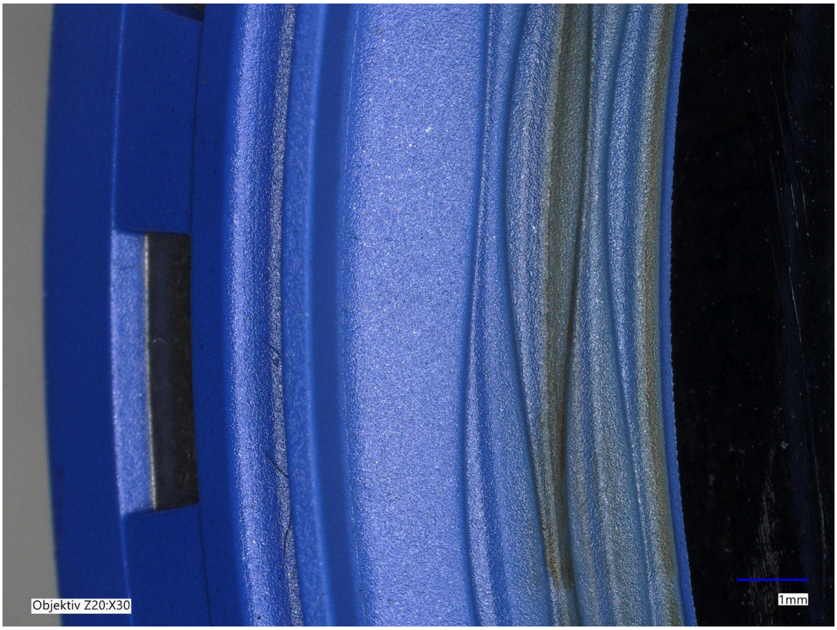


Figure 6: Dynamic test cycle in the durability test (1,000 h)



a)



b)

Figure 7: Running surface on the seal a) before and b) after the durability test (1,000 h)

The combination of low friction, negligible wear and robust back-pumping highlights the effectiveness of the phase-shifted wave design. The experimental results confirm that the concept not only achieves bi-directional functionality but also enhances overall sealing performance.

5 Summary and conclusion

A novel shaft seal concept based on a phase-shifted wave geometry has been developed and experimentally validated. The design addresses the fundamental challenges associated with bi-directional sealing in high-speed applications by introducing a continuous hydrodynamic pumping mechanism. The phase-shifted wave arrangement of grooves enables fluid to be transported seamlessly across the sealing interface, ensuring that any oil present within the contact region is redirected toward the oil side. This mechanism operates independently of the direction of rotation and maintains its effectiveness across a wide range of operating conditions.

Experimental investigations demonstrate that the proposed design achieves significantly reduced friction, negligible wear and reliable leak-tightness. These improvements stem from the combined effects of hydrodynamic pressure generation and optimized fluid transport pathways. Compared with conventional sealing concepts, the phase-shifted wave technology provides a unique combination of directional independence, continuous pumping and minimized contact interaction. This makes it particularly suitable for modern drive systems, where efficiency, durability and bi-directional capability are critical requirements.

In conclusion, the presented concept represents a significant advancement in rotary shaft sealing technology and offers a promising pathway toward next-generation sealing solutions for demanding high-speed applications.

6 References

[1] Müller, H. K., Nau., B. S.: *Fluid sealing technology*, Marcel, New York, 1998, ISBN 978-0-8247-9969-4.

[2] Horve, L.: *Shaft seals for dynamic applications*. CRC Press, 1996. ISBN 978-0-8247-9716-4.

[3] Schallamach, A.: *How does rubber slide?*. Rubber Chemistry and Technology 44 (5), 1971, 1147–1158.

[4] Dakov, N.: *Elastohydrodynamic lubrication analysis of a radial oil seal with hydrodynamic features*, Tribology International 173, 2022, 107653.

[5] Dakov, N.: Elastohydrodynamische Simulation von Wellendichtungen am Beispiel der PTFE-Manschettendichtung mit Rückförderstrukturen. Dissertation, 2020, Institute for Machine Components, University of Stuttgart, Germany.

[6] Bauer, F.: *PTFE-Manschettendichtungen mit Spiralrille: Analyse, Funktionsweise und Erweiterung der Einsatzgrenzen*. Dissertation, 2008, Institute for Machine Components, University of Stuttgart, Germany.

7 Authors

Trelleborg Sealing Solutions
Schockenriedstr. 1, 70565 Stuttgart, Germany:

Peter Bauer, peter.bauer@trelleborg.com

Dr. Nino Dakov, ORCID 0000-0002-0989-9943, nino.dakov@trelleborg.com

Martin Franz, ORCID 0009-0008-0457-9116, martin.franz@trelleborg.com

https://doi.org/10.61319/J2MFEV3N