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Full Scale Test of Slewing Bearing Seals

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Today's requirements for sustainability, energy efficiency, and functionality create new challenges for us as bearing manufacturer. This is particularly evident in the development of sealing systems for slewing bearings, which can achieve diameters of up to 6 meters. To meet these requirements, we work with various partners to further develop and optimize existing sealing system and adapt them specifically to the relevant operating conditions.

This presentation highlights our experience in developing and optimizing sealing systems for large-diameter bearings, particularly those used in wind turbines. After an introduction to relevant bearing designs, the historical development of the requirements for sealing systems will be presented – from simple sealing lips, as still used today in slewing bearings, to radial shaft seals for continuously rotating main bearings in wind turbines.

On our full-scale slewing bearing test riges, various designs of radial shaft seals, including those with garter or finger springs, were tested for performance under realistic operating conditions. The results show that sealing concepts for small bearings in frequently used industrial applications cannot simply be scaled up for large bearings. In large roller bearings, the deformation of the rings and also of the connecting structure plays a decisive role in the operating behaviour of the sealing system.

We present how our findings and results from the tests have been incorporated into the optimization of alternative sealing lip systems.

1 Introduction Slewing Bearings

Unlike conventional industrial bearings, large-diameter bearings are generally custom-engineered for their intended application. They frequently serve as critical components that enable the rotational movement of major structural assemblies. The installation position of the bearing within a machine or structure has a significant influence on both its design and operational behaviour. Consequently, bearing replacement is often a complex and labour-intensive process that may require the partial or complete disassembly of the surrounding equipment.

Large-diameter bearings are typically subjected to combined radial, axial and moment loads. To accommodate these operating conditions, they are designed as moment bearings capable of transmitting high overturning moments. In contrast to conventional bearings, moment loading is an inherent aspect of their operation, resulting in a non-uniform circumferential load distribution. The magnitude and location of these load zones depend on the direction and intensity of the external loads and may vary continuously during service.

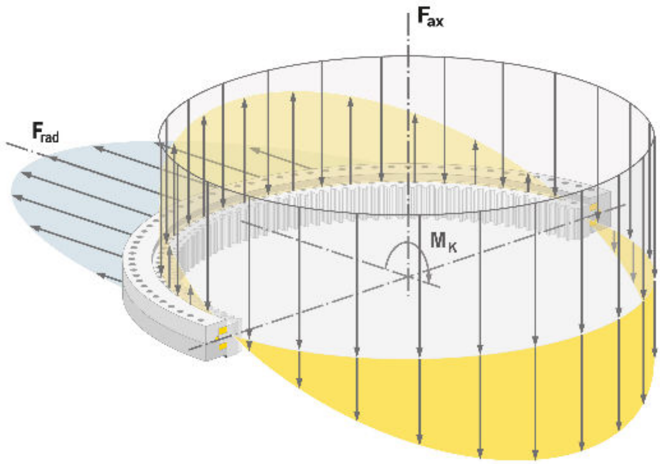

Figure 1: Load distribution in bearings

Owing to their design, large-diameter bearings generally have a relatively small cross-sectional height compared with their diameter and therefore exhibit lower structural stiffness than conventional bearings. Combined with fluctuating operating loads, this can result in ring deformations of up to ±2.5 mm. As the direction of the principal load changes, the deformation pattern continuously shifts around the bearing circumference.

The resulting relative movement between the bearing rings leads to variations in the sealing gap that must be accommodated by the sealing system. Reliable sealing performance is therefore essential to retain lubricant within the bearing while preventing the ingress of external contaminants such as water, sand and dust.

Large-diameter bearings are manufactured in a wide range of sizes depending on the application. Bearing diameters typically begin at approximately 0.8 m and can exceed 22 m. For diameters greater than 9 m, segmented bearing designs are commonly employed to facilitate manufacturing, transportation and installation.

The substantial variation in bearing dimensions requires sealing solutions tailored to the respective bearing size.

2 Sealing requirements for Slewing Bearings

The functionality of a large-diameter bearing is based on rolling contact between the bearing rings and rolling elements. To ensure reliable operation throughout the bearing's service life, adequate lubrication must be maintained under all operating conditions. In the vast majority of applications, this is achieved by means of grease lubrication. Consequently, the sealing system plays a vital role in maintaining bearing performance by retaining lubricant within the bearing while simultaneously protecting it from environmental influences.

Effective lubrication depends on two key factors: the availability of a sufficient quantity of lubricant at the rolling contacts and the preservation of lubricant properties throughout service life. The sealing system must therefore minimize lubricant loss while preventing the ingress of contaminants that could degrade lubricant performance and accelerate wear of the bearing components.

Since the large-diameter bearings are installed without external housing, the seals are placed directly between the bearing rings. These seals must maintain their functionality under all operating conditions, including variations in the sealing gap caused by bearing deformation and changing load conditions

2.1 Prevention of uncontrolled grease leakage

Large-diameter bearings operate under a wide spectrum of motion conditions, ranging from slow oscillatory movements to continuous rotation. As a result, grease fill levels vary according to the application and operating requirements. Bearings are typically supplied with a grease fill corresponding to approximately two-thirds of the available free volume, which redistributes naturally during operation.

Fresh grease is supplied through relubrication ports, while aged or displaced grease is discharged through dedicated outlet openings. The sealing system is responsible for preventing grease leakage between the bearing rings and ensuring that an adequate supply of lubricant remains within the bearing throughout its service life.

2.2 Protecting the bearing from environmental influences

Large-diameter bearings frequently operate in demanding environments and are exposed to adverse weather conditions such as rain, snow and solar radiation, as well as abrasive contaminants including sand, dust and soil particles. A typical example is a slewing bearing used in an excavator operating on a flooded construction site.

Contaminants such as water and abrasive particles can significantly impair grease performance by altering its physical and chemical properties. This reduces the lubricant's ability to form an effective lubricating film and increases the risk of wear and surface damage.

Regardless of the type and concentration of contamination, contaminant ingress accelerates wear and reduces bearing service life, making reliable sealing essential for ensuring operational reliability and the required lifetime of large-diameter bearings.

3 Types of Slewing Bearings and their sealings

Sealing systems for large-diameter bearings are selected according to the operating environment, loading conditions and performance requirements of the application.

The selection of a sealing system is influenced not only by the operating conditions but also by customer-specific requirements, maintenance considerations and required service life.

3.1 Swivel bearings

Swivel bearings are predominantly used in oscillatory applications, with angular movements ranging from a few degrees to multiple revolutions. Depending on the application, these movements may occur intermittently or continuously.

In applications such as construction machinery, industrial equipment and wind turbines, large-diameter bearings are commonly equipped with seals manufactured from continuously extruded elastomeric profiles, also known as seal lips. These p seal lips are cut to the required length and joined during assembly to form a closed sealing ring adapted to the bearing diameter.

The profile geometry is selected according to the operating conditions and environmental requirements of the application. Where enhanced sealing performance is required, multiple seal profiles may be combined within a single bearing arrangement.

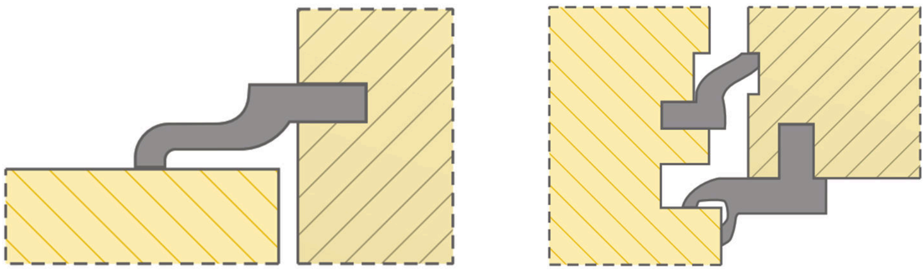

Figure 2: seal lips (left: Single seal lip; right: Double seal lip (internal and external))

3.2 Continuous rotation bearings (e. g. main bearings for wind turbines)

The development of torque-supporting wind turbine concepts, in which rotor loads are transmitted through a large-diameter main bearing, has led to the increasing use of radial shaft seals (RWDRs) as an alternative to conventional slewing bearing sealing systems.

3.2.1 RWDR with a garter-spring

With the introduction of wind turbine main bearings, the dimensions of the seals also had to be increased compared to conventional applications. These seals were typically manufactured from nitrile rubber (NBR), while the necessary sealing force was generated by a spring-loaded sealing lip supported by a garter spring acting against the bearing ring.

Figure 3: RWDR with a garter-spring on a main bearing (Ref.: CARCO GmbH)

The garter spring provides a uniform radial contact force along the circumference of the seal, thereby maintaining consistent contact between the sealing lip and the counterface throughout operation.

3.2.2 RWDR with a finger spring

Experience gained from early applications revealed limitations in the reliability of garter springs during installation and operation. In some cases, assembly issues and spring-related failures adversely affected sealing performance and ultimately contributed to bearing failures.

To address these shortcomings, the seal design was modified by replacing the garter spring with a finger spring integrated directly into the radial shaft seal through the vulcanization process.

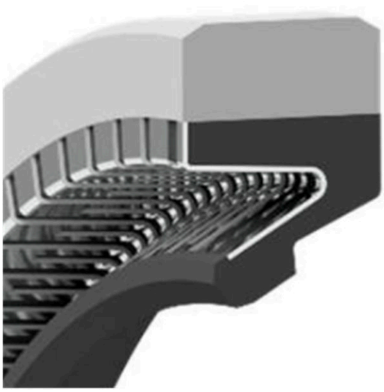

Figure 4: RWDR with an integrated finger spring on a main bearing (Ref.: CARCO GmbH)

This design eliminated several risks associated with the separate spring element and improved assembly robustness. Nevertheless, the application of radial shaft seals in large-diameter bearings continued to present installation challenges.

One significant issue was the potential twisting of the seal during installation. If twisting occurred, uniform contact between the sealing lip and the counterface could no longer be guaranteed.

While such issues require careful attention during initial assembly, they become even more critical during maintenance and seal replacement in the field, where working conditions are often considerably less controlled than in a manufacturing environment.

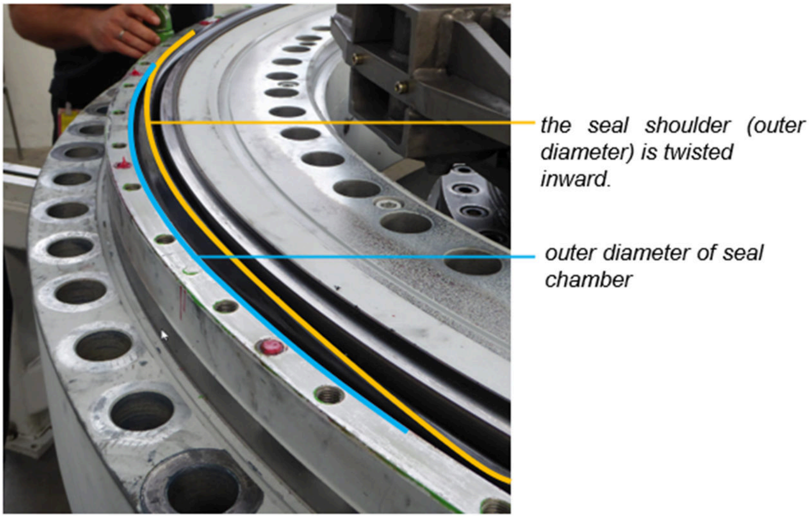

Figure 5: Installation-related challenges associated with an RWDR

3.2.3 RWDR based on the helix principle

These challenges prompted the investigation of alternative sealing concepts. One promising approach was based on the well-established helix sealing principle, which was subsequently developed into a commercially available sealing solution.

Unlike conventional radial shaft seals, which utilize a continuous circumferential sealing lip, the helix seal incorporates multiple sealing lips arranged in a helical pattern. During operation, these helical structures generate a pumping effect that actively returns lubricant towards the bearing interior. This mechanism improves lubricant retention and reduces grease loss.

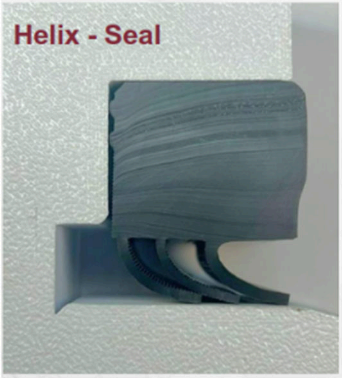

Figure 6: Cross section of a helix seal (ref.: Stallion Fluid Power GmbH)

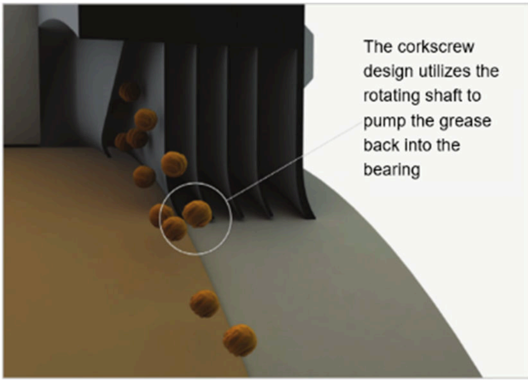

Figure 7: RWDR based on the helix principle (ref.: System Seals GmbH)

Because wind turbine main bearings predominantly rotate in a single direction during operation, the helix sealing principle is particularly well suited to this application.

An additional dust lip provides protection against the ingress of external contaminants. At standstill, this auxiliary sealing element also prevents grease leakage through the helical sealing structure.

However, concerns remained regarding applications involving alternating or reversing rotational directions, where the pumping effect may be reduced or compromised. These concerns led to the investigation of additional sealing concepts.

3.2.4 RWDR with a wave-shaped sealing lip

One promising alternative is the use of a wave-shaped sealing lip. Owing to its geometry, the wave-shaped contact surface generates a local pumping effect along the sealing interface, independent of rotational direction.

This promotes the distribution of lubricant at the sealing contact, ensures adequate lubrication of the sealing lip and reduces the risk of dry running. Improved lubricant distribution also contributes to lower friction and reduced wear.

In addition to the primary sealing element, the design incorporates a dust lip that prevents contamination ingress and improves seal stability by reducing the tendency of the sealing element to tilt during operation

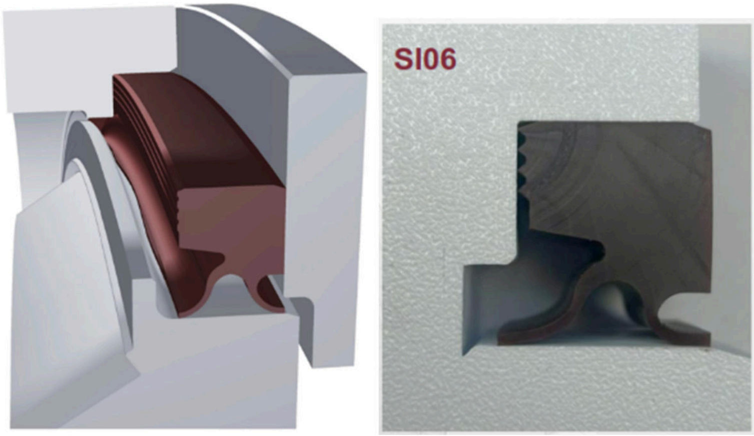

Figure 8: RWDR with a wave-shaped sealing lip (ref.: Stallion Fluid Power GmbH)

3.3 Special bearings

Radial shaft seals are also utilized in specialized large-diameter bearing applications, including underwater and offshore installations. In these applications, the seals are typically retained by specially designed contours integrated into clamping rings.

To improve sealing reliability and extend service life, multiple radial shaft seals are often arranged in series within the sealing system. This arrangement enables individual seals to be repositioned axially during maintenance, allowing the sealing lip to operate on a previously unused region of the counterface.

As a result, wear is distributed over a larger surface area, reducing localised wear and extending the effective operating life of the sealing system. This approach has proven particularly beneficial in applications where seal replacement is difficult, costly or associated with extended downtime.

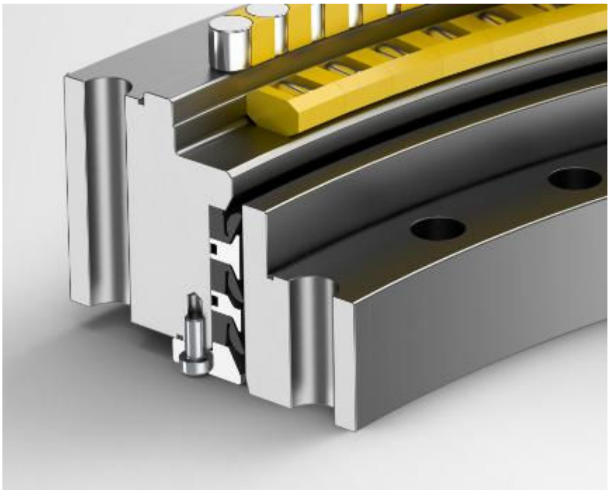

Figure 9: Bearing with a specialized sealing arrangement

4 Test procedures für Slewing Bearings sealings

Before being introduced into a customer application, sealing systems must successfully complete a multi-stage qualification process involving both Liebherr and the customer. A key element of this process is the functional validation of the sealing concept under realistic operating conditions using a full-scale test rig.

For this purpose, the sealing system is installed in a representative test bearing and subjected to endurance testing under conditions that closely replicate those encountered in service. The objective is to verify sealing performance, durability and operational reliability over the expected service life of the bearing.

Such testing is not only required for newly developed sealing concepts but also forms an integral part of the qualification process for new seal suppliers, materials and manufacturing methods.

4.1 Validation procedure

4.1.1 Preparation of the test program

The validation of a main bearing sealing system begins with an assessment of available sealing concepts and potential suppliers. Initial discussions focus on identifying the most suitable sealing principle, material selection and manufacturing technology for the intended application.

During this phase, all relevant technical and commercial requirements are defined. Particular attention is paid to operating conditions, environmental influences, service-life requirements, maintenance considerations and installation constraints.

These requirements form the basis for the subsequent validation program and provide the framework for the definition of representative test conditions.

4.1.2 Determination of test loads by Finite Element Analysis

Prior to testing, Finite Element Analysis (FEA) is performed to determine the load distribution within the bearing system, the stiffness of the surrounding structure and the resulting deformations of the bearing under both laboratory and application-specific operating conditions.

Particular emphasis is placed on evaluating relative ring movements, local structural deformations and variations in the sealing gap. These parameters have a direct influence on the contact conditions between the sealing lip and the counterface and must therefore be considered during the design and specification of the sealing system.

The results of the numerical investigations are subsequently used to define representative load cases and operating conditions for the validation program.

4.1.3 Documentation of the sealing and the installation space

Prior to assembly of the test bearing, the geometry of the seal installation space is measured and documented. Particular attention is paid to dimensions that may influence seal positioning, retention and compression during operation.

In addition, the initial condition of the seal counterface is recorded, including:

- Surface roughness
- Surface hardness
- Geometrical accuracy

These measurements establish a reference state against which any changes occurring during operation can subsequently be assessed.

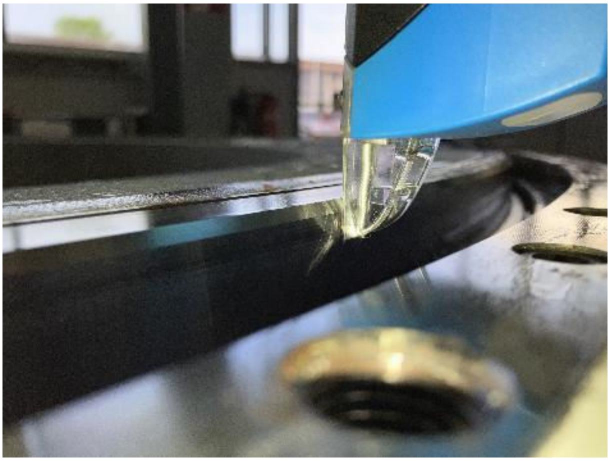

Figure 10: Surface roughness measurement of the sealing counterface

The seals under investigation are supplied by the respective manufacturer and installed during assembly of the test bearing. For newly developed sealing concepts, installation is frequently supervised by specialists from the seal supplier to ensure compliance with the specified installation procedure.

Following assembly, relevant bearing parameters are verified, including friction torque with and without the installed seals, seal positioning and overall assembly quality. Once these checks have been completed, the bearing is integrated into the full-scale test rig.

The necessary instrumentation and monitoring equipment are then installed and commissioned in preparation for the test program.

4.1.4 Execution of the tests program

Following commissioning, the bearing is subjected to a predefined test programme designed to simulate realistic operating conditions. During operation, all relevant measurement and condition-monitoring data are continuously recorded and evaluated against warning and shutdown limits to ensure safe operation and enable early detection of abnormal behavior.

The primary monitoring parameters include:

- Rotational speed
- Applied loads
- Bearing and seal temperatures
- Vibration levels
- Friction torque
- Drive power
- Additional application-specific parameters

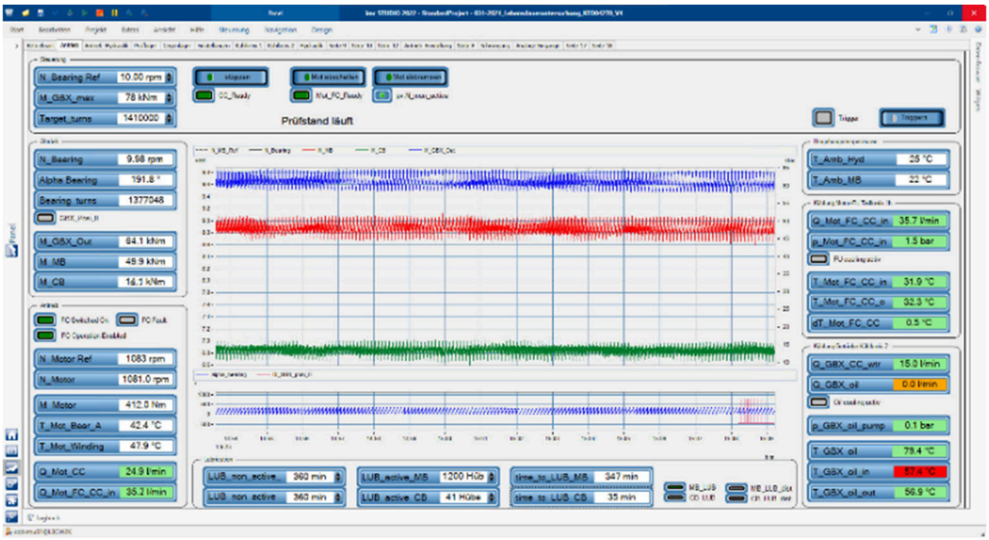

Figure 11: Control panel with real-limit monitoring

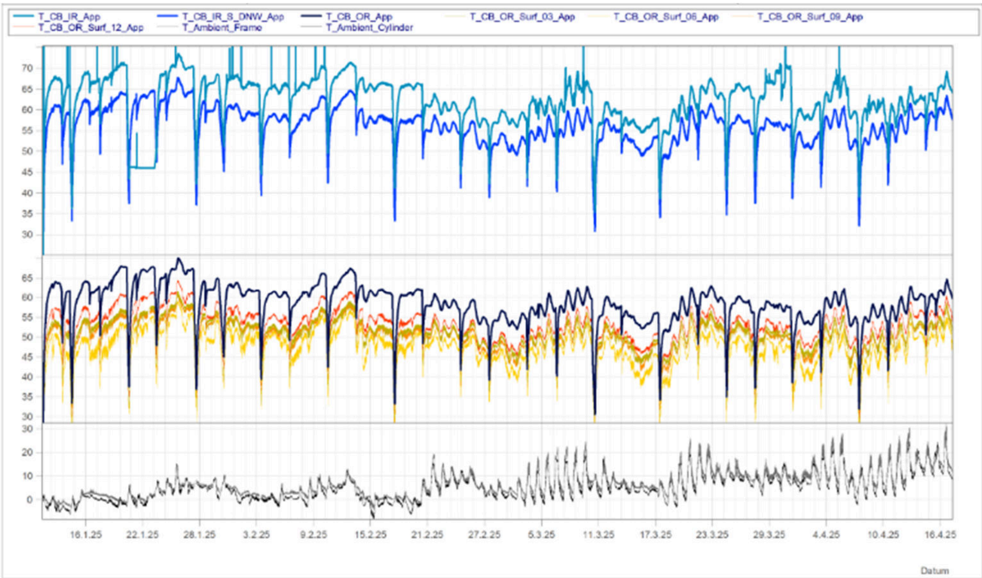

Figure 12: Monitoring of the bearing and seal temperature throughout the test program

In addition to continuous data acquisition, periodic inspections are carried out during the test campaign. For this purpose, testing is interrupted at predefined intervals to permit a detailed assessment of the bearing condition and sealing performance.

Typical inspection activities include:

- Analysis of grease samples to evaluate lubricant condition
- Inspection of seal condition and wear
- Documentation of grease distribution within the bearing
- Quantification of grease in collection containers and at leakages

Figure 13: Example of grease analysis results

The combination of continuous condition monitoring and regular inspections allows for the evaluation of the sealing system's effectiveness and enables the early detection of deviations from the specified test conditions. If necessary, corrective actions – such as additional cooling, additional lubrication, or the replacement of seals – can be taken to maintain the defined boundary conditions throughout the entire validation program.

4.1.5 Post-Test Inspection

Upon completion of the test program the bearing will be dismantled and subjected to a comprehensive inspection.

Particular care is taken during disassembly to preserve evidence of the operating condition of the sealing components. Representatives of the seal manufacturer are frequently present to supervise the removal process and assist in the evaluation of the results.

Special attention is given to:

- Wear patterns
- Permanent deformation
- Material ageing
- Contact marks
- Thermal damage
- Evidence of lubricant leakage
- Signs of contamination ingress

Following disassembly, all parameters documented before testing are measured again.

By comparing the pre-test and post-test measurements, any changes resulting from operation under realistic service conditions can be identified and assessed.

Figure 14: Seal following completion of the test program prior to removal

The findings obtained during the post-test inspection provide essential information for evaluating the suitability of the sealing concept and identifying opportunities for further optimization.

4.1.6 Reporting and evaluation

Following completion of the validation program, all results are compiled into a comprehensive final report.

The report documents:

- Test objectives
- Test configuration and operating conditions
- Measurement results
- Inspection findings with observed deviations and anomalies

The report concludes with a technical assessment of the sealing concept and recommendations regarding its suitability for series production and application-specific deployment.

Figure 15: Example cover page of a validation report (background image generated using AI)

4.2 FullScale Test rigs

Liebherr has two specialized full-scale test benches with different load capacities, which enable the testing of a wide range of bearing sizes and application scenarios.

4.2.1 Main bearing test rig 1 (> 2 MW)

In response to the growing demand for reliable main bearing systems for wind turbines, Liebherr commissioned a special full-scale test rig in 2017 that enables realistic validation of large-diameter bearings under the representative operating conditions of that time.

The test rig supports investigations including:

- Service-life testing
- Functional validation, including the sealing system
- Temperature-distribution analysis
- Friction-torque measurements
- Wear investigations

The principal technical specifications are:

- Maximum tilting moment: 8,000 kNm
- Maximum radial load: 2,000 kN
- Maximum rotational speed: 15 rpm
- Drive power: 300 kW
- Maximum raceway diameter: approximately 2,500 mm

Figure 16: Main Bearing Test Rig 1 at the Large-Diameter Bearing Test Facility

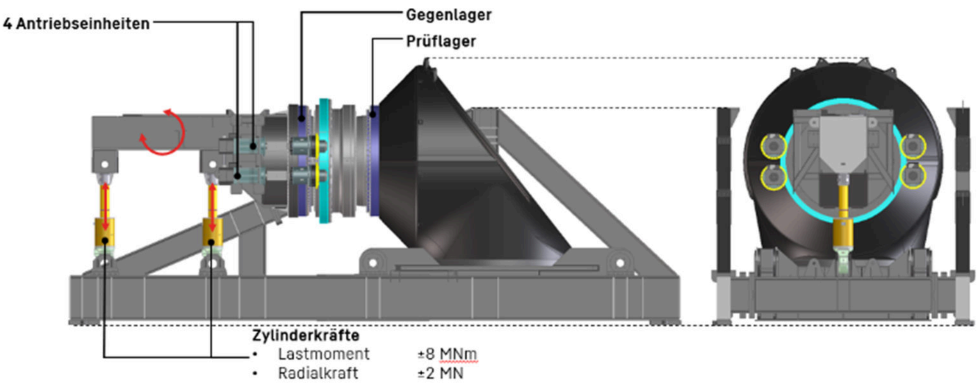

Figure 17: Schematic illustration of the Main Bearing Test Rig 1

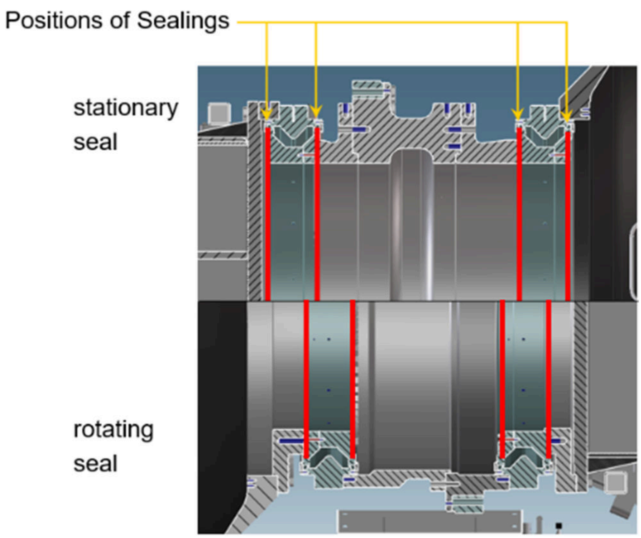

Figure 18: Possible seal installation positions on Main Bearing Test Rig 1

4.2.2 Main bearing test rig 2 (> 8 MW)

As wind turbine ratings continued to increase, Liebherr commissioned Main Bearing Test Rig 2 in 2022 to enable the validation of main bearings for turbine of up to 14 MW.

Like its predecessor, the facility supports a broad range of investigations, including:

- Service-life testing
- Functional validation, including the sealing system
- Temperature-distribution analysis
- Friction-torque measurements
- Wear investigations

The principal technical capabilities of the test rig are:

- Static tilting moment: up to −30 MNm
- Dynamic tilting moment: +5 to −25 MNm
- Radial load: up to 3,000 kN
- Rotational speed: up to 15 rpm
- Drive power: 165 kW
- Maximum bearing raceway diameter: approximately 4,500 mm

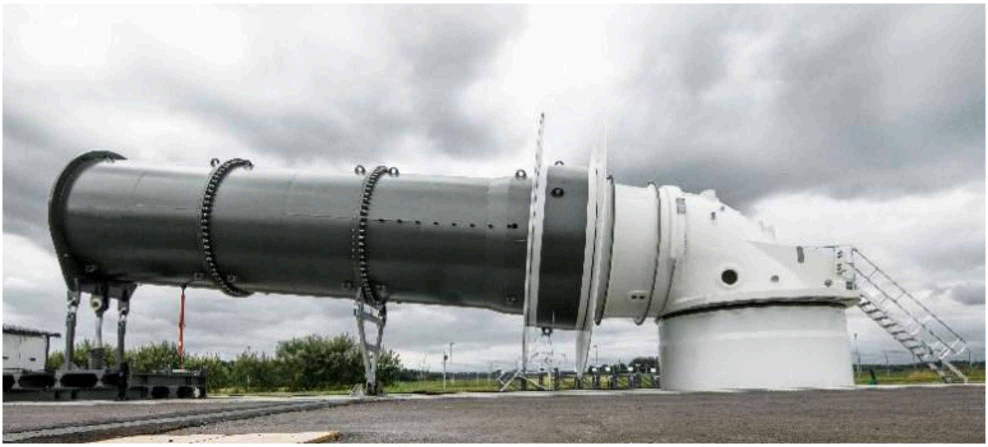

Figure 19. Main Bearing Test Rig 2 at the Large-Diameter Bearing Test Facility

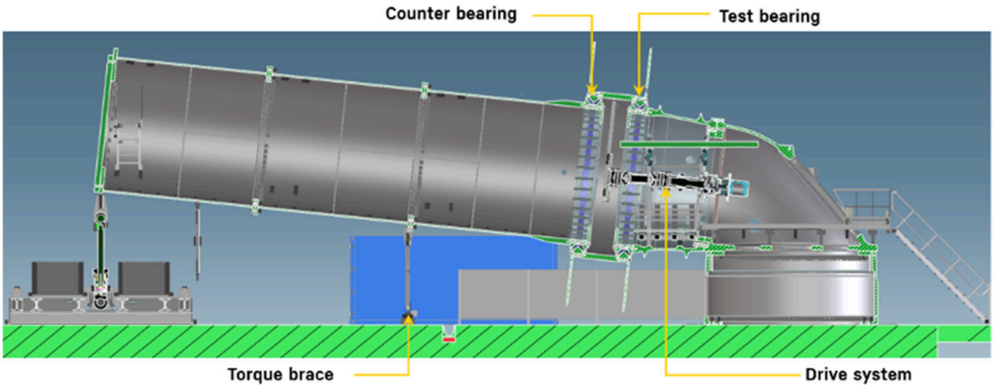

Figure 20: Cross section of Main Bearing Test Tig 2

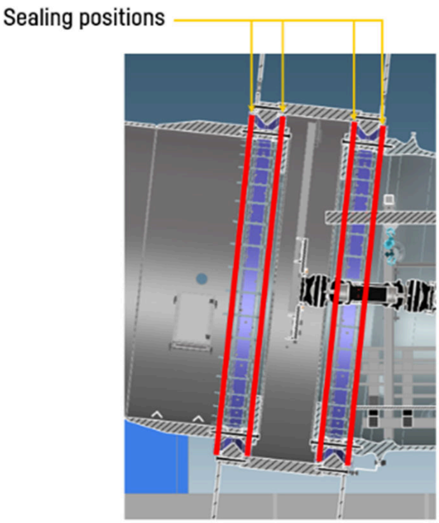

Figure 21: Possible seal installation positions on Main Bearing Test Rig 2

5 Benefits and advantages of full-scale testing at Liebherr

5.1 General benefits

Full-scale testing is a key element in the validation of sealing systems for large-diameter bearings. It allows sealing performance to be assessed under realistic operating conditions, providing evidence of reliability and increasing confidence among customers.

Unlike laboratory-scale tests, full-scale investigations capture the complex interactions between the seal, bearing, lubricant, and surrounding structure. Realistic thermal loads, structural deformations, lubricant distribution, and environmental influences can be reproduced, resulting in a more representative evaluation of sealing performance and service life.

As a result, the full-scale validation successfully supported the market launch of the helix seal.

5.2 Opportunities for sealing system improvement

Full-scale validation not only demonstrates the suitability of a sealing concept but also provides valuable insights that support continuous product development. Investigations performed on the test rigs have contributed significantly to improvements in seal materials, sealing geometries and installation procedures.

5.2.1 Material performance under realistic thermal conditions

The thermal conditions on the test bench differ slightly from those in the final wind turbine application. Due to reduced air circulation, heat dissipation is less effective, resulting in higher operating temperatures for both the bearing and the seal. This increased thermal stress accelerates material ageing and enables the evaluation of seal performance under end-of-life conditions within a reduced testing period.

In addition, the tests provide valuable information on the interaction between the seal material, lubricant, and temperature, supporting further material optimization and durability improvements.

5.2.2 Optimization of seal and installation space design

Seal performance is strongly affected by the surrounding installation environment. Large-diameter bearings are subject to significant elastic deformations during operation, which can influence seal contact conditions and local contact pressures.

Full-scale testing allows these deformation effects to be evaluated under realistic loading conditions. The interaction between the sealing lip, the counterface and the installation space can therefore be assessed throughout the complete operating cycle.

The knowledge gained has supported the optimisation of sealing lip geometries, contact pressure distributions, retention concepts and installation-space designs. These improvements have increased sealing robustness and reliability under realistic operating conditions.

5.2.3 Evaluation of Installation and Maintenance Procedures

In addition to technical performance, the installation and replacement of sealings in a wind turbine applications differ significantly from the conditions encountered during bearing assembly or testing on laboratory and scaled test rigs. As part of the validation program, a seal replacement was carried out under application-relevant conditions to assess the practical aspects of field installation.

The investigations revealed practical challenges related to restricted working space, limited accessibility, lubricant leakage during maintenance activities and the handling of large sealing components.

Several challenges were identified during the seal replacement process, including restricted working space, limited access to fastening elements, lubricant leakage during seal removal, and application-specific seal behaviour during installation. These observations provided valuable insights into the practical requirements of maintenance procedures.

Based on these findings, recommendations for installation procedures and technician training were derived to support reliable seal replacement and consistent sealing performance in the field.

6 Summary and Conclusion

The development of sealing systems for large-diameter bearings requires more than just theoretical design and simulation. While modern calculation methods provide valuable information on bearing loads, deformations, and sealing requirements, the actual performance of a sealing system can only be verified under realistic operating conditions.

Full-scale validation tests allow for the evaluation of seal performance while taking into account complex interactions between structural deformation, lubrication, environmental influences, and installation conditions. The insights gained from these tests have led to continuous improvements in seal geometry, material selection, and installation concepts.

As a result, the combination of simulation and full-scale testing, as conducted at Liebherr, significantly increases the reliability of the seals and provides a competitive advantage by ensuring robust performance throughout the entire service life of the bearing system.

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8 References | Figures