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Designing seals for offshore wind turbine applications using static gas tightness simulation

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Seals for offshore wind turbine applications play a critical role because they prevent seawater from entering the foundation, therefore reduce corrosion, and protect the structural integrity of the system. Without reliable sealing, damages to steel structures, components, cables, and sensitive equipment as well as human beings can occur, which are significantly affecting the turbine's lifetime and safety. In this context, one seal is the airtight platform (ATP) seal. The ATP seal is vital to prevent gas leakage from the area below the platform, which serves as the central access and working area for personnel and equipment in an offshore wind turbine. Main function of this seal is ensuring safety and protecting workers as well as equipment. There is a market trend to shift from static axial seals using a landing ring on the monopile to static radial seals without this landing ring. This results in challenges like increasing tolerances, complicated installation methods, rougher countersurfaces, and makes long-term sealing performance harder to achieve in harsh offshore conditions. This is where static tightness simulation originally developed by Lorenz and Persson is applied to design a functional seal: The roughness of both contacting surfaces is considered, as well as material properties, loads etc. Also, coatings can be simulated, and the fluids can be liquid or gas. This paper aims to provide new insights into designing ATP seals for offshore wind turbine applications using the implemented simulation methods. The function of the seal can be assured with unprecedented confidence for the whole desired lifetime

1 Introduction

Offshore wind energy generation is a crucial pillar of Europe's energy strategy to become more resilient and independent from a fast changing and uncertain future [1]. As a result, the development of new concepts for more efficient and robust manufacturing is needed. One area of these developments is focusing on the connection between the monopile and the transition piece (MPTP) connection for classical offshore wind turbines. There are mainly two seals needed in this connection, see Figure 1 highlighted in blue:

1. MPTP seals to protect the inside of the wind turbine tower from outside environmental conditions (e.g. sea water) or ambient air
2. Air tight platform (ATP) seals to protect the inside of the wind turbine tower from environmental conditions below the platform (e.g. toxic gases)

Without reliable sealing, damages to steel structures, components, cables, and sensitive equipment as well as human beings can occur, which are significantly affecting the turbine's lifetime and safety.

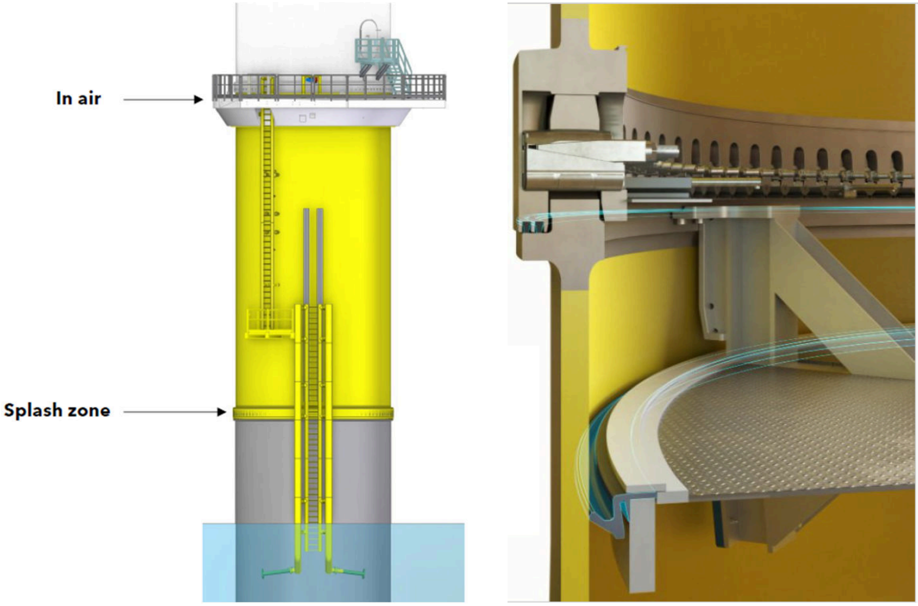

Figure 1: Overview of connection and location of MPTP (upper) & ATP (lower) seals [2]

Especially the ATP seals are facing significant changes. Main function of this seal is ensuring safety and protecting workers as well as equipment. There is a market trend to shift from static axial seals using a landing ring on the monopile to static radial seals without this landing ring. This results in challenges like increasing tolerances, complicated installation methods, rougher countersurfaces, and makes long-term sealing performance harder to achieve in harsh offshore conditions. The benefits of such sealing systems are reduced overall cost, comparing steel cost savings with seal cost increase, and reduced risk during installation.

In this paper, the combined usage of FEM simulations and static gas tightness simulations including evaluation of different coating systems both on the countersurface as well as the sealing surface is illustrated. The combined usage of these methods demonstrates how they can be used to support seal design, reducing the risk of overengineering achieving an optimized and balanced performance with respect to defined boundary conditions, taking quantitative trends for gas leakage into account.

2 Application and Investigated Sealing Concept

The biggest challenge for designing radial ATP seals is the gap that needs to be covered. Depending on the boundary conditions, radial gaps starting from 50 mm up to a maximum of 650 mm are possible. In addition, tolerances from manufacturing and during assembly lead to potential changes of +/- 50 mm. Diameter of platforms and inner diameter of the counter surface is 6.500 mm to 7.500 mm but may vary and is still increasing as turbines are scaling up. The boundary conditions valid for this investigation are summarized in Table 1.

Table 1: Short list of requirements for the ATP seal development

Requirement	Description
Pressure resistance	up to ± 1 bar
Radial Gap	150 mm
Overall radial Gap Tolerance	± 30 mm
Expected Lifetime	35 years
Mean operating temperature	max. 30 °C
Countersurface roughness	rough (Sq 12 mm) / smooth (Sq 0.5 mm)

As mentioned before, the most challenging part of this application is the radial gap combined with overall radial tolerance. This tolerance includes ovality of the whole setup of the platform and the inner tube geometry. This results in a gap that needs to be covered during operation between 120 to 180 mm. Another challenge for designing such seals is the potential pressure or vacuum, which can be generated below the platform. These boundary conditions will be used for a detailed design and explained in more detail in section 2.1.

The sealing area for the ATP seal is on the inner side of the lower tubular. There are several potential coatings which are commonly used. In this study, we focus on two different types of coatings which will be used in this application and will be described in more detail in section 2.2.

2.1 Seal Design

Baseline for the design of such an ATP seal is specification sheet, which includes all necessary technical information. A short list of selected specifications is shown in Table 1. The design process itself includes review of existing designs from previous projects and idea generation. After a conceptual design is defined a more detailed analysis is conducted using the specifications for a FEM simulation. This simulation includes assembly of the seal, pressure loads and displacements after assembly. In addition to stresses, strains and displacements contact lengths during these conditions are evaluated. Using these physical characteristics allows the evaluation of the air tightness of individual design concepts and provides the opportunity to optimize specific designs to the best compromise fulfilling customers specification.

In Figure 2 the conceptual design for the wedge connection can be seen. The seal is already installed using minimum (left) and maximum (right) tolerance for the radial gap. The resulting deformation of the seal in both worst-case scenarios underlines the challenge in designing such ATP seals including pressure resistance.

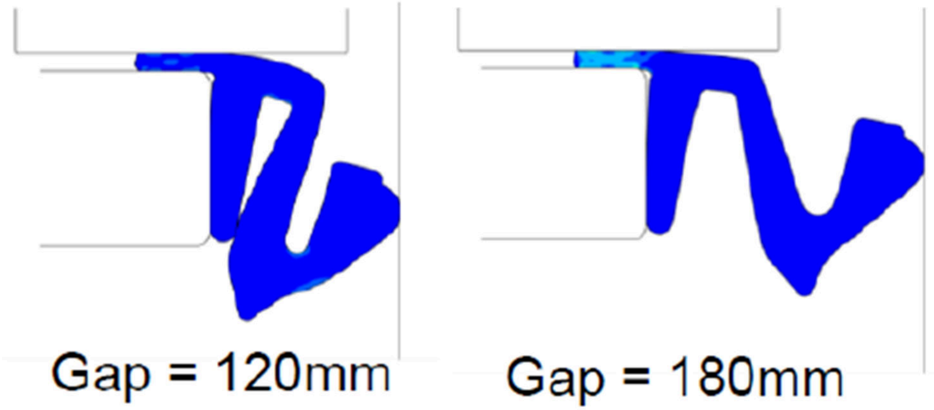

Figure 2: Assembled seal with minimum and maximum tolerance for the radial gap

The seal can be split in three main sections with separate functions, see Figure 3. These main sections and functions are:

1. Clamping area for seal assembly on the platform
2. Elastic area for covering the gap
3. Sealing area to ensure air tightness

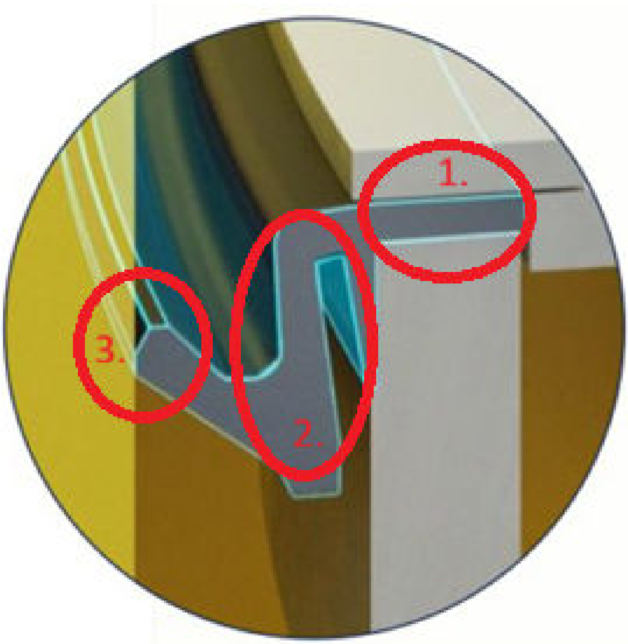

Figure 3: Main sections of ATP seal design [2]

2.2 Coatings

As mentioned in previous section, in this paper the focus of evaluating air tightness of ATP seal is on two potential metal coatings for the inner side of the tubular. These two coatings are quite different, which underlines the selection of these, because they can be seen as a representative selection.

First coating is a black coloured one, which is an epoxy finished coating with PU topcoat. This coating fulfils the CX coating standard acc. ISO 12944 and results in quite smooth surfaces.

The second coating is white coloured. It is manufactured via a thermal spray metallization (TSM) based on molten zinc and aluminium sprayed onto the flange. This coating results in a relatively rough surface finish.

In Figure 4 illustrates the difference between both coatings. The upper test specimen is coating by using the TSM and for the test specimen below the epoxy finished coating with PU topcoat is used. These specimens were analysed in more detail with respect to the needed characteristics for air tightness and will be discussed in more detail in the next section 3 Materials and Surface Characterization.

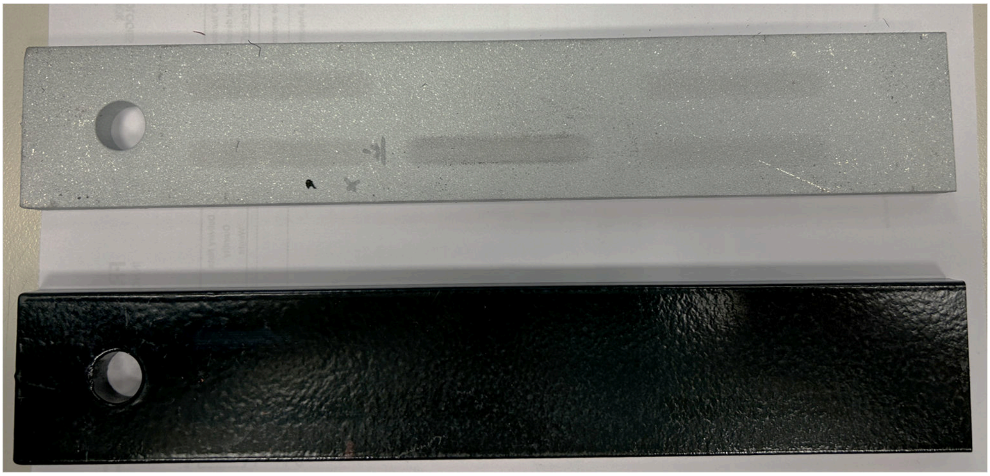

Figure 4: Coated test specimen – white metallized coating (top) and black (bottom)

In addition, friction reducing coatings on the elastomers were analyzed, although not relevant for the ATP seal. However, this feature can be of interest in other applications, e.g., for the MPTP seal. Therefore, these coatings are taken into consideration for knowledge gain for future developments.

3 Materials and Surface Characterization

The analyzed materials are listed in Table 2

Table 2: Materials

Material	Coating	Roughness
Steel	Epoxy/PU (“black”)	Sq 0.47 µm
Steel	TSM (“white”)	Sq 12.1 µm
EPDM, 70 Shore A	None	Sq 0.63 µm
EPDM, 70 Shore A	Epoxy-PTFE-coating, black	Sq 7.2 µm
EPDM, 70 Shore A	Epoxy-PTFE-coating, grey	Sq 8.8 µm

The coated steel samples were used as substrates with elastic modulus of 210 GPa. No difference in mechanical properties of the coatings on the steel was considered. They are assumed to be very stiff compared to the (coated) rubber materials, i.e., their influence is negligible.

The simulations were conducted at ambient temperature, where the rubber material can be approximated by an elastic modulus of 4.8 MPa. The coatings were estimated from the respective datasheets to be 15 µm thick and have an elastic modulus of 200 MPa.

For the leakage simulations (see Section 4), air was used with its well characterized properties at ambient conditions (density 1.2 kg/m³, viscosity 18.2 µPa s).

The roughness of all samples was measured using White Light Interferometry (WLI) and Atomic Force Microscopy (AFM). The WLI was used to measure 700 µm by 800 µm sections of the topography with a lateral resolution of approximately 2 µm, with the AFM, areas of 10 by 10 micrometer fields were analyzed with a resolution of 10 nm. This was done to also detect small sub-micrometer gaps which could cause leakage when gases are sealed.

4 Simulation Methodology

The sealing performance of static elastomer seals is strongly governed by the multiscale roughness of the contacting surfaces. Even under nominal contact pressure, real contact occurs only at discrete asperity regions, while a connected network of non-contact regions remains, potentially forming leakage pathways across the interface [3], [4].

The theoretical framework applied in this work is based on the contact mechanics theory developed by Persson and co-workers, which allows to describe contact between randomly rough surfaces over multiple length scales [3], [4].

In contrast to classical asperity-based models, Persson’s approach considers the surface roughness statistically in Fourier space and evaluates the contact mechanics as a function of increasing magnification. At low magnification, surfaces appear smooth and full contact is assumed; with increasing magnification, smaller-scale roughness features become resolved and the apparent contact area decreases continuously [3].

This multiscale approach yields key quantities such as

- the real contact area A,
- the interfacial separation distribution, and
- the contact pressure distribution,

which are all directly related to friction and leakage phenomena in sealing systems [3], [4].

A central result of the theory is that, with decreasing contact area, a percolating non-contact channel forms when the normalized contact area A/A_0drops below a critical threshold of approximately 0.4. At this point, a continuous leakage path across the interface becomes available [3].

Based on the percolation concept, leakage is assumed to be dominated by the most restrictive point along the first percolating flow path, commonly referred to as the *critical constriction* /3,4/.

Assuming pressure-driven flow through this constriction, the volumetric leakage rate Q can be approximated by

$$Q \sim \frac{L_y}{L_x} \frac{u_c^3}{12\eta} \Delta P \qquad (1)$$

where u_c denotes the height of the critical constriction, η the fluid viscosity and ΔP the pressure difference across the sealing interface [3]. L_y and L_x are the length and width of the sealing contact.

For gases, the flow through very small constrictions may deviate from classical continuum assumptions. In such cases, the leakage model can be extended to include both viscous (diffusive) and ballistic (Knudsen-type) transport regimes, depending on the relation between the mean free path of the gas molecules and the characteristic size of the constriction [5], [6].

Within this theoretical framework, the leakage behavior is determined by the interplay of

- surface topography (power spectral density of roughness),
- elastic or viscoelastic properties of the elastomer, and
- mechanical properties of coatings and counterfaces.

Rougher surfaces or stiffer coatings typically lead to a reduction of the real contact area and a shift of the system towards the percolation threshold, thereby increasing the probability of leakage [4], [6].

This effect is particularly relevant for coated elastomer systems, where thin stiff coatings can significantly increase the effective surface roughness amplitude and reduce compliance, resulting in larger interfacial gaps [6].

The predictive capability of the Persson-based leakage model has been demonstrated in several independent studies. For liquid leakage, experimental validation has shown good agreement between measured and predicted leak rates for elastomer seals on rough surfaces [4].

For gas leakage, Tiwari and Persson demonstrated that theory accurately predicts air leakage rates in suction cup systems, including the influence of surface roughness and material stiffness [5].

Furthermore, Rodriguez et al. extended the approach to syringe sealing systems and showed that the leakage rate strongly depends on interfacial roughness and coating properties, with gas transport often occurring in the ballistic regime for very small gaps [6].

These studies provide a consistent validation basis for applying the model to gas leakage problems in static sealing applications.

Additionally, the predictive capabilities of the model were validated at FTI for liquids using hexadecane as fluid and flat rubber gaskets loaded with deadweights. The leakage was observed as reduction in height of the fluid column, the agreement with measurements was very good (Figure 5).

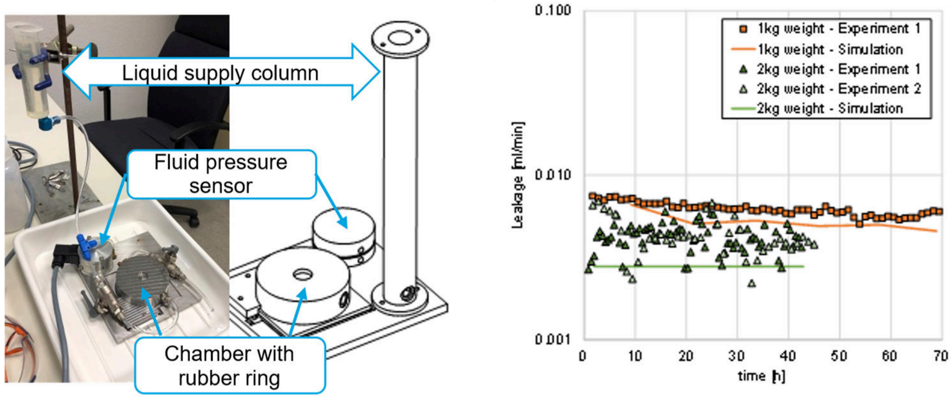

Figure 5: Internal Validation of Leakage Simulation

5 Results and Discussion

The roughness measurements of WLI and AFM were combined in the Fourier space to create a description of the roughness from order mm to order 10 nm. Particularly the WLI results were analyzed very carefully as it is known that they are prone to artifacts at higher roughness frequencies [7]. Figure 6 shows the curves used for the simulations.

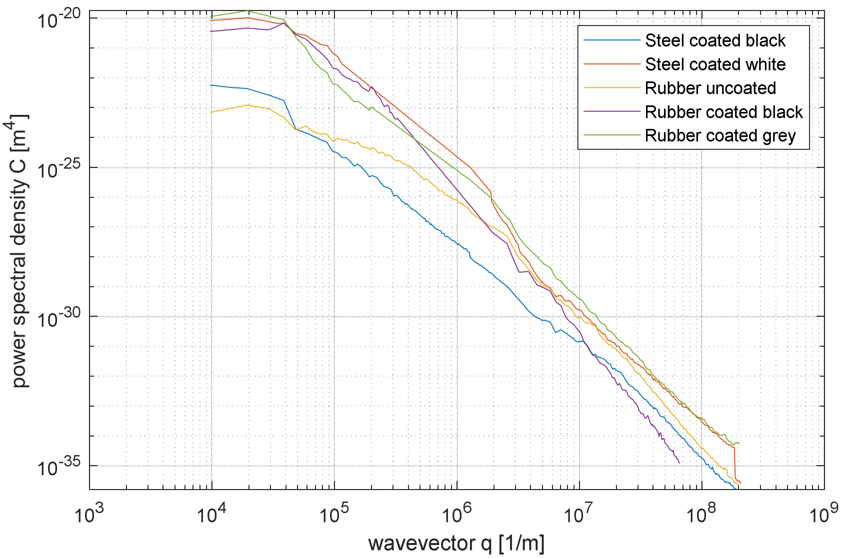

Figure 6: Power spectral densities of surface roughness of used surfaces, angular average. Combination of WLI and AFM results.

Figure 7 shows the calculated relative contact area for the respective surface pairings. Unsurprisingly, the rougher surfaces show a significantly reduced contact area, but it is particularly the stiffer coating on the rubber material that leads to contact areas below 10 %. For these pairings, leakage is expected according to Section 4.

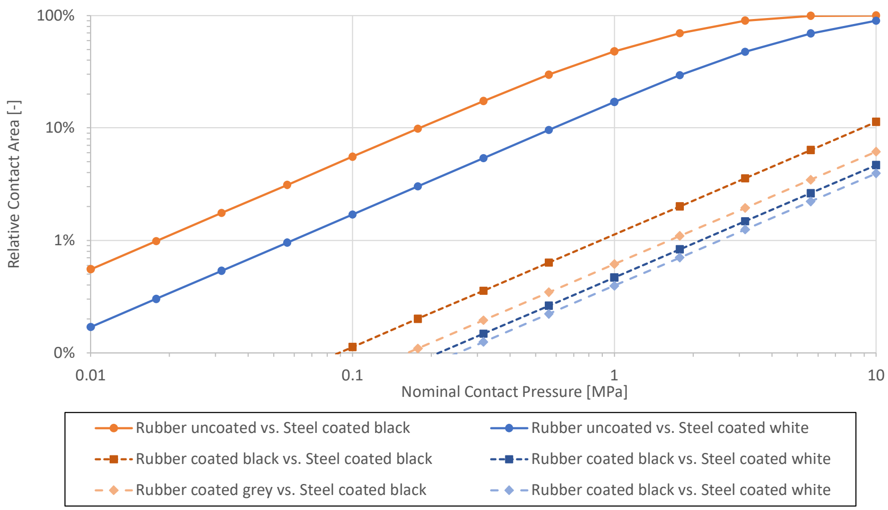

Figure 7: Relative contact areas for investigated surface pairings

This is reflected in the results for the static sealing function: The rougher the pairing, the higher contact pressures are required for tightness. Furthermore, the increased stiffness of the epoxy-based coating on the elastomer also increases the necessary pressure, potentially offsetting any friction advantages during assembly (Figure 8).

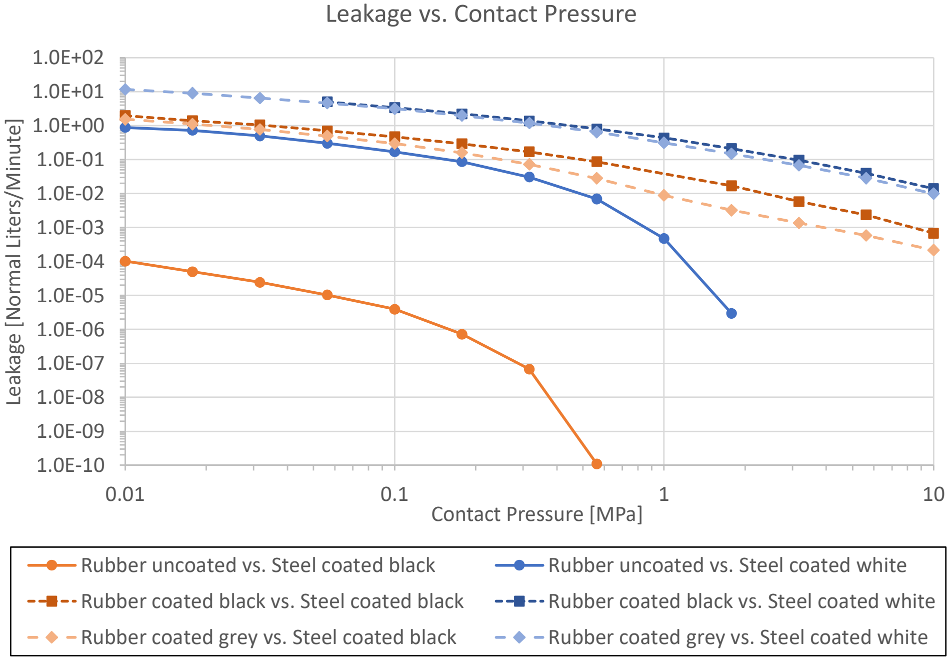

Figure 8: Calculated gas leakage for the surface combinations. Gas is air at ambient conditions, pressure difference is 1 bar, the leakage is normalized to 1 mm in length and 1 mm in width.

6 Summary and Conclusion

This paper presented a simulation-based approach for designing static radial ATP seals for offshore wind turbine applications, with particular focus on the influence of surface roughness, coating selection and contact conditions on gas tightness. The investigated sealing concept addresses the transition from axial sealing systems with a landing ring to radial sealing systems without such a ring, which introduces larger radial gaps, relevant assembly tolerances and rougher counterfaces. These boundary conditions make a purely experience-based seal design insufficient and motivate the combined use of FEM-based contact analysis and static gas leakage simulations.

The methodology combines measured multiscale surface topographies from WLI and AFM with Persson-based contact and leakage modelling. This allows the real contact area, the tendency towards percolating leakage paths and the expected gas leakage to be evaluated for different combinations of steel counterfaces and elastomer surfaces. The results show that surface roughness is a decisive parameter for static gas tightness. Rougher counterfaces reduce the relative contact area and require higher contact pressures to suppress leakage. In addition, stiff coatings on the elastomer can further reduce local compliance and may therefore increase the contact pressure required for gas-tight sealing, even if such coatings are beneficial for handling or assembly.

Within the investigated design space, the simulations indicate that static gas tightness of radial ATP seals can be assessed more systematically when surface characterization, material properties and contact mechanics are considered together. The approach provides quantitative trends for comparing design variants and coating systems, supporting an optimized balance between sealing reliability, assembly conditions and avoidance of unnecessary overengineering. At the same time, the results underline that coating selection cannot be assessed only from the perspective of corrosion protection or friction reduction; its influence on roughness, stiffness and interfacial leakage paths must also be considered. The presented workflow therefore offers a useful basis for the development of robust ATP sealing solutions for offshore wind turbines under demanding geometric and environmental boundary conditions.

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8 Nomenclature

List of symbols used in this paper. Latin symbols are listed first, followed by Greek symbols.

Variable	***Description***	***Unit***
A	Real contact area	m²
A_0	Nominal contact area	m²
A/A_0	Relative contact area	-
E	Elastic modulus	Pa
L_x	Width of the sealing contact in flow direction	m
L_y	Length of the sealing contact perpendicular to flow direction	m
p	Contact pressure / surface pressure	Pa
ΔP	Pressure difference across the sealing interface	Pa

Variable	*Description*	*Unit*
Q	Volumetric leakage rate	m³/s
q	Wave vector / roughness wave number	1/m
S_q	Root mean square height of the surface topography	m
u	Interfacial separation	m
u_c	Height of the critical constriction	m
η	Dynamic viscosity of the sealed fluid	Pa s

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