Design for contact lubrication of large seals

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Abstract
In recent years, the requirements placed on large seals in wind turbines have become increasingly stringent, leading to the development of new sealing concepts with novel lubrication properties. In this context, it is a technical challenge to design sealing solutions for such diverse criteria as reliable lubrication, prevention of lubricant loss, good lubricant circulation, robustness to tolerances and operating vibrations, as well as low friction and wear with the longest possible service life. In addition, greases are used as lubricants. As non-Newtonian fluids, their behavior ranges from oily liquid to pasty solid, depending on the strain condition.

This paper presents how these challenges can be overcome using various simulation tools early in the development process. Structural and fluid engineering simulation tools are suitable for identifying the key design parameters and fluid transport mechanisms and can thereby help optimizing the seal design.

On the structural side, the installation tolerances and kinematic oscillations during operation are small in comparison to the size of the mating parts, but enormous in relation to the section geometry of the seal profile. This requires a very flexible seal lip design, able to follow all movements to avoid high friction forces on one side and contact losses with leakage on the other side.

On the fluid side (grease), it is shown that the non-Newtonian behavior leads to two main schemes: In the region of seal contact with the moving mating part, the grease is oil-like due to high fluid shear rates. The seal geometry is optimized to support the grease film and to transport escaping grease back to the grease side. Further away from the contact zone, at low liquid shear rates, the grease behaves pasty due to its soap components and deposits in existing cavities. During operating oscillations, this process can be dynamically reversed so that the grease is deposited in a potential reservoir where it is stored and repeatedly released. With optimized design and initial filling with grease, the service life is extended. Furthermore, it is shown that other transport forces such as centrifugal force and gravity play only a minor role in grease transport, while operating conditions such as temperature and the operating conditions, must be taken into account in any case.

Structural and fluid simulations in combination with accompanying experimental investigations allow effective consideration of seal kinematics and lubrication physics. This promotes the development process for an optimized large seal design.

1 Technical Introduction

1.1 Seal for Wind Turbine

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In sealing technology, wind turbines are not only a special case in terms of large dimensions and poor accessibility, but the sealing systems must also be particularly robust in terms of lubrication, cooling, tolerances, power loss, installation options, service life and media compatibility. In addition, when sealing the wind turbine of a wind power plant, the sealing element rotates with the wind turbine, which generates non-negligible flow forces at a speed of up to 30 revolutions per minute and a sealing element diameter of over 3 meters.

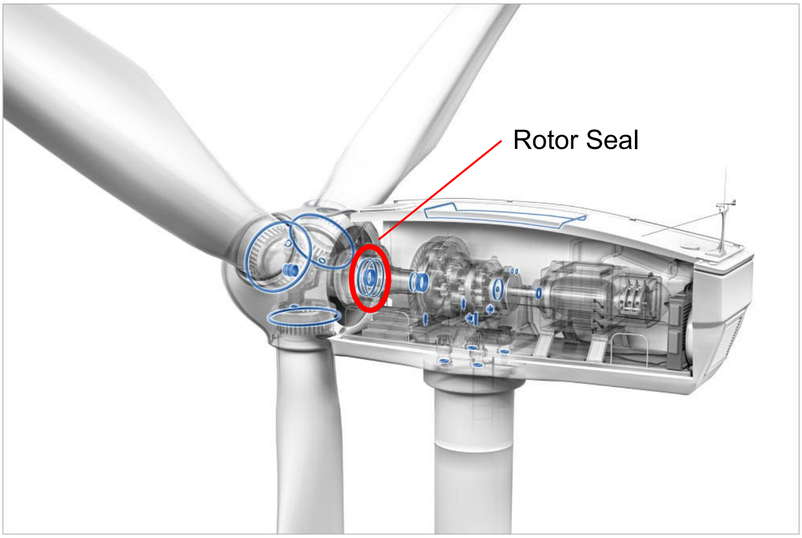

Figure 1: Seals in the vessel of a wind turbine [2]

This means in performance mode of the wind turbine, the seal rotates at a speed of approx. 5 meters per second, in the area of the tribological contact. Since the rotor cannot be equipped with recirculating or dry sump lubrication due to its design, the lubrication and cooling of the sealing system must be ensured by grease lubrication.

Whereas grease lubrication systems are generally considered to be simple lubrication systems, in wind turbines they are complex systems that have to withstand high loads with large tolerances. The grease in a wind turbine in the area of the rotor seal is not intended exclusively to supply the sealing system, but must also ensure the lubrication of the bearing with which the rotor is suspended from the vessel. The demands on the grease and the lubrication system are correspondingly high.

Similar to the sealing system, the bearings in the rotor bearing arrangement are also exposed to high loads. On the one hand, the bearing arrangement must support the weight of the rotor together with the pitch units, which in the case of a wind turbine can only be achieved by an overhung bearing arrangement. On the other hand, the bearing arrangement must also handle the operating forces, which are essentially the result of axial forces from wind load. However, the bearing arrangement also has to withstand additional loads, such as the unilateral axial force interruption when the rotor blades pass the tower or forces resulting from deformation from the hollow rotor shaft and the softly fixed outer rings in the vessel housing.

In order to be able to be robust against the high loads at the bearings for the hole planned lifetime, cylindrical roller or tapered roller bearings with particularly high load capacity are used, but these must be lubricated particularly well with high performance and therefore tough grease. This is the only way to prevent increased wear, chipping in the tribologically stressed surfaces and damage due to the large deformation at high load, such as “Ringwandern”. [4]

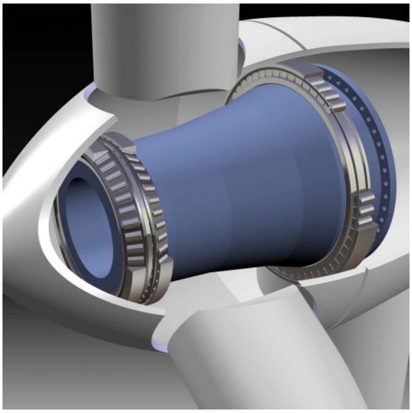

Figure 2: Bearings to fix the rotor to the vessel [3]

The challenge in designing a sealing system for wind turbines is therefore to reliably prevent grease leakage over a long service life with the lowest possible friction loss in the case of a large diameter, large tolerances, deformations and non-uniformities when using highly viscous grease, and at the same time to prevent any medium from penetrating into the sensitive bearing arrangement from the outside.

Requirements for sealing systems for rotor sealing of wind turbines:

Tasks:	Sealing against grease leakage and media ingress
Lubrication:	High-viscosity bearing greases, replenishing grease
Inner diameter:	up to greater than 3 m
Outer diameter:	up to greater than 3 m
Tolerances:	+/-5 mm misalignment rotor to hollow shaft +/-2 mm component tolerances
Service life:	longer than 5 years
Temperatures:	-20 °C up to 60 °C
Contact speed:	up to 5 m/s
Power loss:	less than 1 kNm per meter of sealing contact

2 The grease, its fluid behavior and simulation

In wind turbines grease is used as a lubricant, which consists of oil, thickener and additives to adjust the desired characteristics. It was aptly described by Bartz [5][6] as lubricating oils prevented by thickening agents from flowing away. Due to its composition it does not behave like a “normal” Newtonian liquid. Its viscosity depends strongly on the shear rate. At very low shear rates grease is like a pasty solid and at high shear rates like an oily liquid. This makes it suitable for wind power turbines, providing a good lubrication but also preventing just flowing away from the seal contact caused by hydrostatic pressure and centrifugal forces.

This special behavior needs to be accurately modeled in CFD. The Herschel-Bulkley-model [7] provides a good description that takes into account all major effects as the yield stress that needs to be overcome to start flowing, the consistency and a flow index (shear thinning exponent) to describe the flow thinning behavior. The equations for the shear stress τ and viscosity η are:

$$\tau = \tau_0 + K \cdot \dot{\gamma}^n$$

$$\eta = \frac{\tau_0}{\dot{\gamma}} + K \cdot \dot{\gamma}^{n-1}$$

with τ_0 = yield stress, K = consistency, n = shear thinning exponent, $\dot{\gamma}$ = strain rate

Additionally, the used software ANSYS CFX provides minimum and maximum shear strain rates for these equations. Outside this range the viscosity remains constant, below minimum as a very thick fluid and above maximum as a thin fluid. By doing this the model accounts for the slow setting behavior of the grease on the slow side and prevents becoming thinner as the base oil due to the flow index on the fast side.

In this case Mobil SHC™ Grease 461 WT is used. It has been characterized using a viscometer. The measured curves and the CFX fluid model are compared in the diagram Figure 3.

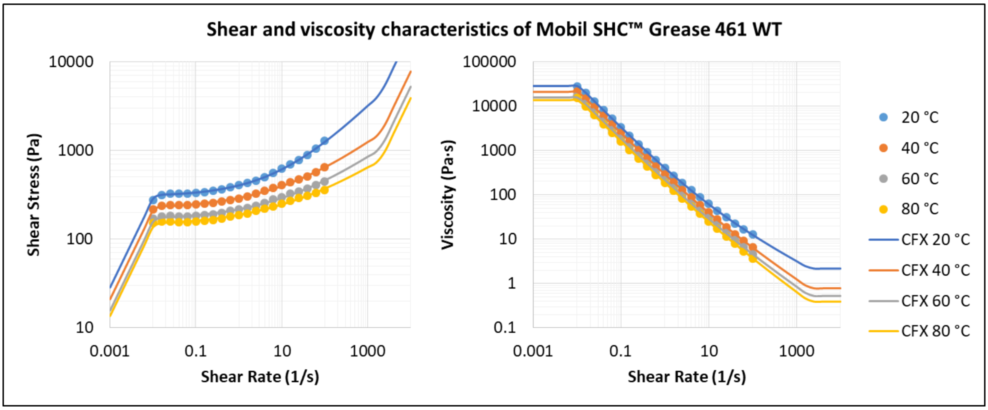

Figure 3: Shear and viscosity characteristics

To validate the material model the cone indentation test according to ASTM D217 is simulated, see Figure 4. The penetration of the cone is 30.5 mm according to the data sheet. In the simulation the initial indentation is 30 mm. Due to the setting behavior caused by the minimum shear strain rate and limited viscosity 31.5 mm indentation is reached after the specified 4.5 s. For this grease the accuracy of the fluid model has been shown.

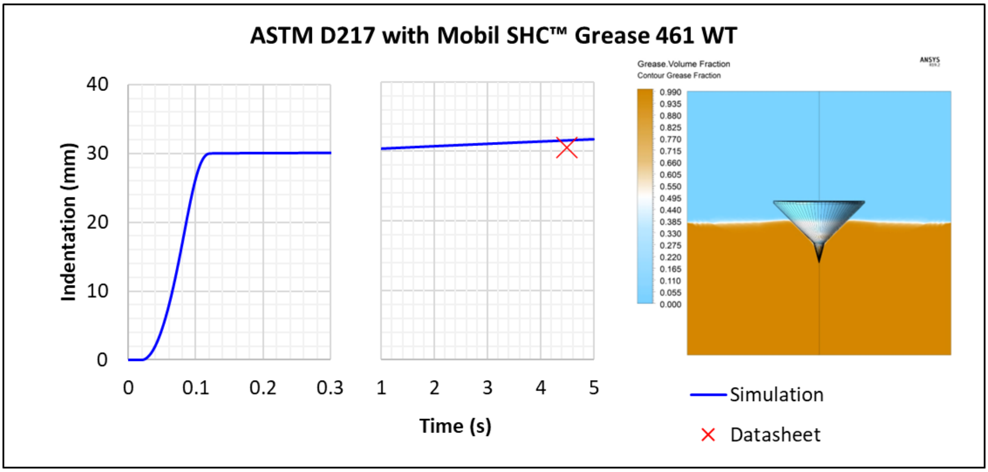

Figure 4: Cone indentation test simulation vs. specification

To fulfill the sealing and lubrication requirements the seal design has to fit to the grease characteristic, so that it uses its beneficial properties and avoids risks caused by problematic properties. Regions with shear or vibration should be used to transport grease to contact areas but to avoid leaking and regions with deposited grease should not stick and block any movement but to provide reservoir, that can be activated to participate in the flow again.

3 Simulation of grease behavior

To understand the specialty of the grease behavior, it is helpful to compare it against its base oil with the Newtonian behavior. Figure 5 compares CFD results of both fluids regarding their viscosity and their velocity of a nearly rectangular sealing gap between two seal lips. The rotor housing rotates with 2 m/s around a static shaft. In quasistatic conditions only near the contact to the shaft the shear strain rate is high enough to enable the grease to flow with low viscosity. Flow means here to have a relative motion to the rotating housing that is induced by the static shaft. In regions enveloped by walls the grease is like a solid plug that sticks to the walls. Contrary to this with the base oil the influence of the shaft reaches far more into the fluid region. This shows that the transport and mixing of grease is not induced as much through the whole fluid as of oils.

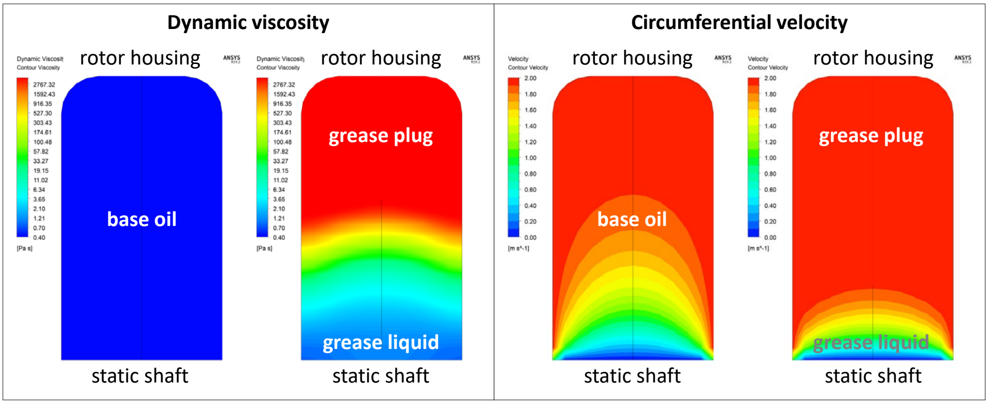

Figure 5: Comparison of base oil and grease (CFD results)

In a real sealing gap the situation is more complex as there is a mixture of grease and air between the two moving walls in dynamic conditions. There are no static boundary layers as the quasistatic result shows, but alternating grease plugs, some sticking to the rotating housing and some to the static shaft. Figure 6 shows CFD results of a transient simulation. Near the shaft there is a region with low viscosity and high shear strain rate and a layer of grease that remains with the shaft (red) while the most grease is transported as plug with the rotor housing (blue).

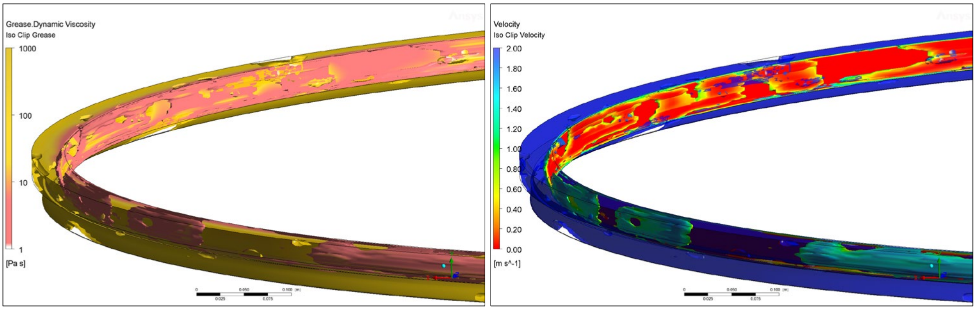

Figure 6: CFD results of the viscosity and velocity in a 90 % grease filled sealing gap

4 Grease transport effects

The grease flow simulations visualized the transport mechanisms very good. Based on that Table 1 lists and explains the different parameters, that influence the grease transport. All these effects need to be considered for the design of a wind turbine sealing. Although they can be evaluated from an engineering point of view, a CFD calculation is able to put these in quantitive relationship to each other. This reduces the risk of assigning too much emphasis to a minor effect while overlooking a major effect. Furthermore, design concepts can be investigated, that use existing mechanisms for a desired grease transport.

Table 1: Grease transport effects

Parameter	**Function**	**Impact**
Non-Newtonian behavior	Grease with high shear near the sealing contact becomes liquid, in regions without shear it becomes pasty	Grease tends to deposit in regions without shear or mechanical forces
Rotor movement	The high shear rates at the sealing contact cause the grease to become liquid and to be transported relatively to the rotor	Strong impact on the transport of liquid grease
Mechanical oscillations	Grease is squeezed between shaft, housing and/or sealing and thereby put in a more liquid condition that makes it more susceptible to flow	Strong impact on the transport of deposited grease
Temperature	Increasing temperature reduces the yield stress, consistency and shear thinning exponent	Higher temperatures increase grease transport
Filling ratio	Less air fraction forces the grease to evade the surrounding structures during oscillation while a high air fraction allows grease to rest as solid paste	Together with mechanical oscillation a strong influence on grease transport
Centrifugal forces	Grease in liquid condition tends to move outwards	Impacts only liquid grease and might reduce the lubrication by grease depletion at the sealing contact
Gravity	Gravity alone has no significant impact on grease in solid condition in the sealing gap. During operation the liquid lubrication film causes hydrostatic pressures	Small impact on transport, but needs to be considered in sealing design because of the big sealing diameters

Interestingly, in quasistatic conditions the grease tends to deposit in the sealing gap between the housing walls. This leads to the depletion of the grease concentration at the contact between the sealing lips and the shaft, which endangers the lubrication. This effect is amplified by the centrifugal forces.

Just because of the mechanical vibrations, e.g. the wobbling induced by the rotor blades passing the tower, and the nonconcentric deflection between rotor housing vs. the shaft the depleted grease is partially reactivated to participate on the flow again. Temperature and gravity amplify this desired effect.

The grease transport effects have to be considered when choosing the seal and the grease. E.g. with narrow gaps a grease with lower yield stress needs to be preferred to avoid extensive sticking. The filling ratio needs to be adjusted that there is enough grease, that deposited regions can be activated again, but not too much to allow remaining air to provide compressibility and to damp high pressures caused by the yield stress of deposited grease.

5 Results

As shown in chapter 3, the lubrication of rotor seals is not trivial. Because of the special situation, the rotating seal and the enormous displacements that the housing can perform with respect to the shaft, the lubricant distribution is based on some special principles that were shown in chapter 4. In particular, the wobbling motion with which the seal rotates around the shaft leads to an efficient and permanent movement of the grease mass, so that the "yield stress" is overcome and the grease mass can be transported to the tribologically stressed zones. Without the effect of the lubricant transport induced by the wobble displacement, the sealing system is in risk to run dry with subsequently increase of the friction torque and sealing contact burn. If the wobble is too strong and the grease cannot move out of the way, there is a risk that the lubricant will be pressed through the sealing contact to the air side. If this happens frequently, the sealing system becomes conspicuous due to excessive leakage grease. The sealing element must therefore be precisely matched to the environment of the sealing system, such as: grease viscosity and quantity, rotational speed, tolerances and, in particular, the misalignments between the housing and the shaft.

5.1 Next level seal development – helix seal

To meet the challenge of precisely matching the sealing element to its environment, the current development for rotor seals for wind turbines is moving towards a new type of sealing element that conveys the lubricating grease back towards the bearing to a greater extent. The additional grease transport is achieved by a helix design of the sealing element. This not only ensures that the grease is transported by the natural sealing mechanism, but also that the helix shape of the sealing element causes the grease to be transported in a similar way to a screw pump:

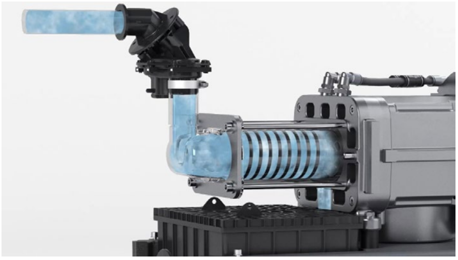

Figure 7: Principle of a screw pump to transport fluids

If you want to transfer the principle of a screw pump to the installation space of a radial shaft seal, this is not easy in view of the dimensions of a diameter of 3 meters and a component width of only a few centimeters. This means that only a few pitches of a single-rotation helix are possible in the seal installation space. Freudenberg Sealing Technologies is currently in the process of developing an innovative helix seal for rotor seals for wind turbines. Freudenberg Sealing Technologies will report on the development and present the new sealing concept soon. First results as shown in Figure 8 look promising regarding a more dynamic and larger induced grease transport through the relative motion between shaft and rotor.

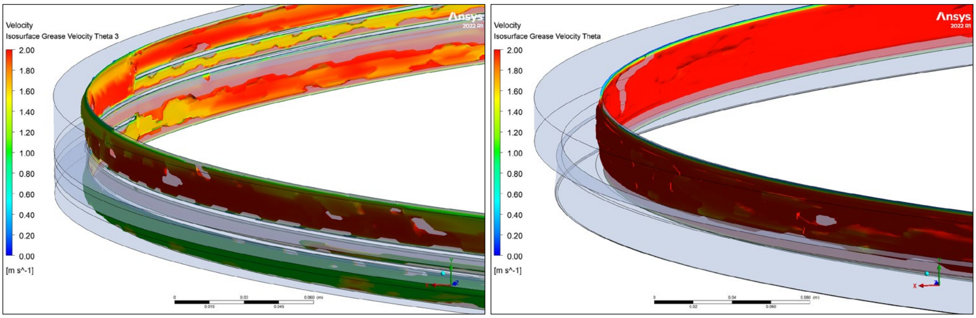

Figure 8: CFD results of helix seal (left) compared to radial shaft seal (right), region of induced grease movement

6 Additional information – appendix

6.1 Literature

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6.2 Pictures

6.3 Tables