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High-Speed Radial Shaft Sealing Solution for eMobility drivetrains

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Summary

Based on the higher requirements of sealing solutions for new eMobility transmissions there is a necessity to develop new economic seals for special demands regarding high-speed and reverse driving. This paper points out the differences in new eMobility transmissions and shows the limits of state of the art sealing solutions. Furthermore the new developments for material and design enhancements already done and the current achieved goals on function and durability tests are described.

Keywords: efficiency, electric drive, EV (electric vehicle), powertrain, transmission

1 Introduction – Classification of the topic

As a supplier for sealing solutions for the automotive industry a major part of the product portfolio is used in combustion engines as well as transmissions and differential gears. In the current eMobility era the electric motor will be the new core for New Energy Car drivetrains. From a theoretical point of view the car manufacturers can pass on using transmissions. Generally the maximum torque is directly proportional to the total weight of an e-motor. Another approach is using smaller lightweight high-speed e-motors with reduction gears. Although both approaches will lead to a more or less similar total weight there are two main advantages for the e-motor-transmission combination. By tuning the reduction gear closer to the optimum e-motor operating point the degree of efficiency will simply increase. Furthermore from a cost optimizational point of view one kilogram e-motor is more expensive than one kilogram transmission [2].

The new eMobility era still has a place for transmissions and therefore also for sealing solutions – with the only difference: higher requirements to all components!

2 State of the art and new challenges

To develop a new sealing solution for high-speed transmissions used in New Energy Cars it is necessary to point out the differences between combustion and e-motor transmissions. Based on these differences the limits of current sealing solutions have to be found and understood.

2.1 New requirements

Compared to transmissions for conventional combustion engines the new eMobility transmissions differ in several properties. With regards to sealing technology the three main differences are the much higher rotational speeds, the increasing usage of lower viscosity oils with plenty of additives inside and the easy change of the input shaft rotational direction for reverse driving which is unknown from common combustion drivetrain transmissions. This, as well as the much higher line speeds for the input shaft seals, is the biggest challenge for future sealing solutions inside new eMobility transmissions. In addition to these new and realistic reverse driving cycles inside the customer's design verification plan (DVP) shown in Table 1 the new Chinese specification QC/T 1022-2015 for reduction gearboxes [3] stipulates that all transmission components for eMobility cars have to pass a 24 min reverse driving test at 90 °C with 30% of the maximum forward drive speed.

Table 1: Model DVP comparison between common and eMobility transmissions.

Application	**Common Transmission**			**eMobility Transmission**		
Oil level	Input shaft centerline			5mm above shaft lower edge		
Description	Duration [h]	Speed [rpm]	Temp.[°C]	Duration [h]	Speed [rpm]	Temp [°C]
One test cycle [24 h]	14	7.000	110	14	4.000	90
				1,5 min	-2.000*	90
				1,5 min	0	90
	6	7.000	130	3	13.300	125
*Reverse driving				1 min	-5.500*	125
				1 min	-3.000*	125
				3	13.300	140
	4	0	RT	3:52	0	RT
Total test time	240 h			240 h		

Even though this specification is not classified as realistic test conditions by many transmission supplier as well as car manufacturer, it still points out the future direction of development for autonomous driving and has to be considered important by the automotive industry.

Autonomous driving will bring up the question if preferred rotational direction won't exist any longer. Then we will start to talk about rotational direction specifications like 50% clockwise (CW) and 50% counter-clockwise (CCW). First books of requirements (BOR) with such kind of bi-directional requirements already showed up on the market.

2.2 Current sealing solutions and their limits

State of the art solutions for transmission shaft input seals are Polyacrylic elastomers (ACM) garter spring seals (Figure 1, left) as well as Polytetrafluoroethylene (PTFE) and rubber laydown designs with a helix for the oil pumping and sealing function. The higher rotational speed as well as the lower oil level reduces the lubrication and cooling function of the sealing edge. These circumstances combined with a few seconds of a possible dry-run within the first launch of a transmission lead to an increased sealing edge wear which might lower the lifetime of a garter spring seal dramatically or even directly lead to malfunction.

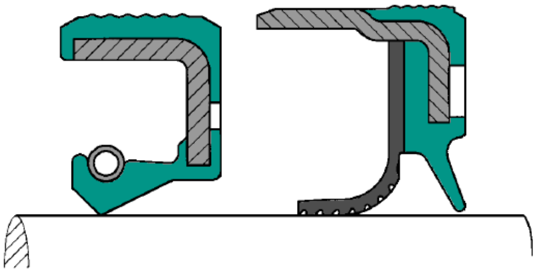

Figure 1: Garter spring seal (left) and PTFE laydown design (right).

On the contrary, optimized PTFE designs (Figure 1, right) are able to deal with these higher speeds and temperatures. But due to the PTFE design, the manufacturing process and the PTFE material properties itself the reverse driving requirements are pretty challenging or even not feasible. Furthermore it is actually pretty challenging to achieve the specific air leakage requirements of the transmission manufacturers during their end-of-line (EOL) tests with this kind of PTFE designs. A specific high-viscosity fluid called air leakage blocker (ALB) has to be applied inside the helix structure to achieve the requested EOL air leakage requirements but also to make sure not to harm the pumping function of the PTFE seal itself during operation. This action increases the costs and also the complexity of the assembly process.

3 New approaches

Similar to the PTFE laydown design there are also existing sealing solutions with a rubber laydown design on the market since many years. The benefits compared to PTFE seals are the lower friction losses and the better performance during the EOL air leakage test, the final step when assembling a transmission or engine. This kind of rubber laydown design with the KACO name FRed®, which stands for Friction Reduced Oil Seals, usually has a unidirectional helix design based on the rotational direction of the transmission which is determined by the rotational direction of the crankshaft finally.

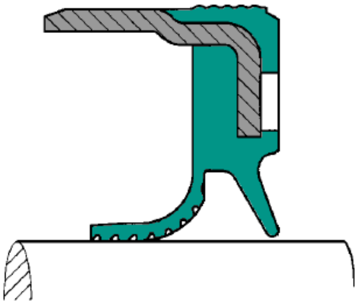

Figure 2: FRed® rubber laydown design.

Based on the new reverse driving requirements for NEV the first approach is to use a bidirectional helix. But a common bidirectional helix design shows in general a lower pumping ability and therefore the maximum line speed is even lower compared to a unidirectional design. Therefore a second approach is to continue using a unidirectional helix design in combination with specific oil-stopping design elements to ensure the reverse driving capability. In fact this approach is counterproductive for the performance of the main direction of the unidirectional helix design (e.g. oil carbon build-up) and the reverse driving capability is still limited with regards to the Chinese reverse driving specification [3].

Keeping in mind the advantages of the FRed® rubber laydown design as a state of the art sealing solution a continuous refining and optimization process of the helix design based on the main objectives as high rotational speed and good reverse driving ability was started.

3.1 Tribological effects of state oft he art bi-directional helix designs

For a better understanding of the new design approach it is useful to be familiar with the tribological effects of commonly used state of the art bi-directional helix designs. The principle of a bi-directional helix design is similar between garter spring seals and seals with a laydown design, no matter either PTFE or elastomer.

With the help of the research work of Nino Dakov [1], the triboligical effects on a PTFE laydown seal are explained hereafter. His research work is based on an EHD simulation with an upstream assembly simulation for accounting the total contact pressure distribution of the sealing system. The mixed friction effects of the used PTFE laydown design with bi-directional helix ribs shown in Figure 3 were also taken into account.

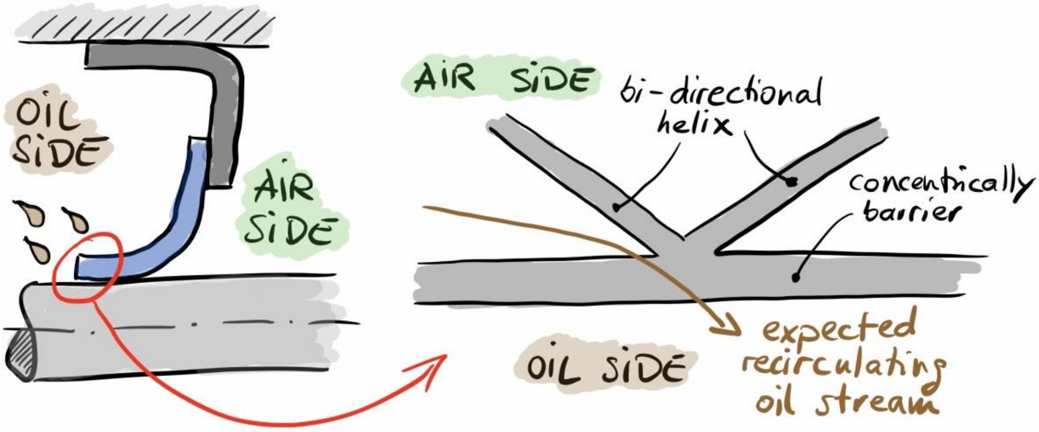

Figure 3: State of the art bi-directional helix design.

The EHD simulation shows that the amount of the oil leakage stream towards the air side can be bigger compared with the recirculating oil stream back to the oil side. This conclusion can be traced back to three sources as follows and is visualized in Figure 4:

1. The direction of the oil flow inside the double convergent gap has to be slightly changed towards the medium side inside the application due to the design of the helix ribs. Therefore the mass inertia of the fluid actually causes a part of the total oil leakage stream.
2. The stagnation pressure located at the narrowest cross-section of the double convergent gap causes a lift-off effect of the helix rib dependent on the circumferential speed of the shaft. The therefore resulted oil leakage stream increases with higher speed.
3. In consequence of the laydown design itself the FE calculation shows that the contact pressure is decreasing in the axial direction towards the air side. This design characteristic leads to a lower contact pressure of the tangential entering helix rib compared to the joining radially closed circle and therefore also supports the oil leakage stream towards the air side.

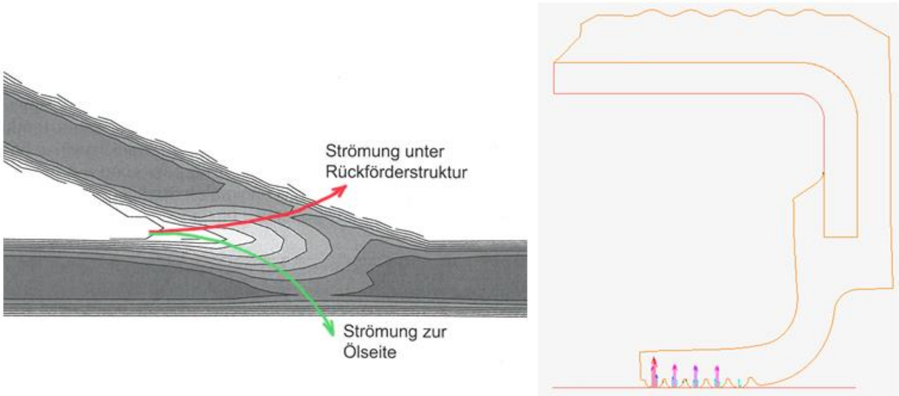

Figure 4: Gap height at the area of a helix rib [1] and contact pressure distribution on a FRed® seal.

3.2 Innovative design approach for a bi-directional helix design

Based on the three mentioned tribology effects above a new and innovative bi-directional helix design was worked out, shown in Figure 5, which is focusing on reducing the oil leakage stream to achieve our main objectives as high speed and reverse driving ability.

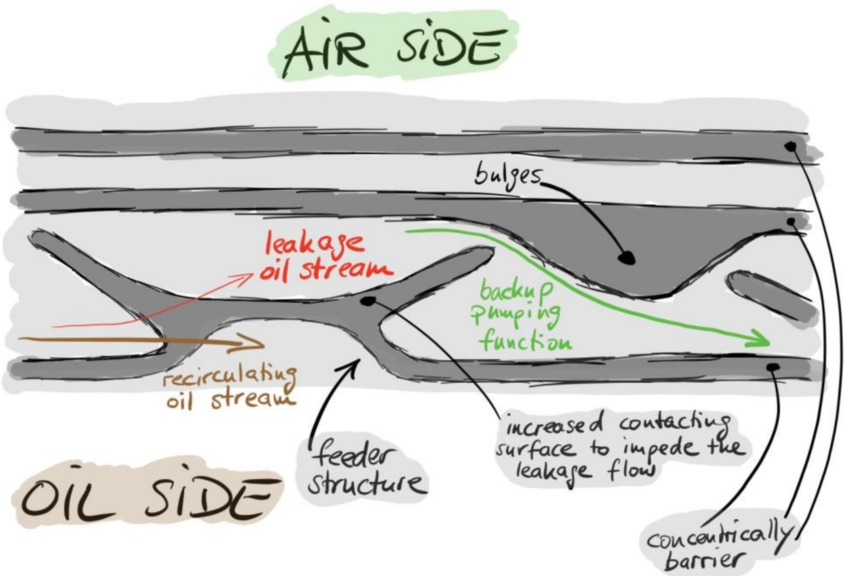

Figure 5: New approach of a bi-directional helix design.

Generally this design can be divided into two main areas described as function area directly facing the oil side of the application and the backup area on the air side to ensure robustness.

The function area starts with a concentrically barrier on the oil side for static and dynamic sealing function. This barrier contains so called feeder evenly distributed on the circumference. The bi-directional helix ribs entering these feeder structures from both directions tangentially and make up the function area. The purpose of the feeder is based on the mass inertia of the fluid. During the pumping action itself inside the double convergent gap the fluid doesn't have to change its direction which causes a reduction of the oil leakage stream. With regards on the decreasing contact pressure in axial direction and the occurring stagnation pressure inside the double convergent gap the contacting surface between the seal and the shaft in the area of the tangentially entering helix ribs got increased to impede the leakage flow towards the air side.

By having the Figure 5 in front of the eyes above the feeder structure and bi-directional helix ribs additional concentrically barriers are located. At the barrier next to the helix ribs so called bulges are located and make up the backup area of the seal. The number of these bulges is equal to the number of feeder but shifted in radial direction. The purpose of these bulges is to put the still occurring leakage stream back into the function area of the helix ribs actively.

This new approach of a bi-directional helix design was optimized within several design loops based on finite-element (FE) calculations and test runs.

3.3 Development of a new Fluor elastomer (FKM)

Besides the development of a new bi-directional helix design it is also necessary to focus on further advancement of the especially for FRed® seals used FKM elastomers. The idea is to combine the advantages of ACM and FKM compounds. As ACM compounds are well known for its very good sealing performance and chemically robustness against transmission oil additives the majority of transmission and original equipment manufacturers (OEM) are using this elastomer for transmission seals. On the other hand FKM compounds have the benefit of a higher maximum operating temperature point and better wear resistance over lifetime.

A disadvantage of state of the art FKM materials is actually the poor resistance against particular additives inside transmission oils. Under high temperatures, starting at 130°C and strongly speeding up at 150°C, the FKM compound interact with certain transmission oil additives which causes a further cross-linking and results in a dramatically quick aging process which, in turn, reduces the lifetime of the seal.

One option could be the usage of special low temperature FKM compounds, but this will increase the material costs of the compound significantly and isn't solving the problem completely. Therefore a way on how to increase the chemical robustness of the FRed® FKM compound against commonly used transmission oil additives had to be found.

The following Figure 6 shows an oil immersion test at 150°C for 168h in DEXRON® 6 transmission oil with the state of the art and a new development FKM compound. Compared to the state of the art FKM compound, which shows a big reduction of the elongation at break and a significantly growth of the tensile stresses at 50% elongation at break, the new FKM development compound behaves much better. These two material properties are indicators for the elastomer aging progress – and therefore it was possible to slow them down what offers the opportunity of using this new FKM compound inside transmission applications for further test runs.

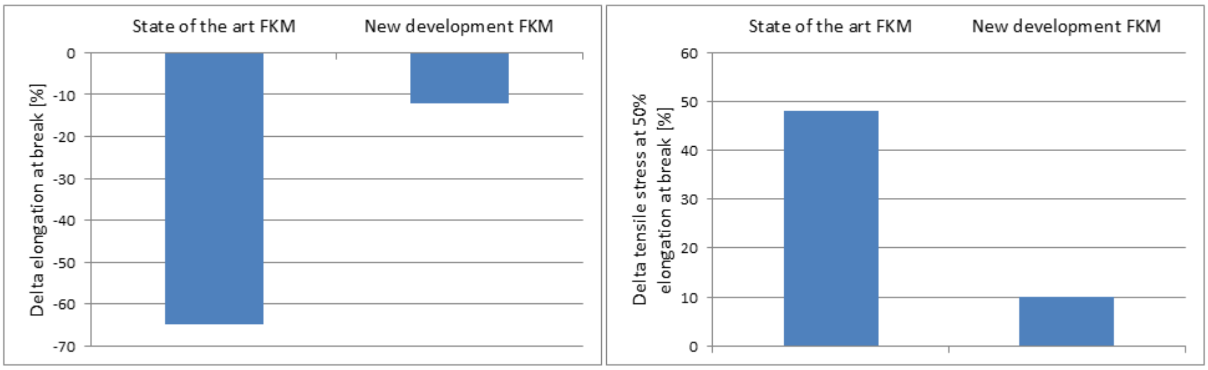

Figure 6: Comparison of delta elongation at break and delta tensile stress at 50% elongation at break.

4 Design verification

In order to verify this new design approach we started to go on test rigs with the first prototypes. To get a reliable impression on the capability of this new design we decided to run a function and durability test first.

The function is tested on our self-developed so called KACO P&K test rig. This function checking test is used to evaluate the sealing and pumping function of a seal design. The P-value, rated from P10 (best) to P1 (leakage), gives a feedback for the dynamic and static sealing function under certain operating conditions such as different temperatures, speeds, standstill, rotational directions, STBM and DRO values. The K-value is a qualitative rating of the pumping behavior, also under different operating conditions. Therefore an oil drop of exactly 20µl is placed on the air side of the seal and the time is stopped the seal needs to pump this oil drop back to the oil side. Taking the used time and rotational speed of the shaft into account the K-value is a qualitative measure to compare the pumping ability of different seal designs and different operating conditions. The first prototypes were tested up to a circumferential speed of 13,2 m/s in both directions up to temperatures of 140°C. The seals showed P ratings in between P7 and P10 and K values in between K30 to K60. Keeping in mind to test a seal in both rotational directions with a bi-directional helix design the result is positive.

In the second step the new design has to pass the durability test of 240h acc. to the DIN3761 with circumferential speeds up to 16 m/s in both rotational directions. This durability test was also passed successfully.

Finally the new design approach has to achieve the reverse driving requirements acc. to the Chinese specification [3]. Based on the QC/T 1022-2015 specification we set up a test run cycle as shown in Table 2 below. This cycle was repeated 5 times for a total testing time of 110h and 50min and accomplished successfully. The maximum forward driving speed was set up to 30 m/s and the reverse driving speed at 9,1 m/s accordingly at a maximum temperature of 140°C.

Table 2: Reverse driving test program acc. to the Chinese specification [3].

Steps	Rotational direction	Temperature	Speed	Duration
1	Forward	90°C ± 5°C	max. speed	13h
2	Reverse	90°C ± 5°C	30% of max. speed	24min
3	Forward	max. Temp.	max. speed	5h
4	Reverse	max. Temp.	30% of max. speed	12min
5	Break		0	3.5h

The occurred frictional torque vary in between 0,02 and 0,03 Nm which is actually quite low for this rotational speed and therefore the tested prototype seals have almost no wear except of dull spots at the contacting surface to the shaft.

5 Outlook

The first function and durability tests show a good sealing and pumping performance for this new bi-directional helix design. With regards to the successfully accomplished Chinese reverse driving cycles this design is capable to fulfil new requirements on eMobility transmissions for NEV.

Nevertheless further optimizations due to our own set of requirement of a high speed seal without any preferred rotational direction which therefore can be operated on maximum speed in both directions already started. This latest design optimization was already tested for 700h with a maximum speed of 17,2 m/s and a maximum temperature of 140°C at 50% CW and 50% CCW rotational direction. To ensure full functionality inside transmission several operating conditions such as low speed at 2,5 m/s, oil level from 5mm above lower shaft edge to centerline and standstill for 48h were also tested. These variations of operating conditions should ensure static sealing ability and parking the car on a hill. This design optimization is currently on a patent process and therefore no design pictures can be presented now. Further high speed tests with an equally rotational direction ratio up to 60 m/s are in progress.

This optimized FRed® laydown design shows the capability to fulfill future eMobility reduction transmission requirements regardless to the rotational direction on an economical cost level.

Nomenclature

ACM	Polyacrylic elastomers
ALB	Air Leakage Blocker
BOR	Book of Requirements
CW	Clockwise
CCW	Counter-Clockwise
DEXRON®	Registered trademark and transmission oil classification of General Motors
DRO	Dynamic run-out
DVP	Design Verification Plan
EHD	Elastohydrodynamic Simulation
E-motor	electric motor
EOL	End of Line
FKM	Fluorelastomers
FRed®	Friction Reduced Oil Seals
ISC	International Sealing Conference
NEV	New Energy Vehicles
OEM	Original Equipment Manufacturer
PTFE	Polytetrafluoroethylene
STBM	Shaft to bore misalignment

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Authors

Konstantin Rempel started to work as a development engineer at KACO in 2015. At the end of 2017 he moved to Wuxi, China to support the local Application Engineering & Testing team on-site for KACO China. Since March 2019 he is back in Germany working as a Team Leader for Oil Seals in the development department at the new KACO headquarters in Kirchardt.

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