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Stochastic analysis on tribological behaviour of radial shaft seals with focus on lubricants

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This study deals with a methodical interpretation into the complex landscape of the tribological behaviour of Radial Shaft Seals (RSS) using dynamic investigations focusing on the influence factor lubricant. The lubricant has been identified as one of the main drivers for the tribological behaviour of RSS, especially due to its chemical structure and physical properties such as viscosity. This study evaluates the impact of lubricants with different chemical structure but similar viscosity on the tribological behaviour of RSS, which allows to gain a deeper understanding of the further physical properties of lubricants. More specifically, the tribological performance of different types of lubricants have been examined on different RSS materials. Thereby, the rotational speed has been varied in relevant ranges. Using stochastic calculus analysis, the tribological behaviour of RSS with lubricants can be evaluated in more detail. The aim of the extensive investigations is to provide a basis for future, more in-depth research into understanding on the tribological behaviour of RSS as well as predictions for specific classified working environments such as minimal lubricant condition, high temperature, etc., for the different RSS systems.

1 Introduction

In the modern industry the application of the combination of Radial Shaft Seal (RSS) with minimal lubrications, such as grease and oil, has been widely developed and utilized, as well as widely researched in the scientific field [1] [2]. The RSS, the shaft as well as the counter surface and the applied lubricant form a specific tribological system [3]. The functional task of the simplified RSS is to avoid fluid leakage [3]. A utilized combination of the RSS and the correctly selected lubricant should help to avoid the irregular wear and extend the service lifetime of the RSS. This work is about to gain a better understanding of the tribological behaviour on different possible combinations of RSS and lubricants, especially how the lubricants with similar physical properties such as viscosities reflect on the tribological behaviours of RSS. In addition, the physical properties of lubricants with similar viscosities are about to be evaluated and discussed using stochastic analysis.

2 Test Procedure and Test Material

In this chapter, the test procedure, or more precisely the test rig and the applied test materials will be introduced. A specially designed RSS test rig is available at the Institute for Machine Elements, Design and Manufacturing for the experimental investigations based on the minimal lubrication principle. Other than that, specifically applied test materials such as the RSS parts and the lubricants are studied according to the minimal lubrication principle. The selection of determinant factors on RSS and lubricants is introduced.

2.1 Test Setup for Tribological Measurement

The tribological measurement in this study has been investigated on a self-developed test rig at the institute, which has been used for many previous friction performance measurements [1] [2]. Specifically, the friction performance parameters of a RSS system such as torque and temperature can be measured with different operating conditions. The test rig includes the fundamental components is described in Figure 1. This test rig was used to collect the significant measurement data for this work.

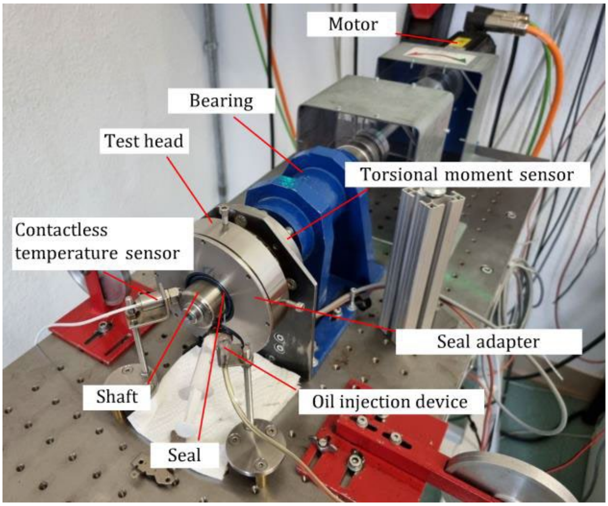

Figure 1: Test rig with sufficient components.

As shown in Figure 1, the main components of the test rig are the motor, bearing, test head including the torsional moment sensor, and the counter face. The RSS is mounted with a seal adapter. The oil injection device and a contactless temperature sensor are placed on the sides with defined distance onto the contact area. During the tests, the oil injection device provides continuously certain amount of lubricants into the contact area.

2.2 Test Material

This chapter is about to introduce the applied materials, more specifically the RSS, the shaft surface and the lubricant.

2.2.1 Radial Shaft Seals and Shaft Counter Surfaces

A specific RSS with a helical spring but without the dust lip from Freudenberg (in Simmerring® BAUM form) has been investigated in this work. This typical RSS is manufactured according to the German standard DIN 3760 [4]. The RSS elements in this work vary in two different materials: seal A is fluoro rubber (FKM) and seal B is nitrile butadiene rubber (NBR), as well as in two different dimensions: 45x75x7 and 38x52x7 ($d \times D \times B$ $[mm]$). Though the comparison between different dimensions is not focused in this work, which has been analysed in previous works [5] [6].

The shaft part in this tribological system serves as the counterface. In this work two different counter faces have been applied. One is a plunge ground shaft made of bearing steel 42CrMo4 specifically for RSS with dimension 45x75x7, while the other is C45R specifically for RSS with dimension 38x52x7. There is no focusing on the comparison of the potential difference caused by different counter faces in this work. This influence factor has been deeply analysed in different aspects in other researches [7] [8].

2.2.2 Lubricants

As it has been researched in the recent years, lubricants have a significant influence on the tribological behaviours of RSS under minimal lubrication environment [1]. In the modern industry, the variations of lubricants are basically classified into nature mineral oil and synthetic oil. More and more synthetic oils have been developed with sustainable and environment friendly considerations. In order to improve the synthetic oil development meeting industrial operation demands, the functional aspects of lubricants need to be examined for stabile tribological behaviours. Based on the applications, synthetic oil should perform stable in higher temperature range such as above 90 °C. In this study mineral oils and synthetic oils with similar physical properties are applied for the specific tribological behaviour analyzing.

The applied lubricants are listed in Table 1. Basically, there are two types of mineral oils and 5 different synthetic oils. The important relevant parameters are shown in Table 1. The synthetic oils share one ISO VG class, while the mineral oils have a higher ISO VG class. The ISO VG class describes the relative temperature dependence of lubricants, which significantly affects the tribological behaviour of RSS.

Table 1: Physical properties of the applied oils with short labels.

Label	Description	Kinematic viscosity [mm²/s]		ISO VG	Density (by 20°C) [g/cm³]
		40°C	100°C		
M1	Mineral oil	320	24	320	0.9
M2	Mineral oil	345	25	320	0.9
PAO1	Poly-alpha olefin oil	234	30	220	0.85
PAO2	Poly-alpha olefin oil	234	22	220	0.85
PG1	Polyglycol oil	220	41	220	1.06
PG2	Polyglycol oil	220	41	220	1.06
PG3	Polyglycol oil	220	41	220	1.06

From the table, it's significant to realize that the oils in each group (M_i, PAO_i or PG_i) share similar physical properties such as kinematic viscosities or densities. Slight differences between the oils in each group are caused by production processes and potentially different proportions of additives, etc., which lead to the hypothesis of this work if the potential different tribological performances are recognisable.

2.3 Measuring Procedure

In this work, the operational variations in the investigations are partially located on different rotational speed profiles. Investigations with different approach profiles have been analysed in a previous study and provided significant results under simple variable method [5]. The specifically applied rotational speed profiles for this work under two or multi variables are listed in Table 2. The measurement results after operating with different rotational speed profiles show significant difference among the individual RSS and lubricant combinations. The different combinations show different tribological performances after operation, which will be analysed in next section.

Table 2: Applied different approach profiles with short labels.

Label	Description	Diagram
E1	Run in profile	2 hours constant high rotation speed
Testing	Short testing profile	Added up rotation speed from minimal to defined maximal n_{max} with short time stepping rate
V_i	Long added up profile	Added up rotation speed from minimal to limit n_{lim} with long time stepping rate

As it's shown in Table 2, the applied approaches can be generally sorted into three groups: run in, short testing and long added up profiles. Approach E1 is performed in 2 hours constantly with the highest rotational speed, which services as running-in process of each new RSS part.

In order to generate the following different rotation speed profiles V_i, one particular testing profile has been introduced to define the maximum and the limit rotation speed. In the testing approach, the rotation speed is added up after each short time period, starting at from minimum to a defined maximal n_{max}. In each step, the rotation speed remains constant in order to observe short time tribological performance and to observe the difference after rotation speed change.

Approaches V_i are all added up profiles from minimum to a defined limit rotation speed n_{lim} with different relative stepping rates. With help of these different approaches in this working, it is possible to identify the different tribological performances of RSS.

3 Results and Discussion

3.1 Measurement Analysis

In the very beginning, approach testing has been used to set a limit rotation speed n_{lim} for further research. Figure 2 shows the measurement results from possible variable combinations among RSS and lubricants. In the diagram the torque developments varied very much from one combination to another. Especially the absolute values differ from each other strongly. This could be explained by the particular tribological behaviour of the combinations of RSS and lubricants. But the tendency of the torque development in the whole testing phase is quite similar. The most significant change in tendency occurs between t_i and t_j, while in one particular combination it occurs earlier between t_h and t_i. One the other hand, the temperature developments varied only slightly from each other till t_h. However, after t_i the tendency of the temperature development varies from each other very strongly.

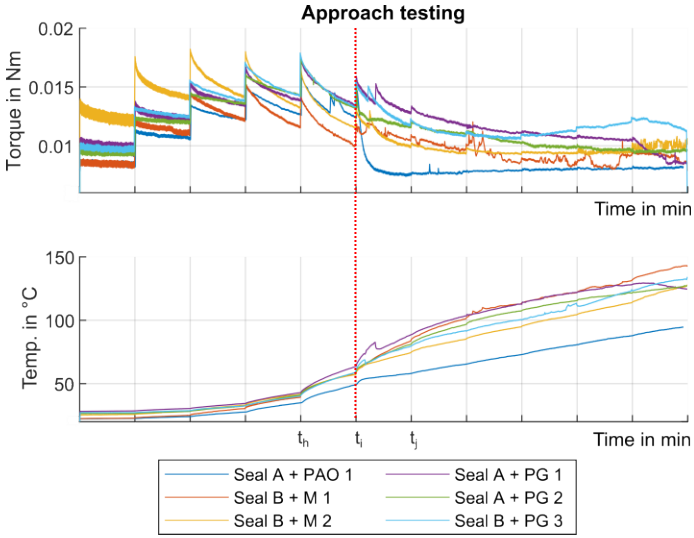

Figure 2: Determination of a limit rotation speed n_{lim}, Seal A – FKM, Seal B – NBR .

To keep the further research, more specifically the investigation process effective in short time, a limit rotation speed n_{lim} has been set for this study to observe the significant different tribological performances among different RSS and lubricant combinations.

After extensive investigations with different measurement setups, the measurement data could be analysed in various ways. In general, similar but in detail different developments on the tribological performance will be discussed in this following section. Figure 3 first shows the measurement results on two RSS rings applied with one specified operating condition (V_i) and with one particular lubricant.

As it’s shown in Figure 3, with one particular rotation speed profile, two RSS parts with different materials displayed similar tribological performance. In this particular rotation speed profile, the rotation speed increases with defined ranges after one hour constantly running. In each testing, the developments of torque and temperature have been measured. In each constant rotation speed phase, the development of torque and temperature is significant recognizable, especially after each rotation speed change.

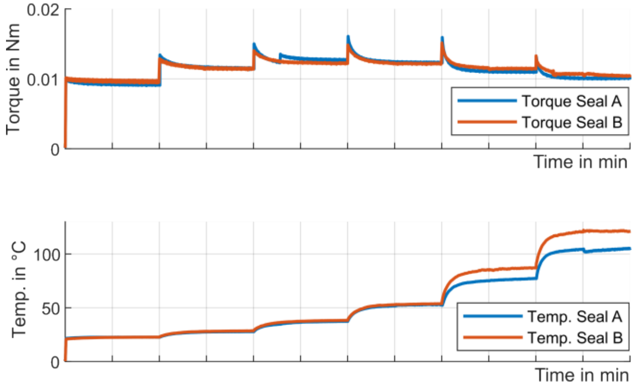

Figure 3: Friction performances from two different RSS, Seal A – FKM, Seal B – NBR, with lubricant PAO1.

On one hand, the development of torque increased immediately due to the break-away friction between the RSS and the shaft. The increasing of rotation speed causes momentary interaction onto the contact area. Along the time, rotation speed in one phase keeps constant. As a result, after the short time break-away, torque decreases to a steady state. This phenomenon in torque development will be changed till next rotation speed change.

On the other hand, the development of temperature presents firstly a climbing due to the increasing relative movement between the RSS and the shaft. Along the time, rotation speed in one phase keeps constant. As a result, the growth rate of temperature tends to be constant. Other than some minimal difference between two different RSS materials, the tribological performances are basically similar according to one rotation speed profile as input.

In Figure 3, some irregular peaks can be observed in torque and temperature development. Especially there is one peak in torque by seal A – FKM, meanwhile no effect on the temperature. On the opposite, friction oscillating can be observed by both different seals in the last time phase with correlated temperature oscillating. The correlation between torque and temperature development need to be further studied. [9]

In another case, the difference among different approaches has been analyzed with the help of Figure 4. The measurement results from seal A - FKM and PAO1 are shown with approach V1 in red, V2 in blue and V3 in black curves. The developments of temperature in three different approaches represents the changing in rotation speed inputs. The climbing in each phase is correlated with the adding up of rotation speed. On the opposite, the developments of torque are not correlated with the rotation speed inputs. Especially the development of torque from V1, has the lowest peak points in the first half time period compared with V2 and V3, but the highest peak points in the second half time period.

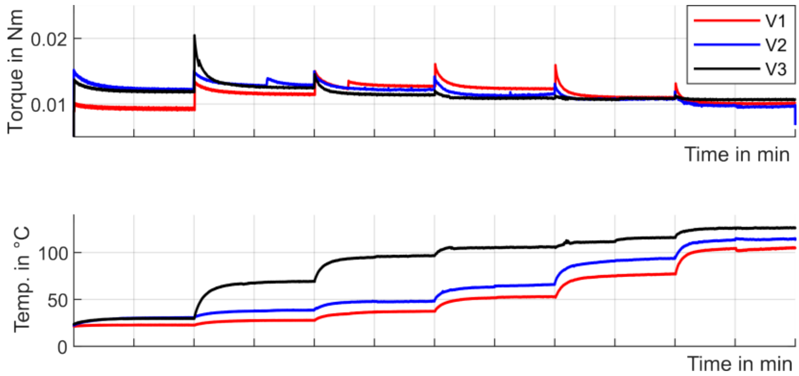

Figure 4: Friction performances from three different approaches V_i and with lubricant PAO1, Seal A – FKM. V1 = blue curve in Figure 3.

This phenomenon could not only be found by analysing on different seal materials, but also could be found by analyzing on different lubricants. In some particular cases, the tribological performance can not be correlated with influence factors such as different lubricants or different approaches. To find out the correlations more deeply in details, large number of investigations need to be implemented with diligent design of experiments.

3.2 Stochastic Analysis

In order to understand the tribological performance of RSS in more details with limited measurement signals, the measurement data will be analysed under aspects such as mean values, variance, tendency and distribution based on a stochastic analyse principle.

Figure 5 shows the distribution of torque and temperature on Seal A - FKM with one particular rotation speed profile and one particular lubricant. It is displayed for both systematic variables in the different time phases, or the constant rotation speed phases. As it is observed from the distributions of torque and temperature, it is clear to conclude that the torque distribution in each constant rotation speed phase stays mostly normal distributed. On the other hand, the temperature distribution shows a continuously increasing trend in the whole process as well as in each time phase.

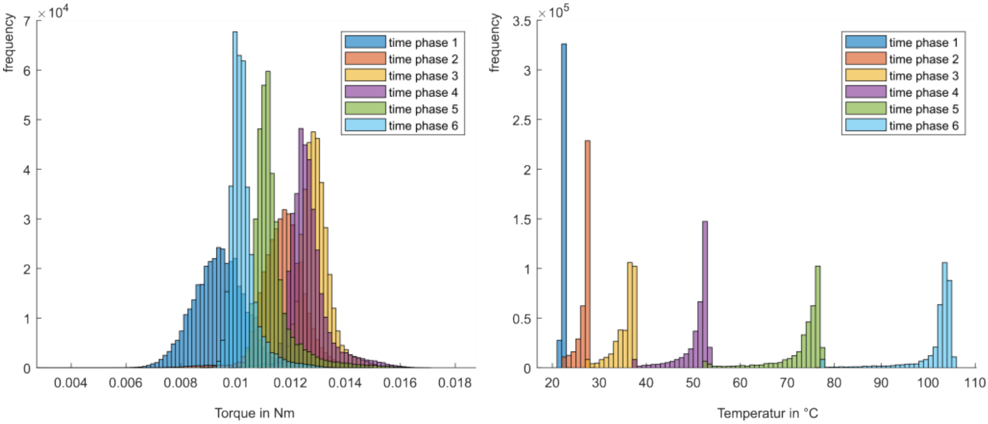

Figure 5: stochastic analyze from one approach with seal A - FKM, with lubricant PAO1 and rotation speed profile V1.

In both diagrams the y-axis represents the frequency of the measured value in torque or temperature. This could be used as a criteria of the stability of this tribological system. In the torque distribution, it could be observed that the frequency of the mean value (as well as the highest frequency in each time phase) of each time phase is higher one after another. On the other hand, the frequency of temperature is increasing in each time phase. However, the highest frequency of each time phase is decreasing, while the interval length in x-axis in each time phase is increasing. This could be interpreted as the slower temperature increasing in the whole time phases, even with smaller temperature changes. While the temperature changing in the final phases is mostly with quicker climbing and greater value changes.

In Figure 6 it’s shown the distribution of torque and temperature on seal B - NBR with the same rotation speed profile and the same lubricant. It could be observed that the distribution in torque and temperature from different seal materials has similar tribological developments and distributions. A slight difference can be observed in the absolute frequency value in torque distribution, especially in the last time phase. Also the trend in temperature distribution differs from the other seal material in Figure 5.

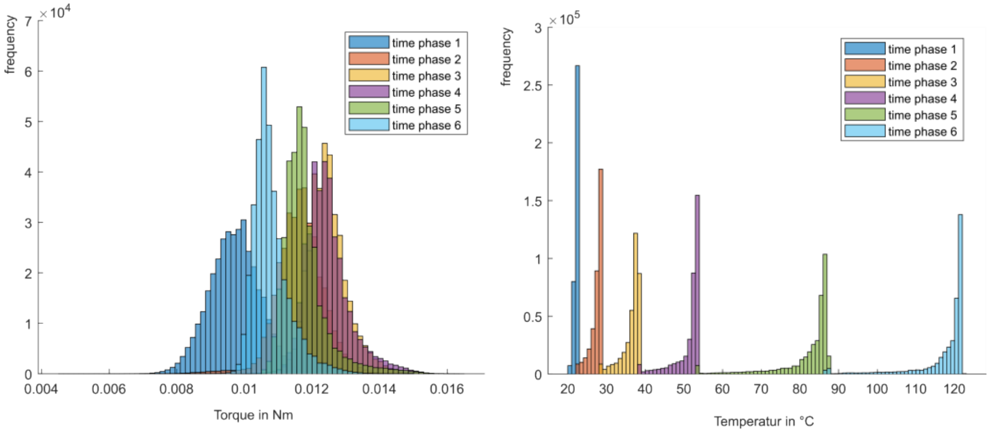

Figure 6: Stochastic analyze from one approach with Seal B - NBR, with lubricant PAO1 and rotation speed profile V1.

Another example in the stochastic analysis in comparison with different lubricants and with repeated runs is shown in Figure 7. Both diagrams show significant analyze results in different ways. In the left diagram, the comparison between different lubricants is presented in sub-figures in each time phase. From one particular rotation speed profile, the torque development as well as the distribution in the first two time phases are similar from one oil to another. But the torque development and distribution varies strongly in the next time phases. In the first two time phases, with lower temperature environment, the two PAO lubricants with similar physical properties present as well similar tribological performance on one particular RSS.

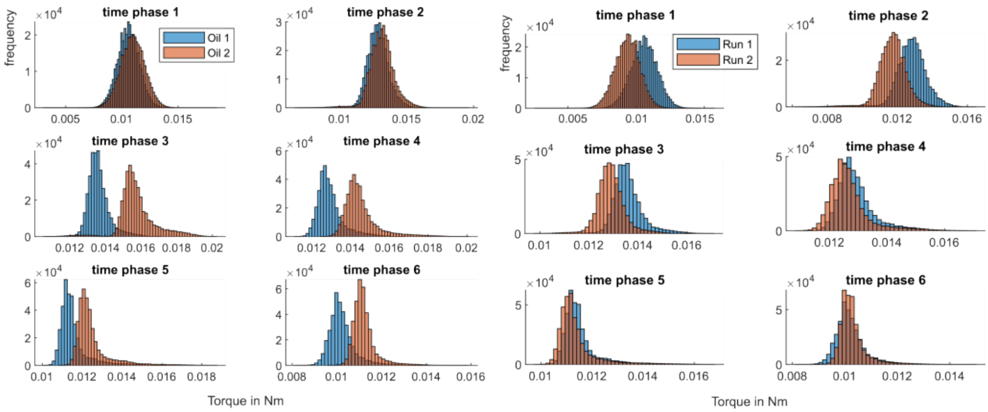

Figure 7: Stochastic analyze in comparison: Left 6 sub-figures: Seal A – FKM with PAO1 and PAO2. Right: Seal A – FKM with PAO1 with repeated runs.

In the right diagram, the comparison between repeated runs is presented as well in sub-figures in each time phase. As each testing set up is manually adjusted, there is a slight difference in the first half time phases. Since in these two repeated runs the set ups are identical, the torque development and distribution approaches from one to another. This could be interpreted as local minor difference in a generally similar situation.

4 Summary and Conclusion

In this work investigations with different combinations of RSS and various operating conditions have been carried out and the results have been analysed in different aspects, with the goal of deeper understanding on this particular tribological system, especially with the focus on lubricants. Among all the lubricants used in this works, which could be classified in 3 essential groups. In each group, the selected lubricants share similar physical properties. This work aims to figure out whether they present similar tribological performance as well. After a large number of investigations with different combinations, the measurement data were first analysed according to the testing process over time. Afterwards, the data has been analysed with different stochastic approaches.

In the end, it shows that different combinations of RSS and lubricants even if the lubricants have similar physical properties, can lead to different tribological performance on RSS. This phenomenon needs to be further studied to gain more in-depth knowledge about the tribological behaviour of RSS with different combinations of lubricants, as well as the potential predictions for special classified operating conditions to extend the potential lifetime.

5 Nomenclature

Variable	***Description***	***Unit***
B	Seal width	[mm]
d	Seal normal diameter	[mm]
D	Seal outer diameter	[mm]
M_d	Torque	[Nm]
n	Shaft rotation speed	[rpm]
n_{max}	Defined maximum shaft rotation speed	[rpm]
n_{lim}	Defined limit shaft rotation speed	[rpm]
T	Temperature	[K]
t	Time	[min]
v	Velocity	[m/s]
ρ	Density	[g/cm^3]
ν	Kinematic viscosity	[mm^2/s]
η	Dynamic viscosity	[Pas]

Abbrev.	*Description*	
E_i; V_i	Approach label	
FKM	Fluoro rubber	
NBR	Nitrile butadiene rubber	
M_i	Mineral oil label	
PAO_i	Poly-alpha olefin oil label	
PG_i	Polyglycol oil label	
RSS	Radial shaft seal	
t_h, t_i, t_j	Time variables	[min]

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