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Fachverband Fluidtechnik im VDMA e. V. Lyoner Str. 18
50628 Frankfurt am Main
Germany

Phone +49 69 6603-1513
E-Mail maximilian.baxmann@vdma.org
Internet www.vdma.org/fluid

Performance Analysis of Radial Shaft Seals in Non-Stationary Rotational Movements

Lenine M. de C. Silva, Yvo Stiemcke, Tim Schollmayer, Oliver Koch, Stefan Thielen

This work aimed to investigate the impact of non-stationary rotational movements on radial shaft seals (RSS). To explore various operational scenarios, a set of experiments was designed, and conducted using the MEGT High Acceleration Test Bench. The tests were realized analysing the development of negative pressure in the intermediate cavity between main and dust lip and observing the influence of the variation of several parameters in this negative pressure appearance. The results showed the occurrence of oil leakage under short oscillation angles and concluded that the negative pressure build-up might change the sealing geometry as well as the followability of the RSS to the movement leading to failure of the sealing lip.

1 Introduction

The number of applications involving rotational non-stationary movements has significantly increased in the past decade. Such dynamic rotational oscillations are often found in applications such as robotic arms. These dynamic rotational oscillations correspond to high levels of acceleration along with frequent changes in the direction of rotation. However, the impact of these oscillations on radial shaft seals (RSS) remains unknown [1] [2] [3] [4]. In practical applications, mineral oil has been found in undesirable situations such as in groceries [5] [6] [7] [8] [9] [10] [11]. Machines from the food production chain for instance work under critical operating conditions being frequently washed with hot water jets. The avoidance of leakage in such situations is primordial and the usage of RSS with dust lip to protect the sealing lip might be recommendable.

A initial study about non-stationary rotational movements has tested several work conditions such as RSS with and without dust lip, RSS with and without garter spring, RSS with and without grease in intermediate cavity, casing completely filled up and up to the middle of the shaft of oil, rolled and ground shafts, and four different types of curves, which the motors should perform during the test, in order to reproduce the non-stationary rotational movements. The study concluded that the use of a contacting, non-vented dust lip is essential for the occurrence of leakage [12] [13]. Although, the role of the dust lip during the non-stationary rotational movements remained unknown.

A later work proposed then an investigation about the role played by a contacting dust lip of an RSS in the non-stationary rotational movements. The study developed a mechanism capable to carry out reproducible pressure measurements directly from the intermediate cavity. These measurements were realized with the aid of pressure sensor and a medical needle, which could be always positioned in the middle of the dust lip to prick and have access to the intermediate cavity of the RSS

(C.f.Figure 2). The work observed that a negative pressure is build-up in the intermediate cavity during the non-stationary rotational movements and that this negative pres- sure deforms the intermediate cavity as well as change the angles formed between the sealing lip and the dust lip with the shaft [14]. The results of this work represented a substantial advancement in the explanation of the reasons why the RSS without dust lip or with a vented dust lip do not present any sign of leakage, and in some cases RSS with a non-vented dust lip produced leakage. However, the non-station- ary rotational movements involve several dynamic variables as well as variables in- herent to the application of an RSS in a mechanical system, whose influence on this negative pressure appearance remain unknown. Such analysis of several parame- ters in various levels of intensity has been described by [15] and might be suitable for practical applications as in the sealing technology.

This current work merges the conclusions drawn by the prior studies carrying out a series of experiments, which vary systematically the work parameters along with the realization of pressure measurements during the tests. The main objective of this work is to point out the influence of the working parameters at different levels in the formation of negative pressure in the intermediate cavity of RSS with contacting dust lip as well as in the occurrence of leakage during non-stationary rotational movements.

2 Materials and methods

To investigate different operational conditions and evaluate the impact of parameter changes on sealing performance during the non-stationary rotational movements, a series of tests was structured. These tests were executed on the High Acceleration Test Bench at MEGT, which features dual test cells directly coupled to two servomotors, enabling dynamic rotational oscillation. In addition, a device was designed to measure the pressure in the intermediate cavity using a pressure sensor and a medical needle. The experiments varied the following parameters: (*i*) the acceleration at the sealing contact; (*ii*) the oscillation angle; (*iii*) the greasing level in the intermediate cavity; and (*iv*) the curve type used in the oscillation.

2.1 The High Acceleration Test Bench

The operating condition of non-stationary rotational movements were executed by the MEGT's High Acceleration Test Bench. This test bench consists of two test cells to which two servo motors are coupled. Each test cell consists of a metallic housing with a driving shaft that is supported by two bearings in an O-arrangement and is lubricated in an oil sump. Each test cell is then sealed with one test shaft and one RSS per side (see Figure 1).

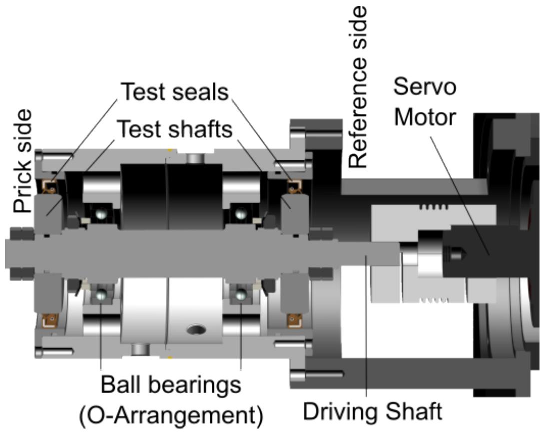

Figure 1: Section view of a test cell

2.1.1 Pressure Measuring Device

In addition to the High Acceleration Test Bench, a pressure measuring device was developed with the aim of measuring the negative pressure, which is formed in intermediate cavity during the non-stationary rotational movements. This device consists of two aluminium profiles for adjusting the vertical position, hand screws in the horizontal position to adjust the angle of the sensor with the horizontal line and a pressure sensor connected with a medical needle that has a diameter of Ø 0.4 mm (see Figure 2). Once the medical needle is positioned in the middle of the dust lip, a linear spindle needs to be rotated by hand to prick the dust lip and connect the pressure sensor with the intermediate cavity of the RSS.

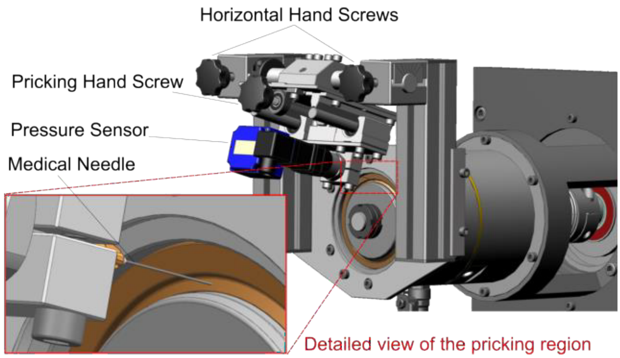

Figure 2: Pressure Measuring Device

After the prick, the puncture area needs to be sealed with silicone sealant, to avoid pressure equalization during the tests. The sealant fully dries after 24 hours, and then the High Acceleration Test Bench is ready for tempering the test cells. The pressure data were recorded during the tests.

2.1.2 Tempering System

Besides the pressure measuring device, the test bench is equipped with a tempering system, whose purpose is to ensure that the oil sump works with the operating temperature of 60°C. Each cell was equipped with a tempering sleeve, which can temper the housing uniformly minimizing the risk of local overheating. In addition, the cells are equipped with a safety system that switches off the entire test bench if a cell temperature reaches 120°C.

2.2 Work Method

The work executed 18 experiments with the High Acceleration Test Bench, each lasting up to 400 hours. The experiments varied several working parameters systematically, to determine the influence of each parameter on the sealing performance. The selected working parameters were: (*i.*) the cycle type, which is the curve that has to be followed by the motor in order to reproduce the non-stationary movements (see Figure 3); (*ii.*) the linear acceleration-maximum between the sealing ring and the shaft (i.e. at the sealing contact); (*iii.*) the angle of amplitude in which the shaft oscillates; and (*iv.*) the degree of greasing, which determines the proportion of grease in the intermediate cavity.

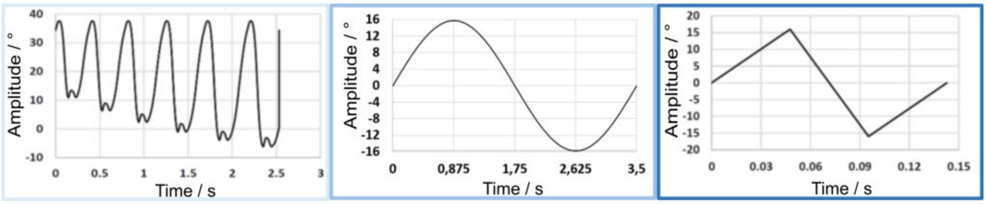

Figure 3: Representation of the cycles used to reproduce the non-stationary rotational movements. From left to right: industrial curve, sine curve, triangular curve.

In addition, the values of each parameter variation were planned according to the results obtained by [12] [13], and each parameter was varied at three levels (light, medium and heavy) to cover the most various situations in non-stationary rotational movements (see Table 1).

Table 1: Parameters with their 3 levels of values variation.

Parameters	**Settings**		
RSS Model	RSS without garter spring, with dust lip, material 75 FKM 585		
Counter surface	Rolled		
Oil Sump	Volume=1000 ml; full filled test cell; Temperature=60°C		
Cycle type	Industrial curve	Sine curve	Triangular curve
Acceleration / m/s²	80	160	240
Angle of Amplitude / °	5	10	15
Degree of Greasing / %	30	50	70

The complete variation of 4 factors in 3 levels would lead to 81 different combinations of tests. Considering that each test could last up to 400 hours, the realization of 81 tests would be a time-consuming process. Therefore, some combinations were chosen in order to cover the most challenging situations with some variations. The detailed test plan can be found in Table 2.

Table 2: Test plan for parameter variations test with non-stationary rotational movements

Test	**Cycle**	**Amplitude/ °**	**Acceleration / m/s²**	**Greasing / vol%**	**Test**	**Cycle**	**Amplitude/ °**	**Acceleration / m/s²**	**Greasing / vol%**
T1	Indus.	5	160	30%	T10	Sine	20	160	30%
T2	Triang.	15	240	30%	T11	Sine	10	160	50%
T3	Triang.	15	240	70%	T12	Sine	5	160	50%
T4	Triang.	15	240	50%	T13	Triang.	10	160	50%
T5	Triang.	10	240	70%	T14	Sine	5	240	70%
T6	Triang.	5	240	70%	T15	Indus.	10	160	50%
T7	Triang.	15	160	70%	T16	Indus.	5	80	70%
T8	Triang.	15	80	70%	T17	Sine	15	160	50%
T9	Sine	20	160	70%	T18	Sine	10	80	50%

Each test lasted up to 400 hours, and the measurement of the pressure in the intermediate cavity was conducted during the tests as well as the monitoring of leakage in both sides of the test cells.

Considering the factorial design method presented by [15] to analyse different variables ranging from different levels of intensity, the test plan presented in Table 2 would be classified as fractioned factorial design 3^4. A fractioned factorial design 3^4 has 4 factors varying in 3 different levels of intensity and its analysis is conducted assuming values of -1, 0 and 1 for the lowest level, the intermediate and the highest level of intensity of each factor respectively to analyse the main effect of each factor. The Table 3 considers also the parameters cycle, angle of amplitude, acceleration and greasing in the intermediate cavity as the factors I, II, III and IV respectively. In order to analyse de interaction effect between two factors, the product of the notation -1, 0 and 1 of the parameters' levels within the combinations should be considered.

Table 3: Fractional factorial design 3^4 for the non-stationary rotational movements' tests.

Test	I	II	III	IV	IxII	IxIII	IxIV	IIxIII	IIxIV	IIIxIV
T1	-1	-1	0	-1	1	0	1	0	1	0
T2	1	1	1	-1	1	1	-1	1	-1	-1
T3	1	1	1	1	1	1	1	1	1	1
T4	1	1	1	0	1	1	0	1	0	0
T5	1	0	1	1	0	1	1	0	0	1
T6	1	-1	1	1	-1	1	1	-1	-1	1
T7	1	1	0	1	1	0	1	0	1	0
T8	1	1	-1	1	1	-1	1	-1	1	-1
T9	0	1	0	1	0	0	0	0	1	0
T10	0	1	0	-1	0	0	0	0	-1	0
T11	0	0	0	0	0	0	0	0	0	0
T12	0	-1	0	0	0	0	0	0	0	0
T13	1	0	0	0	0	0	0	0	0	0
T14	0	-1	1	1	0	0	0	-1	-1	1
T15	-1	0	0	0	0	0	0	0	0	0
T16	-1	-1	-1	1	1	1	-1	1	-1	-1
T17	0	1	0	0	0	0	0	0	0	0
T18	0	0	-1	0	0	0	0	0	0	0

The calculation of the main effect and the interaction effect shall be conducted as follows:

$$E = \overline{y_+} - \overline{y_-} \quad (1)$$

which,

E: the effect, and

$\bar{y}_{+\,or-}$: the mean of the response variable for the negative or positive variation

3 Results

The results confirmed the expectation of a negative pressure buildup in the intermediate cavity during the non-stationary rotational movement tests (e.g. see Figure 4). Moreover, the results showed different responses according to the variations applied on the parameters. Table 4 summarizes the tests carried out presenting the following information:

1. the maximum negative pressure during the test,
2. the time required to reach the maximum negative pressure during the test,
3. the highest net flow rate during the test,
4. the time required to reach the highest net flow rate during the test,
5. whether there was leakage on the pricking side or on the reference side.

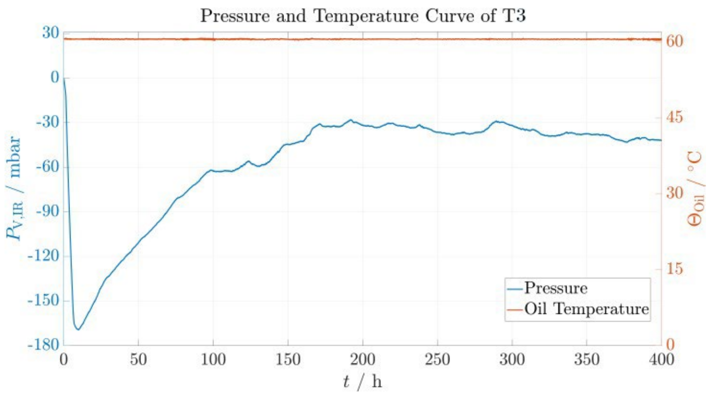

Figure 4: Pressure curve of T3

The net flow rate mentioned in point 3 is the volume of air per unit of time that was aspirated out of the intermediate cavity during a test. It was determined based on the theoretical amount of air that must be aspirated to create the measured pressure change [14]. Suctioning this volume of air creates a negative pressure in the intermediate cavity.

Table 4: Parameters and results from the non-stationary rotational movements' tests

Test	Cycle	Amplit. / °	Accelerat. / m/s²	Greasing / vol%	Pressure		Net Flow Rate		Leakage	Side
					Max. / mbar	Time / h	Max. / m³/h	Time / h		
T1	Indus.	5	160	30%	-15	321	3	45	-	-
T2	Triang.	15	240	30%	-41	137	18	1	-	-
T3	Triang.	15	240	70%	-169	12	47	4	Grease	Prick
T4	Triang.	15	240	50%	-21	17	5	1	-	-
T5	Triang.	10	240	70%	-73	66	6	4	Grease	Ref.
T6	Triang.	5	240	70%	-47	102	6	287	Oil	Both
T7	Triang.	15	160	70%	-98	25	16	2	-	-
T8	Triang.	15	80	70%	-54	124	4	109	Grease	Ref.
T9	Sine	20	160	70%	-177	24	24	0	-	-
T10	Sine	20	160	30%	-76	192	10	54	-	-
T11	Sine	10	160	50%	0	89	0	89	-	-
T12	Sine	5	160	50%	-44	28	7	1	Oil	Ref.
T13	Triang.	10	160	50%	-57	48	7	1	-	-
T14	Sine	5	240	70%	-67	37	6	6	-	-
T15	Indus.	10	160	50%	-39	164	7	0	-	-
T16	Indus.	5	80	70%	-115	90	8	315	-	-
T17	Sine	15	160	50%	-16	186	5	157	-	-
T18	Sine	10	80	50%	-43	335	6	1	Grease	Both

3.1 The Most Negative Pressures: T3, T9 and T16

Considering that the negative pressure in the intermediate cavity is an important variable to be analysed, since it changes the geometry of the intermediate cavity as well as the angles from the dust and the sealing lip [14], the T3, T9 and T16 were the tests, which presented the most negative pressures and so should be highlighted among the other tests. The Table 5 exhibit the mentioned tests with their applied parameters along with their respective results in terms of negative pressure, net flow rate and leakage.

Table 5: Parameters and results from T3, T9 and T16

Test	Cycle	Amplitude / °	Acceleration / m/s²	Greasing / vol%	Pressure		Net Flow Rate		Leakage	Side
					Maximum / mbar	Time / h	Maximum / mm³/h	Time / h		
T3	Triang.	15	240	70%	-169	12	47	4	Grease	Prick
T9	Sine	20	160	70%	-177	24	24	0	-	-
T16	Indus.	5	80	70%	-115	90	8	315	-	-

The comparison between the applied parameters on T3, T9 and T16 shows that:

1. each test used a different cycle from the other two tests,
2. T9 applied the greatest angle of amplitude, as T16 used the smallest angle of amplitude among the others,
3. T3 applied the highest acceleration at the sealing contact, as T16 applied the lowest acceleration among the others, and
4. all three tests applied the highest level of greasing in the intermediate cav- ity.

The comparison between the results obtained on T3, T9 and T16 shows that:

1. T9 presented the greatest negative pressure among the others test, which is 8 mbar greater than T3 and 62 mbar greater than T16,
2. the time of achievement in T3 (12 hours) is two times shorter than T9 and 7,5 times shorter than T16, and
3. the net flow rate values are inversely proportional to time of achievement.

3.2 The Oil Leakage Cases: T6 and T12

A similar analysis has been made considering the leakage cases, i.e. T6 and T12. Table 6 displays the specified tests along with the parameters used and their corresponding outcomes, including negative pressure, net flow rate, and leakage occurrences.

Table 6: Parameters and results from T6 and T12.

Test	Cycle	Amplitude / °	Acceleration / m/s²	Greasing / vol%	Pressure		Net Flow Rate		Leakage	Side
					Maximum / mbar	Time / h	Maximum / mm³/h	Time / h		
T6	Triang.	5	240	70%	-47	102	6	287	Oil	Both
T12	Sine	5	160	50%	-44	28	7	1	Oil	Ref.

The comparison between the applied parameters on T6 and T12 shows that:

1. both tests applied the same angle of amplitude, and,
2. theoretically, T6 applied in parameters cycle, acceleration and greasing one level more critical than the parameters applied on T12.

The comparison between the results obtained on T6 and T12 shows that:

1. the difference of maximal negative pressure developed by both tests is 3 mbar and both tests presented similar pressure curves,
2. the difference of maximal net flow rate achieved by both tests is 1 mm³/h, and
3. T6 produced oil leakage in both sides of the test cell, as T12 produced oil leakage at reference side of the test cell.

3.3 The Factorial Design Analysis of the Results

In order to calculate the main effects and the interaction effects the Table 3 was filled with the results obtained with the realized tests. The correlation between fac- tors, interactions and results can be visualized in Table 7. The application of the Equation (1) for the main effects of each factor and for the interactions' effects be- tween fac- tors can be visualised in Table 8 and Table 9 respectively.

Table 7: Fractional factorial design 3^4 for the non-stationary rotational movements' tests and their results.

Test	I	II	III	IV	Ix II	Ix III	Ix IV	IIx III	IIx IV	IIIx IV	P	t_p	N	t_N
T1	-1	-1	0	-1	1	0	1	0	1	0	-15	321	3	45
T2	1	1	1	-1	1	1	-1	1	-1	-1	-41	137	18	1
T3	1	1	1	1	1	1	1	1	1	1	-169	12	47	4
T4	1	1	1	0	1	1	0	1	0	0	-21	17	5	1
T5	1	0	1	1	0	1	1	0	0	1	-73	66	6	4
T6	1	-1	1	1	-1	1	1	-1	-1	1	-47	102	6	287
T7	1	1	0	1	1	0	1	0	1	0	-98	25	16	2
T8	1	1	-1	1	1	-1	1	-1	1	-1	-54	124	4	109
T9	0	1	0	1	0	0	0	0	1	0	-177	24	24	0
T10	0	1	0	-1	0	0	0	0	-1	0	-76	192	10	54
T11	0	0	0	0	0	0	0	0	0	0	0	89	0	89
T12	0	-1	0	0	0	0	0	0	0	0	-44	28	7	1
T13	1	0	0	0	0	0	0	0	0	0	-57	48	7	1
T14	0	-1	1	1	0	0	0	-1	-1	1	-67	37	6	6
T15	-1	0	0	0	0	0	0	0	0	0	-39	164	7	0
T16	-1	-1	-1	1	1	1	-1	1	-1	-1	-115	90	8	315
T17	0	1	0	0	0	0	0	0	0	0	-16	186	5	157
T18	0	0	-1	0	0	0	0	0	0	0	-43	335	6	1

Table 8: Main effects of the factors on the response variables.

Main Effects	P / mbar	t_P / h	N / mm³/h	t_N/ h
Cycle	-13,67	-127,3	7,62	-68,87
Ampli.	-23,9	-25,97	10,125	-89,8
Accel.	1	-121,17	8,67	-91,17
Greas.	-56	-156,67	4,29	57,54

Table 9: Interactions' effects between the factors and their impact on the response variables.

Interact. Effects	P / mbar	t_P / h	N / mm³/h	t_N / h
Cycle + Amp.	-26,28	1,71	8,4286	-218,86
Cycle + Accel.	-23,67	-53,33	11	-7
Cycle + Greas.	2	-5,17	0,67	-82,83
Amp. + Accel.	-30,5	-23,67	14,17	-53,75
Amp. + Greas.	-33,4	-10,4	9,2	-100,6
Accel. + Greas.	-19	-62,75	6,25	-66,41

4 Conclusions

This work carried out successfully a series of experimental tests varying systematically several working conditions in order to reproduce the non-stationary rotational movements and monitored the impact of the variation of these parameters on RSS and their sealing effectiveness. The results showed that:

- The grease volume in the intermediate cavity has the major effect on the negative pressure induction.
  - The negative pressure is on average increased in -56 mbar, when the greasing level is raised from a lower level to a directly upper level.
  - The effect of the greasing on the formation of the negative pres- sure can be visualized by taking T3, T4 and T16 into account, which had just the greasing level as a common parameter in the same level.
- The amplitude has second greatest effect on the negative pressure induc- tion and the greatest effect on the net flow rate.
  - T9 applied a greater amplitude than T3 and T16 and, although, T9 had applied lower levels of cycle and acceleration than T3, T9 pro- duced the highest negative pressure among all tests.
  - The amplitude has the major effect on the net flow rate induction, and this can also be visualized in the interaction effects involving the amplitude and the other parameters.
- The amplitude might have a major effect in the cases of leakage of oil.
  - T6 and T12 just had the level of the amplitude as a common parameter, which was the smallest angle tested.
  - The effect of small oscillations angles on the followability of the dust lip of RSS must be considered for further studies.
- The acceleration shows a small influence on the negative pressure formation as main effect, but its interactions' effects with parameters are considerable.

5 Nomenclature

P: Maximal pressure in intermediate cavity,

t_P: Time of achievement of the maximal pressure in intermediate cavity,

N: Maximal net flow rate, and

t_N: Time of achievement of the maximal net flow rate.

6 Acknowledgements

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8 Authors

University of Kaiserslautern-Landau, Chair for Machine Elements, Gears and Tribology (MEGT)

Gottlieb-Daimler Straße, 67663 Kaiserslautern, Germany:

Lenine M. de C. Silva, M. Sc., ORCID 0000-0003-1272-0171, lenine.silva@rptu.de
Yvo Stiemcke, Dipl.-Ing., yvo.stiemcke@rptu.de

Tim Schollmayer, Dipl.-Ing., tim.schollmayer@rptu.de

Prof. Dr.-Ing. Oliver Koch, ORCID 0000-0001-5967-0242, oliver.koch@rptu.de

Jun. Prof. Dr. -Ing. Stefan Thielen, ORCID 0000-0003-3310-7659, stefan.thielen@rptu.de

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