



INVESTIGATION OF ROLLING BEARING LUBRICATION CONDITION

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Abstract

The research aimed to assess the lubrication condition of rolling bearings dismantled from previously operated passenger car alternators. The tests measured the vibrations and evaluated the technical condition of the bearings based on selected estimators of the vibration acceleration signal subjected to earlier band-pass filtration in the high-frequency range of 8-10kHz. Next, the bearings have been disassembled, allowing inspection of the lubricant condition for each measured bearings and the visual assessment of individual components. Based on the test results, it was observed that the mean value and standard deviation of considered features of vibration acceleration signals in the 8-10kHz band might be helpful in the classification of the lubrication condition.

Keywords: rolling bearing, diagnostics, lubrication, vibration, CBM

BADANIA STANU NASMAROWANIA ŁOŻYSK TOCZNYCH

Streszczenie

Celem badań była ocena stanu nasmarowania łożysk tocznych wymontowanych z wcześniej eksploatowanych alternatorów samochodów osobowych. Badania polegały na pomiarze drgań i ocenie stanu technicznego łożysk w oparciu o wybrane estymatory sygnału przyspieszeń drgań poddawanego wcześniejszej filtracji pasmowo przepustowej w zakresie wysokich częstotliwości 8-10kHz. Następnie łożyska zostały zdemontowane, co pozwoliło na zbadanie stanu smaru każdego łożyska i ocenę wizualną poszczególnych elementów. Na podstawie wyników badań zaobserwowano, że wartość średnia i odchylenie standardowe wybranych cech sygnałów przyspieszeń drgań w paśmie 8-10kHz mogą być przydatne w klasyfikacji stanu nasmarowania.

Słowa kluczowe: łożyska toczne, diagnostyka, smarowanie, drgania, CBM

1. INTRODUCTION

One of the essential maintenance activities during the machine operation is to provide proper lubrication of different machine parts, including rolling bearings. Improper lubrication of the rolling bearing leads to premature bearing degradation, which can cause unexpected machine failure.

According to research published in [1], [2], and [3], 80% of bearing faults is caused by improper lubrication conditions. The leading cause of poor lubrication conditions is over-or under- lubrication and change of physical and chemical properties of the grease, e.g., by overheating or moisture. There are many in-field testing techniques to control and monitor bearing lubrication conditions. Very often a portable mini-labs [4] ultrasonic equipment, infrared cameras [5] as well as vibration measurements [6] are applied. Many of the machine bearings are under continuous vibration monitoring. It makes possibilities for constant assessment of machine condition including bearings lubrication one. According to some publications [7] [8] [9], poor lubrication condition affects the increase of the level

of vibration acceleration signal, usually in high-frequency bands. As stated in [10], lack of lubrication influences acceleration RMS values differently in frequency bands 1Hz-2 kHz, 2-4 kHz, 4-6 kHz, 6-8 kHz and 8-12 kHz. They concluded that the RMS of vibration acceleration signal at the frequency band of 8-12 kHz was the most sensitive for detecting poor lubrication conditions in the test arrangement and bearing type used. Depending on the grease film thickness, the vibration level increases when thinner [9]. This phenomenon can be explained by the rising of the grease viscosity [11]. Based on the research presented in [12], the relation between the roughness and the oil film thickness, marked as λ , can be related to the higher vibration level value. The crucial λ value is estimated at around 1.6, and this is a point when the vibration level starts to rise [13] [14] [15].

In this paper, the authors focused on assessing the lubrication condition of deep groove rolling bearings based on statistical parameters of vibration signal estimators. To do that, authors have tested a series of ball-bearing, first measuring the vibration signals and then disassembling the bearings, performing few

grease condition tests, and visually inspect bearings rolling elements. A detailed discussion on the assessment of the tested bearings' condition based on the vibration signal features has been described in another article [19].

2. RESEARCH

The research has been performed on a set of 19 ball bearings type 6303 dismantled from car alternators. Bearings were different manufacturers, and their conditions were unknown. Before estimation of bearing grease conditions, a vibration test was performed.

2.1. The vibration measurement and signal analysis

All vibration measurements have been carried out on a test bench designed and manufactured by scientists from the Department of Fundamentals of Machinery Design at the Silesian University of Technology. The stand was controlled by an industrial PLC – Siemens S7-1200. Vibration signals were acquired and processed by measurement setups (Fig 1) consisted of an industrial accelerometer (SLC144TB-MB; 2 Hz-10 000 Hz and 100 mV/g) connected to a conditioning module (SPM Intelinova) and then to NI data acquisition card NI-USB-4432. Digital signal from DAQ module was processed by software developed in NI LabView environment.

The tested bearing was mounted on the test bench shaft, blocked by the specially designed holder, and fixed on the horizontal electric actuator's rod. The accelerometer was installed on a platform that allows vertical movement, ensuring constant and controlled, by actuator controller, bearing load of 60N in a radial direction, and good contact between the sensor probe and an outer bearing ring. Each bearing was measured in four positions, as shown in Fig. 2. The shaft speed during the test was 3000 RPM, and each measurement took 10 seconds.

The collected signals have been proceeded to extract the following commonly known [20] acceleration signal estimators:

- RMS;
- Peak;
- Crest Factor (CF);
- Kurtosis (KF);
- Clearance factor (CLF);
- Impulse factor (PF).

All that estimators have been evaluated in the following frequency bands:

- 0.5 - 10 kHz;
- 1 - 10 kHz;
- 2 - 10 kHz;
- 5 - 10 kHz;
- 8 - 10 kHz.

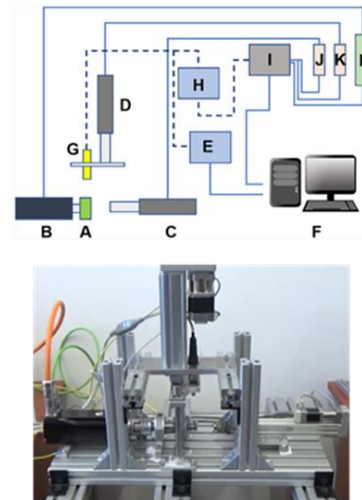


Fig. 1. Test stand. A – bearing, B – servo drive, C, D – linear actuators, E – NI signal analyser, F – PC, G – accelerometer, H – SPM vibration analyser, I – PLC, J, K – actuators controllers, L – servo drive controller.

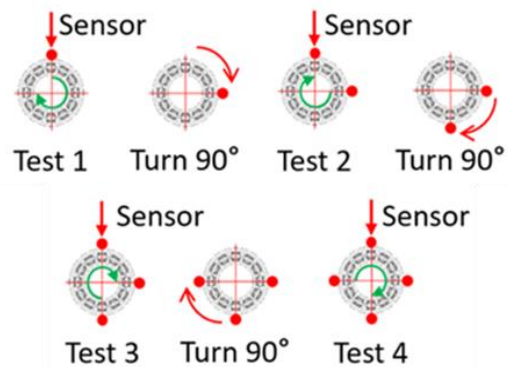


Fig. 2. The testing procedure schema

After all measurements, plots for all estimators have been made. Fig 3 presents an example of elaborated plots for selected bearing. The given case is the plot of the mean Peak value in the band from 8 kHz to 10 kHz. More detailed discussion devoted to vibration analysis results of tested bearings can be found in [19]. The obtained values are placed in increasing order. What can be seen in the presented plot is that increasing the standard deviation is related to increasing the mean of the feature's value. The further considerations focused on using the mean and the standard deviation of selected signal features to assess bearings grease condition.

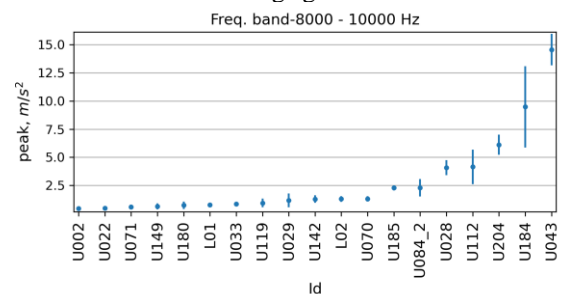


Fig. 3. Averaged peak values of acceleration signal with standard deviation during measurements.

In Table 1 are aggregated average values of vibration signal features, for investigated bearings, in ascending order, the highest value of the parameter, the worst bearing condition. And for example, bearings marked as U028, U043, U084, U184, and U204 are among the worst conditions. The bearings' ID listed in Table 1 are authors' identification and are irrelevant in distinguishing new and used bearings.

Table 1. Average values of acceleration signal's features in 8 - 10 kHz band

ID	Peak m/s ²	Rms m/s ²	CF -	KF	PF	CLF
L01	0.76	0.10	7.35	3.30	9.28	10.98
L02	1.29	0.11	11.74	4.91	15.18	18.13
U002	0.45	0.07	6.49	3.15	8.15	9.61
U022	0.48	0.07	7.05	3.01	8.76	10.27
U028	4.07	0.16	26.37	44.55	39.95	49.43
U029	1.17	0.09	12.40	4.49	15.99	19.10
U033	0.86	0.13	6.81	3.83	8.78	10.50
U043	14.57	0.82	17.71	14.42	27.12	34.93
U070	1.29	0.12	10.72	5.18	14.00	16.79
U071	0.58	0.08	7.65	3.45	9.69	11.48
U084	2.28	0.15	15.00	11.82	21.14	25.98
U112	4.15	0.35	11.63	4.97	15.13	18.12
U119	0.94	0.12	7.82	3.40	9.85	11.63
U142	1.28	0.10	12.21	4.23	15.62	18.58
U149	0.62	0.08	8.06	4.59	10.51	12.60
U180	0.73	0.08	9.00	4.26	11.56	13.76
U184	9.48	0.41	22.63	28.13	38.39	51.81
U185	2.27	0.16	13.99	6.13	18.63	22.55
U204	6.11	0.25	25.07	27.10	38.00	47.97

2.2. The grease condition evaluation

The next step of investigations was the determination of the grease condition of the tested bearings. Bearings' grease was subjected to a series of tests using an SKF grease test kit (TKGT1) [4], presented in Fig 4. The following tests were carried out:

- Test No. 1 – Visual assessment of a grease sample;
- Test No. 2 – Consistency test;
- Test No. 3 – Oil leakage test;
- Test No. 4 – Contamination test.

Additionally, one new bearing was also tested as a source of reference results for the grease parameters comparison. This bearing is marked as N00. We did not perform a vibration test for this bearing. During the visual assessment, the following grease features were examined:

- a) colour of the grease,
- b) consistency,
- c) shine,
- d) visible contamination, discolouration, and any anomalies [16].

Fig 5 presents exemplary sealing rings with bearing grease for bearings with the highest vibration values.

The consistency test lied to determine the NLGI consistency number for each sample and determine how the wearing process affects the grease consistency properties [17]. The analysis was based

on putting a specific load on a prepared sample for 15 seconds. The level of flattening is a factor allowing to assign the NLGI number. The test results are presented in Table 2 and are shown a description of correspondent NLGI numbers according to ISO 6743-9 standard [18].

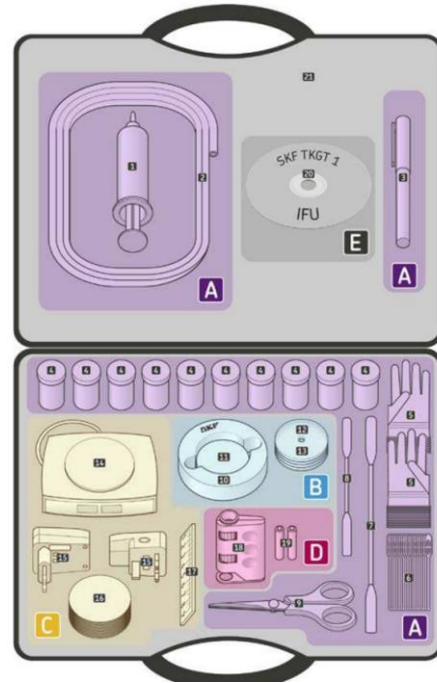


Fig. 4. The SKF grease condition test set. Sampling accessories (A), Consistency test accessories (B), Oil leakage test accessories (C), Contamination test accessories (D), Manual (E). [4]



Fig. 5. The examples of grease samples

The oil leakage test consisted of heating the grease sample at a temperature of 60°C, in a time of 2 hours, on a special absorbent pad. After the heating process, the diameter of the circular mark created by leaked oil was measured. The lower mean value of measured diameter refers to the more reduced lubrication properties of the grease. Table 3 presents the results of the measurements. Due to insufficient grease in bearings U112 and U184, it was impossible

to make an oil leakage test. We decide not to consider those bearing in further considerations.

Table 2. The consistency test results

Bearing ID	NLGI number	NLGI number	Appearance
N00	2	000	Fluid
L01	1		
L02	4	00	Semi-fluid
U002	4		
U022	4	0	Very soft
U149	4		
U071	4	1	Soft
U142	5		
U180	4	2	“normal” grease
U029	4		
U119	4	3	Firm
U033	4		
U070	5	4	Very firm
U185	5		
U028	5	5	Hard
U084	4		
U204	4	6	Very hard
U112	1		
U184	1		
U043	3		

Table 3. The oil leakage test results

Bearing ID	Mean of measured diameters [mm]	The difference to a new bearing
N00	26.25	0%
L01	23.00	12.38%
L02	20.50	21.90%
U002	25.25	3.81%
U022	19.50	25.71%
U149	20.50	21.90%
U071	19.75	24.76%
U142	20.50	21.90%
U180	22.75	13.33%
U029	24.25	7.62%
U119	19.25	26.67%
U033	24.75	5.71%
U070	19.75	25.76%
U185	15.75	40.00%
U028	19.50	25.71%
U084	17.00	35.24%
U204	19.50	25.71%
U112	Not enough grease to create a standard sample	
U184	Not enough grease to create a standard sample	
U043	23.75	9.52%

The last performed test consisted of an assessment of contaminations in the grease. The test was carried out using an optical microscope. The main goal of the test was to find out any marks of the wearing process in grease, such as small metallic particles, dirt nuggets, and so ones. Microscopic images presented the three most contaminated grease samples are shown in Fig 6. On those images, we can see many intrusions in grease in the form of different-sized forging particles.

The results of the performed tests were ranked using grades from 1 to 5, where one means terrible and five means excellent. It allows us to indicate bearing in good and bad conditions. Quantitative results of bearing grease condition evaluations are presented in Table 4.

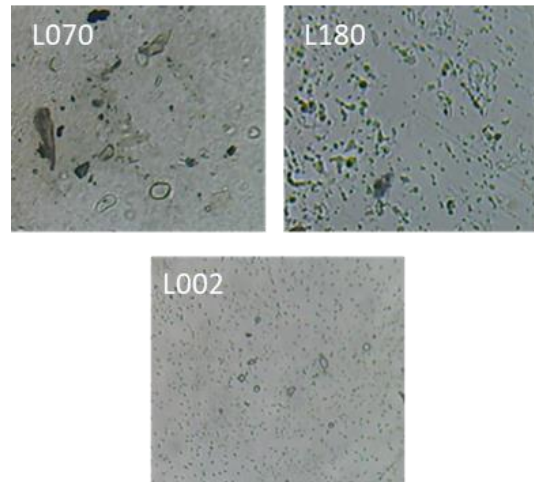


Fig. 6. Selected microscopic images of tested samples

Table 4. The summary of grease condition investigation results

Bearing ID	Visual assessment	Consistency	Oil leakage	Contamination	Average overall score
U070	2	2	2	2	2.0
U185	2	2	2	3	2.3
L01	1	4	3	1	2.3
U112	3	2	-	3	-
U184	3	2	-	3	-
L02	3	3	2	2	2.5
U180	2	3	3	2	2.5
U028	1	2	2	5	2.5
U142	3	3	2	3	2.8
U149	4	3	2	3	3.0
U204	2	3	2	5	3.0
U002	4	3	4	2	3.3
U029	1	3	4	5	3.3
U084	4	3	2	4	3.3
U071	4	3	2	5	3.5
U119	4	3	2	5	3.5
U033	2	3	4	5	3.5
U043	3	4	3	5	3.8
U022	4	3	2	3	4.0
N00	5	5	5	5	5.0

Quantitative parameters like the NLGI number and mean measured diameter of oil mark (from test 3) were compared in Fig 7. Comparison of the two reliable quantitative parameters indicates that the grease condition of bearings U185 and U084 (dotted line ellipse) are not satisfactory due to dry grease. For comparison in Fig 8 presented the result of SPM HD vibration measurements where parameter HDc confirms the worst lubrication conditions of those bearings.

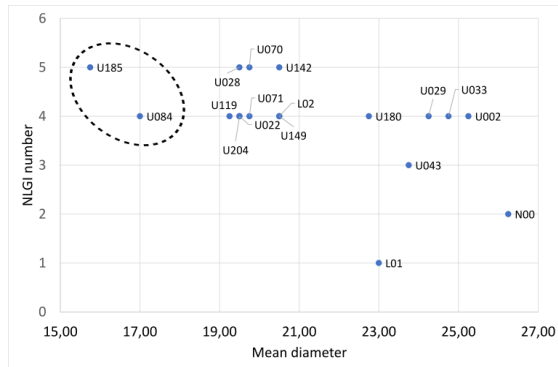


Fig. 7. The diagram showing the relation between the NLGI number and mean diameter of oil leakage mark

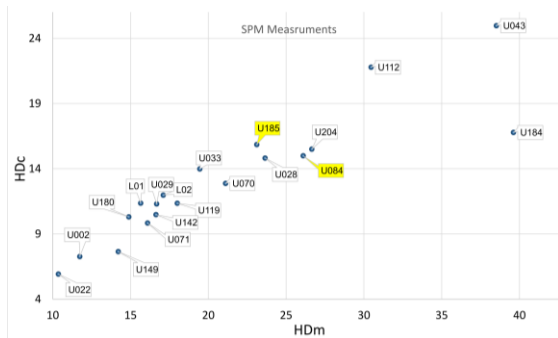


Fig. 8. Results of SPM HD measurements of investigated bearings

differs the most from the other bearings, as shown in Fig. 7.

Table 5. The visual inspection results summary. Where: DC - discolouring, PT - pitting, IM - imprint, SC - scratches, AB - abrasion, W – wear, and OK - normal condition

Bearing ID	Outer ring	Inner ring	Balls	Cage	Overall condition
L01	OK	OK	OK	OK	5
L02	OK	OK	OK	OK	5
U002	OK	DC	OK	OK	4,5
U022	W	OK	OK	OK	3
U028	AB	DC	OK	OK	2
U029	OK	OK	OK	OK	5
U033	DC	DC	PT	OK	1
U043	PT	PT	PT	OK	1
U070	OK	DC	OK	OK	4,5
U071	OK	OK	OK	OK	5
U084	SC	OK	OK	OK	3
U112	OK	AB	OK	OK	3
U119	OK	OK	OK	OK	5
U142	OK	OK	OK	OK	5
U149	W	AB	AB	OK	2
U180	OK	OK	OK	OK	5
U184	IM	IM	IM	OK	1
U185	OK	OK	OK	OK	5
U204	IM	IM	OK	OK	2

2.3. Visual inspection

After vibration analysis and grease condition evaluation, all tested bearing has been disassembled and cleaned for visual inspection. All signs of wearing, such as pitting, overheating, cracks, and others, have been noticed during the examination. All spotted defects are photographed and described. In Table 5, the authors arbitrary summarised the visual inspection results, where the overall condition is graded on a 1 to 5 scale, where 1 means a poor condition, and 5 means excellent condition.

Fig. 9. are shown examples of found defect.

3. ANALYSIS OF STATISTICAL PARAMETERS OF VIBRATION SIGNAL FEATURES

After collecting all data related to the bearings grease and mechanical condition and vibration signals, authors put their effort to observe a relationship between the mean and standard deviation values of signal features and the result of grease condition evaluation.

Based on the research, one can assume that vibration parameters' statistical parameters could be helpful to classify bearings grease conditions. But it must be considered that the vibration signal cares about the grease condition and mechanical damages. Some mechanical defects can be caused by insufficient lubrication, and inadequate lubrication can accelerate some damages. Bearings marked as U084 and U185 have been selected as references for comparisons. The reason for that is that their grease



Fig. 9. Images of defects of specific bearings: a) discolouring on the inner ring of U028. b) scratch on the outer ring of U028. c). d). e) pitting of U043 bearing's elements. f) pitting of U084 bearing's outer ring

The following research step was essential to answer the vibration signal that allows for the lubrication condition identification. To find such a relationship, the authors have prepared a series of graphs showing the relationship between the mean value of the considered signal features and standard deviation calculated on four measurements - Fig. 10 to Fig. 14 present examples of obtained plots.

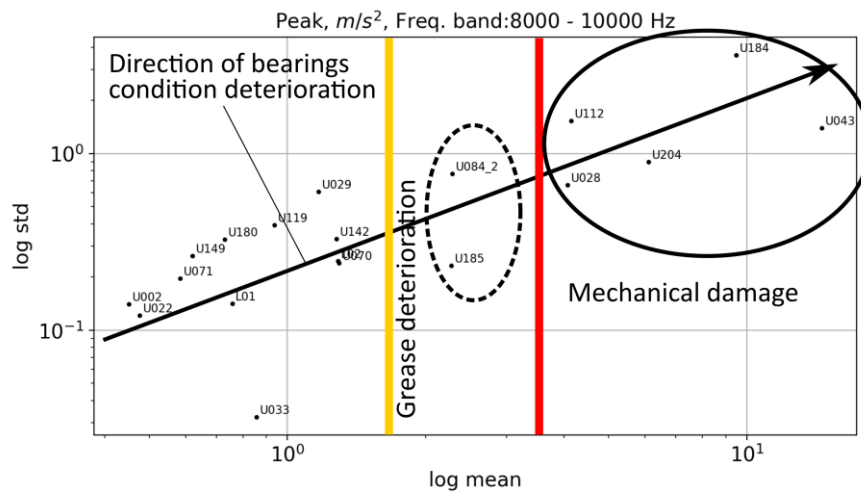


Fig. 10. Plot of mean and standard deviation values of Peak accelerations of investigated bearings in band 8000 Hz to 10000Hz

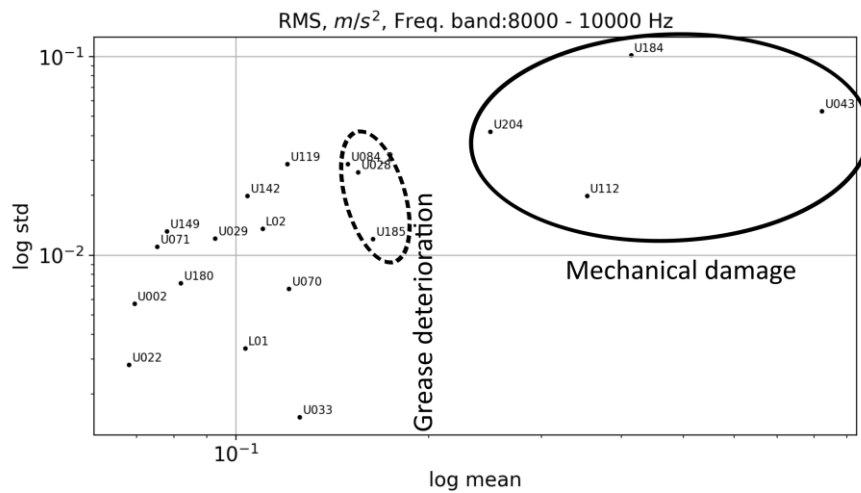


Fig. 11. Plot of mean and standard deviation values of RMS accelerations of investigated bearings in band 8000 Hz to 10000Hz

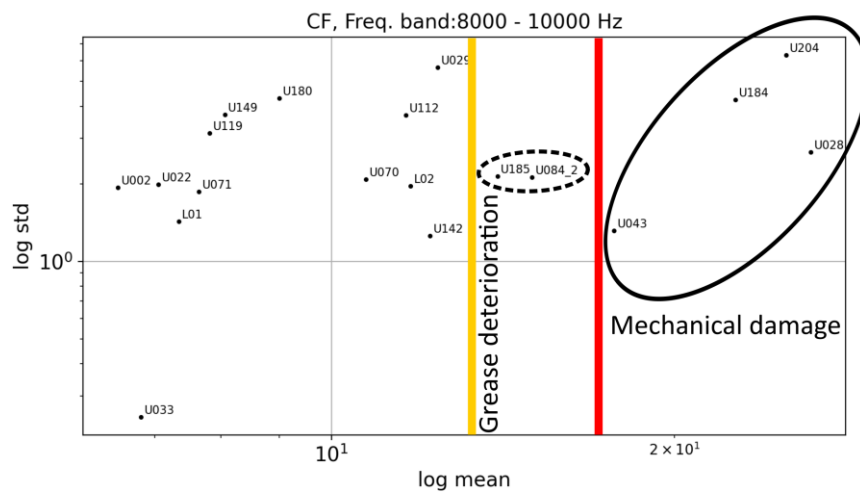


Fig. 12. Plot of mean and standard deviation values of Crest factor of accelerations of investigated bearings in band 8000 Hz to 10000 Hz

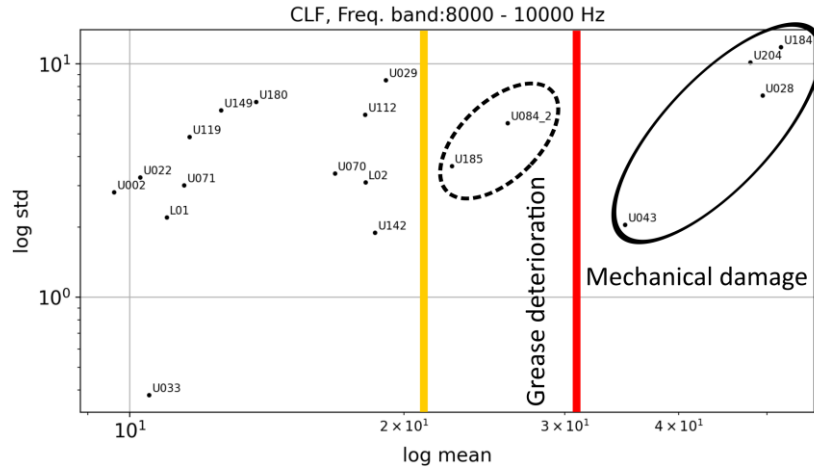


Fig. 13. Plot of mean and standard deviation values of Clearance factor of accelerations of investigated bearings in band 8000 Hz to 10000 Hz

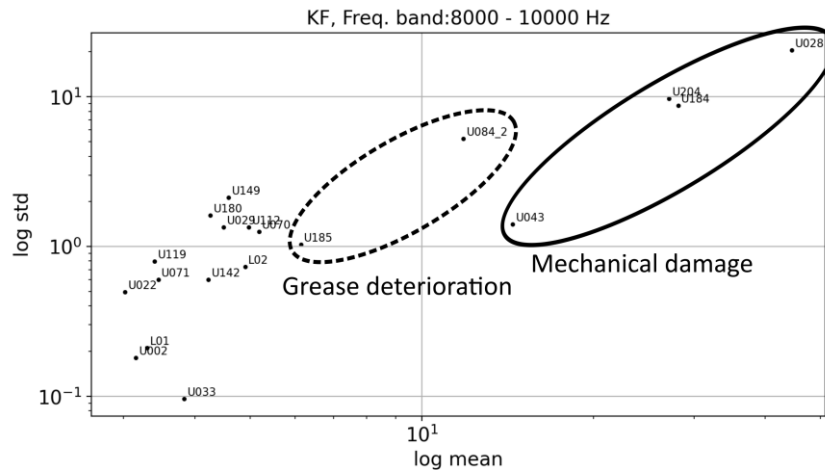


Fig. 84. Plot of mean and standard deviation values of kurtosis of accelerations of investigated bearings in band 8000 Hz to 10 000 Hz

The plots' axes are in logarithmic scale for better distribution analysis of mean value and standard deviation of considered signal features. The first step of the research has been looking for frequency band influences on the value distribution. The best separation and bearings identification is seen in a band between 8 kHz and 10 kHz. In the presented plots, it is also clear which bearings have some mechanical damage or poor grease condition. The best separation of defected bearings is observed for Peak (Fig 10) and Clearance (Fig 13) features. A hypothesis can be made that in the case of the investigated bearings before mechanical damage occurs, gradual deterioration of the grease condition and mechanical wear of the bearing occurs. It leads to fatigue damage. Such a process can be associated with the distribution of Peak and Clearance values visible in the plots. It has been observed that Kurtosis (Fig 14) is a feature that mainly identifies mechanical damage of the bearings.

4. CONCLUSIONS

In this paper, the authors try to answer whether it is possible to define the lubrication condition based on the vibration signal. According to the research results, we can quite reasonably say that not only acceleration RMS could be helpful in lubrication diagnostic [4][5][6]. It is possible to define the grease condition of the roller bearing using mean and standard deviation values of standard signal estimators such as, e.g. Peak and Clearance factor. The best classification of bearings grease condition based on vibration parameters is obtained for the band between 8 kHz to 10 kHz. According to the results, the signal feature's mean value and standard deviation allow for grouping features belonging to different bearing conditions.

For detection and classification of different bearing conditions, a two-dimensional diagram of the mean and standard deviation of signal estimators could be used. This type of diagram can show the trend of bearing condition deterioration. Further research considered the larger population of bearings

must be conducted to support the obtained results fully.

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