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Influence of Grease Contamination on Acoustic Emission Monitoring of Low-speed Roller Bearings

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Abstract. This study presents an investigation into the influence of particle contamination in grease on acoustic emission (AE) condition monitoring of low-speed roller bearings. Eight experiments involving both natural and artificial contamination of the grease are reviewed. These tests have been conducted with two bearings of vastly different geometries that were instrumented with multiple piezoelectric AE transducers in the frequency range between 40–580 kHz. Tests with artificially-introduced contamination indicated that the amount of abrasive particles is directly correlated with the load-cycle-normalised hit-rate over all investigated frequencies, while non-abrasive particles are indistinguishable from uncontaminated baseline measurements. In a natural degradation test the same linear relationship has been observed. The results suggest that AE condition monitoring can be used to indicate the requirement to regrease a bearing, and that contamination under the safe working limit will not obfuscate AE signals from other degradation sources.

Keywords: Acoustic Emission, Condition Monitoring, Roller Bearing, Lubrication Contamination, Offshore.

1. Introduction

The offshore energy infrastructure is heavily reliant on the safe and continuous operation of low-speed roller bearings. Notable examples are single-point mooring systems of floating oil and gas installations, the nacelle yaw and blade pitch bearings in wind turbines, and the heavy-lifting cranes supporting the transition from the former to the latter.

Proper lubrication is instrumental to the smooth operation of these bearings. However, the harsh seawater environment and unpredictable loading by wind and waves pose a challenge to maintaining proper lubrication. With limited movement of the bearing under variable loading, the lubrication film may be broken, giving rise to adhesive wear. Alternatively, water ingestion following on the failure of seals, may lead to corrosion of the rolling elements. Both of these mechanisms deposit particles in the grease, which may cause

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further abrasive wear, and could give rise to surface cracking. In short, the failure of a bearing is a process of interconnected mechanisms, which is governed by lubrication through friction [1].

Techniques for monitoring low-speed roller bearings through the use of acoustic emission (AE) have been under investigation since the late ‘70s. Early studies applied AE monitoring techniques to low-speed bearings in the field [2, 3], recognised its potential, but lacked clarity on the actual state of the bearing. In later studies, this potential was confirmed through laboratory tests with pre-worn bearings from the field [4, 5] and extensive natural degradation experiments in laboratory environments [6, 7].

Focussing on the grease lubrication of the bearings, studies have investigated the generation of AE for varying qualities and quantities of greases [8, 9]. Controlled experiments with introduced contamination have shown that hit-rate correlates with the number of particles [10, 11], and that AE amplitude is correlated with the size, weight, and hardness of the introduced particles [10–14]. Besides characterising the AE due to contamination, artificial intelligence has also been applied to differentiate between clean and contaminated grease in operation [15, 16]. The potential of monitoring the grease condition in a bearing through AE has been shown in the prior art, however, the connection between the imposed contaminated condition and the natural development of contamination during the degradation of a bearing over its lifetime is lacking.

This paper presents an investigation on the influence of grease contamination on AE condition monitoring of low-speed roller bearings. It discusses several experiments that have been conducted in various regimes of artificial and naturally-developed particle contaminated lubrication, and proposes a strategy for condition monitoring.

2. Methodology

The presence of particles in the lubrication grease of a bearing may be a source of ultrasonic stress waves. Since these particles could cause abrasive damage on the rolling elements, their detection is of use when implementing a condition monitoring system on a roller bearing. However, the prominence of such contamination-induced signals should ideally not be of a magnitude that would obfuscate other degradation induced sources, such as crack growth. This balance between detection and obfuscation is governed by the relation between AE activity and the severity of particle contamination.

2.1. Experimental Set-ups

In earlier work, several experiments have been conducted that involved both naturally-developed and artificially-introduced particle contamination to the grease. These experiments have been conducted on two test set-ups with vastly different geometries. The results of these experiments are compared in terms of normalised hit-rate and possibly known contamination severity.

2.1.1. Slew Bearing Segment

The first set-up is a double linear bearing representing a segment of a turret bearing. A schematic overview and a picture of the set-up are shown in **Fig. 1**. It is a modular set-up, composed of two chambers (upper and lower) with an acoustic isolation in between. The central nose-components make a cyclic linear movement perpendicular to the depicted cross-section under vertical load applied through the support substructures. The rolling elements of the set-up are exchangeable and may be configured for three or two rollers. The raceways are composed of Hardox 600, the rollers of 100Cr6 through hardened bearing steel.

Five tests have been conducted using this set-up; (A-i) a baseline test to identify the background AE of the set-up [17], (A-ii) an artificial contamination test introducing three levels of particle contamination originating from abrasive work [17], (A-iii) a corrosion test with a pre-corroded raceway [17], (A-iv) a natural degradation test [7], and (A-v) a continuation of the natural degradation test with a different roller-set [18].

Contamination samples have been prepared by mixing a weighted ratio of 40,000 mg/kg of particles sourced from abrasive work on through hardened bearing steel in grease. The thoroughly mixed sample has twice been iteratively diluted 50 times to obtain the reduced contamination-to-grease ratios of 800 mg/kg and 16 mg/kg.

Testing is performed at three speed (6–12 mm/s) and four load (100–1305 kN) levels. Baseline and contamination tests are conducted for the twelve combinations of these levels, with a three-roller configuration containing rollers of 75 mm diameter. The natural degradation tests are performed solely at the highest load and speed level, with two-roller configurations containing rollers of 69 mm diameter for the initial test (A-iv) and rollers of 75 mm diameter for the continuation (A-v). To mitigate for slipping of the rolling elements, the rollers and cages are re-centred frequently.

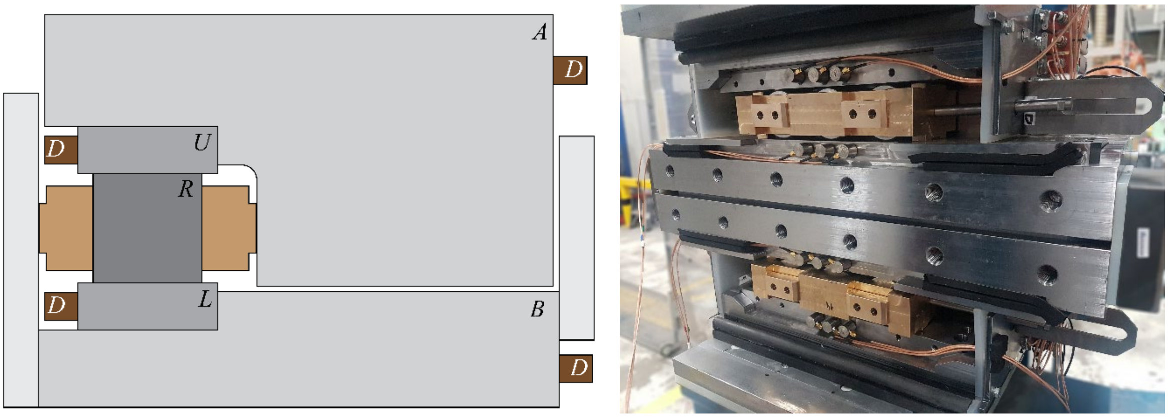

Fig. 1. Schematic overview of the upper chamber the of the slew segment test set-up (left), and a picture of the test set-up (right). Labels in the cross-section indicate the roller (*R*), nose raceway (*L*), support raceway (*U*), nose substructure (*B*), support substructure (*A*), and sensor nodes (*D*).

2.1.2. Bogie Wheel Bearing

The second set-up is a decommissioned bogie wheel that has supported a lifting beam on an offshore construction vessel. A schematic overview of the bearing and arrangement in the testing machine are shown in **Fig. 2**. The bearing primarily supports a radial load through four rows of 42 rollers composed of 100Cr6 through hardened bearing steel. The inner and outer rings that act as raceways are composed of quenched and tempered 42CrMo4 alloy steel. In the testing arrangement, the outer surface of the outer ring is pressed against the rotating test wheel to load and rotate the bearing.

Three tests have been conducted using this set-up; (B-i) a baseline test [19], (B-ii) an artificial contamination test introducing three levels of iron particle contamination [19], and (B-iii) a natural degradation test [17].

Contamination samples have been prepared by mixing weighted ratios of 10 µm pure iron powder into grease. The used ratios of contaminant to grease are; 1,500 mg/kg, 10,000 mg/kg, and 20,000 mg/kg, reflecting common warning thresholds used by the industry.

Testing is performed at two speed (7.5–60 rpm) and two load (170–343 kN) levels. Baseline and contamination tests are conducted for the four combinations of these levels. The natural degradation test is performed primarily at the higher speed and load, with intermittent short instances of the lower speed. To reduce the lifetime of the bearing, the contact pressure has been increased during the natural degradation test through a reduction of the load bearing rollers. For this reduction, all but eight steel rollers per row had been replaced by polytetrafluoroethylene (PTFE) rollers.

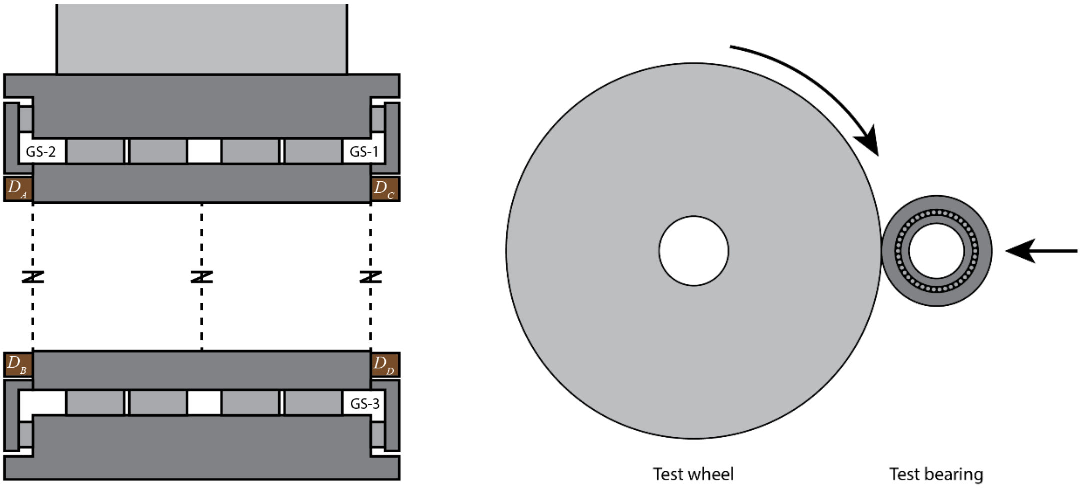

Fig. 2. Schematic overview of bogie wheel bearing (left), and testing arrangement (right). Labels in the cross-section indicate the sensor nodes (D_x) and grease sampling locations (GS-*n*).

2.1.3. Instrumentation

All of the experiments utilise the same principles for data collection. Herein, the generated ultrasound signals are recorded in the frequency range of 40–580 kHz by means of sensor nodes composed of three types of commercial piezoelectric AE transducers. The amount and placement of the sensor nodes differ for each set-up to accommodate the specific geometry of the instrumented bearing.

The three transducers in each sensor node are all sensitive to a particular part of the selected frequency range and bounded through digital band-pass filtering. A 60 kHz resonant R6α-transducer by Physical Acoustics is used to cover the low-frequency range between 40–100 kHz, a 150 kHz resonant R15α-transducer for the mid frequencies between 95–180 kHz, and a broadband WSα-transducer for the high frequencies between 180–580 kHz. All of these are amplified for a gain of 40 dB through external AEP5H pre-amplifiers by Vallen Systeme. An AMSY-6 acoustic emission measurement system fitted with ASIP-2/A signal processing cards by Vallen Systeme is used to record the detected ultrasound signals.

Threshold-based detection and recording of AE signals is used in all experiments. The threshold is tuned for each test case to mitigate continuous background noise. For the slew segment (A-i–v) a threshold of 50 dB is used, for the bogie wheel (B-i–iii) a threshold of 55 dB. Upon crossing the threshold, a transient recording of 812 µs was sampled at 5 MHz. These contain a 200 µs pre-trigger recording to capture the onset of the signal prior to the threshold crossing.

2.2. Data processing

In order to facilitate comparison between the different bearing geometries, processing of the data is focussed on normalising the ultrasound activity. A common representation for this activity is the hit-rate, that is the amount of acoustic emission per unit time. However, this representation would be ineffective to compare bearings of different geometry operating at different speeds. Therefore, an alternative hit-rate has been proposed based on the amount of load cycles the raceway of a bearing experiences [17].

Using this definition, the normalisation for the segmented bearing is 2 load cycles per linear cycle (extension and retraction), and the normalisation for the bogie wheel is 21 load cycles per revolution for the baseline and contamination cases, while it is 4 load cycles per revolution for the natural degradation case to account for the PTFE rollers.

In pre-processing the data is filtered for minimum-acceptable signal-to-noise ratio (SNR) and test machine operations. The SNR filter compares the peak amplitude in a window before the threshold crossing to the peak amplitude of the whole signal. A minimum SNR of 10 (20 dB) is imposed for all test cases. Test machine data is used to omit spurious signals resulting from starting and stopping, so that only AE during continuous movement is evaluated.

3. Results

The results are discussed in the order of similarity. First the artificial contamination cases are compared (A-ii, B-ii), which are considered relative to their respective baseline measurements (A-i, B-i). Insights from this comparison are used to elucidate the observations made for the corroded raceway (A-iii), the natural degradation of the bogie wheel (B-iii), and the natural degradation of the bearing segment (A-iv, A-v).

For brevity, results for a single sensor node are discussed for each test case. To facilitate consistency, each selected node is raceway mounted. As such the node on the nose raceway is selected for the segmented set-up (D_L in **Fig. 1**), and for the bogie wheel the node near grease sampling point 2 is selected (D_A near GS-2 in **Fig. 2**).

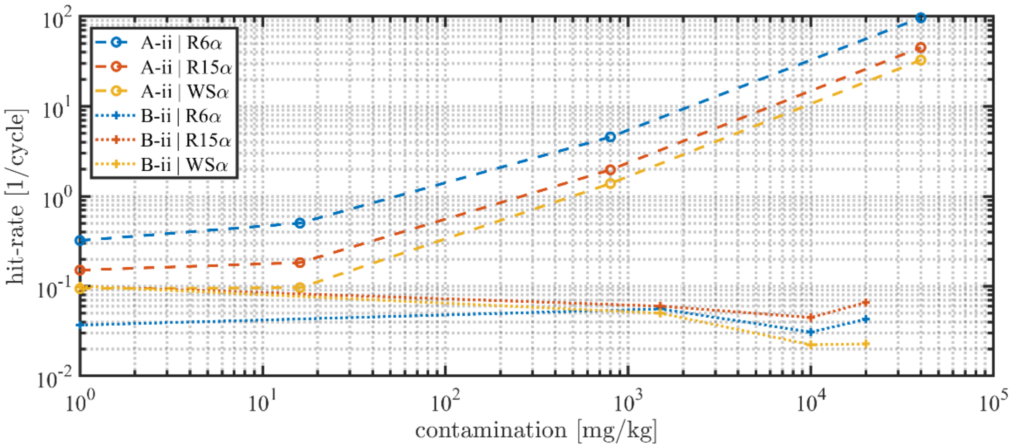

Fig. 3. Overview of load-cycle normalised activity for artificial contamination tests with the slew segment set-up (A-ii) and the bogie wheel set-up (B-ii). The baseline activity measurements for both set-ups (A-i, B-i) are plotted at 10^0 mg/kg contamination.

Results of the contamination tests and their respective baselines are summarised in **Fig. 3**. An obvious difference may be observed between the slew segment (A-ii) and the bogie wheel (B-ii) contamination tests, where the latter seems to show no activity exceeding the baseline measurement. In contrast, the slew segment shows a linear correlation between the amount of contamination and the load-cycle normalised hit-rate. During visual inspection of the rolling elements after all samples had been tested, significant wear had been observed. Therefore, it is likely that high hit-rates are indicative of excessive abrasive wear. Considering the industry defined safe limit at 1,500 mg/kg, the contamination is already clearly distinguishable from AE before it is of serious concern to the operator.

The absence of AE activity for the bogie wheel is expected to be the result of the type of contamination used in the experiment. The particles in the 10 μm pure iron powder are likely to be too soft and too small to generate any significant AE. Visual inspection of the rolling elements after these test also showed no signs of increased wear.

This presumption on softer and smaller particles is supported by the results of the corrosion test (A-iii). During this test, initially a minor increase in low-amplitude low-frequency activity had been observed, which returned to the baseline thereafter. Visual inspection after the test indicated the removal of corrosion products from the raceway, which thus have to be suspended in the grease. It was theorised that during the first cycles the softer corrosion products were flaked off of the raceway and ground to a fine powder, which was the cause of the increased low-frequency activity near the start of the test. The absence of increased activity after milling the corrosion flakes to a fine powder is in line with the absence of increased activity for the fine iron powder contamination during the bogie wheel artificial contamination test.

Note that although the AE data suggests the corrosion flakes in the grease are crushed to fine non-abrasive particles, the constant removal of corroded material and continued exposure to corrosive conditions can be detrimental to the lifetime of the bearing, as it could gradually erode the rolling elements. The resulting surface roughening induces stress concentrations that could initialise surface cracking.

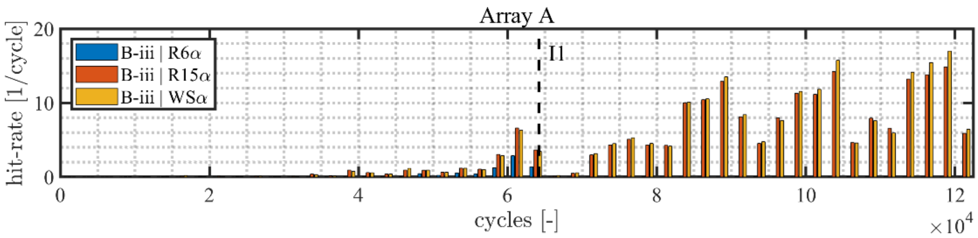

Fig. 4. Load-cycle normalised activity during the natural degradation test with the bogie wheel set-up (B-iii) recorded by the sensor node D_A near GS-2.

Results of the natural degradation test with the bogie wheel are shown in **Fig. 4**. Grease sampling has been performed at the indicated inspection (I1 in **Fig. 4**) and at the end inspection. The respective average wear particle indices (WPI) of the three sampling locations are 2,036 and 5,362 for the two inspections. Both of these WPI indicate the bearing is at risk of abrasive wear. The load-cycle normalised activity shows increasing trends leading up to each inspection, with a sudden reduction of the hit-rate just after the intermediate inspection. During this intervention, the bearing was fully cleaned for visual inspection and subsequently regreased for continuation of the test. Both the recorded hit-rate and the WPI see an increase in the order of two-and-a-half times, confirming the near linear correlation between hit-rate and the amount of contamination that was also observed in the artificial cases.

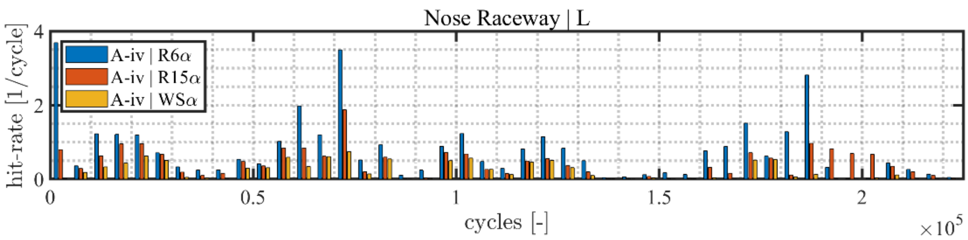

Fig. 5. Load-cycle normalised activity during the natural degradation test with the slew segment set-up (A-iv) recorded by the nose raceway sensor node.

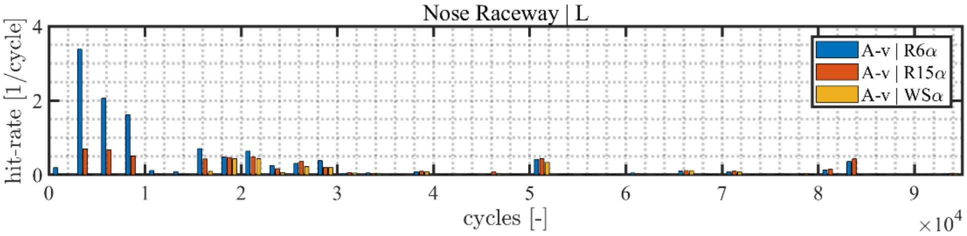

Fig. 6. Load-cycle normalised activity during the continued natural degradation test with the slew segment set-up (A-v) recorded by the nose raceway sensor node.

Results of the natural degradation test and continuation thereof with the slew bearing segment are shown in **Fig. 5** and **Fig. 6** respectively. The load-cycle normalised hit-rate of these tests strongly contrasts the high activity observed in the natural degradation test with the bogie wheel. Also considering the trends observed for artificial contamination, it is suggested that the lubrication in these tests remained clear of excessive or abrasive particle contamination. Considering the testing procedures, this was to be expected, since the frequent repositioning of the cage and rollers to mitigate for slipping also required frequent regreasing of the bearing. This indicates that the possible obfuscation of other degradation types by AE generated by particle contamination may be mitigated by frequent regreasing of the bearing.

4. Conclusions

The influence of particle contamination on AE in low-speed roller bearings has been investigated through a review of experiments from earlier work. Eight test cases involving both naturally-developed and artificially-introduced contamination performed with two different test set-ups are considered. Results indicate that (i) there is a direct correlation between the amount of abrasive particle contamination and the load-cycle normalised hit-rate, (ii) non-abrasive particles (i.e. small or soft particles) do not generate significant AE, (iii) frequent regreasing may be used to keep particle contamination under a safe limit, and (iv) under the safe limit obfuscation of other degradation types can be prevented. This study shows promising potential for the use of AE monitoring grease condition of low-speed roller bearings.

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