Simultaneous use of Acoustic Emission Signals and Statistical Analysis to Distinguish between Lubrication Modes in Rolling Element Bearings

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Abstract: The lack of lubricant in bearing surfaces could be considered as the main cause of wear and faults in bearing surfaces. To avoid unexpected failures, special emphasis on adequate evaluation of lubrication mode (lubricated/dry) on the bearing surfaces is demanded. To that end, the proper use of reliable techniques and tools, including sensory information from acoustic emission (AE) signals is among popular methods when real-time condition monitoring evolves. The current work intends to evaluate the sensitivity of AE parameters to different levels of process parameters on the basis of statistical analysis. In this context, rotational speed and radial load were used as the main experimental parameters. Following that, adequacy of a new AE signal parameter for real-time condition monitoring of rolling element bearing is presented. Experimental and statistical results confirmed the great capability of AE signals to differentiate between two types of bearing modes, in particular, dry and lubricated. Signal processing and statistical analysis conducted in this study exhibited that several time series AE parameters, in particular, Std, Max, Mean, and Variance are sensitive to the variation radial load and rotational speed. It was observed that radial load has insignificant effects on computed values of AE parameters from both bearing modes. The statistical analysis revealed that rotational speed (A) has a significant effect on all computed AE parameters from the dry bearing.

Keywords: Acoustic Emission, Bearing, Condition Monitoring, Lubrication

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1 INTRODUCTION

Bearings are considered as critical parts of rotating machines, which could be found in almost all machines. The main sources and reasons for bearing failures are listed in [1]. Amongst, friction is one of the main reasons hindering the adequate application of the bearings. The first solution to avoid or at least decrease the induced friction between the bearing surfaces is the use of lubrication. Moreover, the use of lubricant may protect the bearings against destructive pitting and rust as well as contamination caused by water. The main types of lubricants are oil and grease which in fact must be chemically neutral and non-corrosive. As mentioned earlier, bearing failures [2] are governed by many factors. In fact, periodic examination and maintenance tests are needed to reduce the risk of failure and non-desirable expenses. To that end, two methodologies were proposed, including (1) bearing life estimation using statistical information and (2) condition based monitoring (CM) using sensory information [3]. The second approach, however, seems to be more reliable as more efficient information can be obtained within the periodic examinations.

2 REVIEW OF LITERATURE

The vibration and AE signals are the most prevalent bearing CM techniques commonly used in academic and manufacturing sectors. Several studies [4-8] ascertains the privilege of AE than vibration signals for bearing condition monitoring. In fact, AE signals are capable of identifying the crack growth, while vibration signals may only discover defects. Also, the energy released from neighbouring components may affect the sensitivity of defected bearing, whereas, AE signals are powerful to detect the upcoming defect before it appears in the vibration range. As noted in the open literature, local bearing defects monitoring can be conducted by life tests [6], [9] and simulated defects approach [7], [10]. The efficiency of several AE time series parameters for defects detection in rolling element bearing was presented in [10].

However, the AE parameters aforementioned are not capable of distinguishing between "significant" and 'non-significant' defects. Despite limitations indicated earlier, several AE parameters including energy, count, and r.m.s are widely applied in bearing errors detection [11]. As noted in [12], other elements such as count and peak amplitudes were also tested to examine the bearing working condition. As discussed in [13-14], stress wave method has a high capability for health monitoring of low-speed rolling element bearings. The extracted AE information from rolling element bearings was assessed in [15]. Other works [1], [16-23] revealed that AE signals could be applied for bearing health monitoring within an acceptable level of accuracy. Numerous applications of AE in many other aspects of manufacturing and mechanical systems were also reported in [24-31]. The proper use of reliable signal information for defects detections of rolling element bearing is highly demanded when real-time condition monitoring evolves. These parameters seem sensitive to experimental conditions including, rotational speed, load, and defects size. However, no clear judgment has been made up until now on the use of statistical techniques to define the sensitive AE signal parameters to a broad range of experimental factors, such as radial load and rotational speed. Based on a review of the open literature, limited studies are still available to describe the competency of time series AE signal parameters to lubrication modes in rolling element bearings ("Fig. 1"). Therefore, the core objectives of this work are (1) evaluating the sensitivity and controllability of the conventional time series and recently proposed AE sensory signal information to the variation of lubrication modes and experimental variables in rolling element bearing surfaces using statistical approaches.

This study is presented as follows; the experimental study, containing the experimental tools and plan are presented in the next section, followed by presenting results in the third section. The conclusion is presented in the section four. As per the author's knowledge, limited studies are available to determine the bearing surface mode (dry/lubricated) by time series AE signal parameters and statistical tools. Knowing that understating the influences of various experimental factors such as rotational speed, radial load, temperature, etc., on AE parameters is demanded for reliable bearing health diagnosis, therefore, seven-time series AE parameters are extracted from AE signals. Statistical approaches were used to assess the effects of experimental factors on AE parameters that were extracted from tested bearings under both lubrication modes, respectively. Furthermore, the capabilities of AE signal parameters to distinguish between dry and lubricated bearings will be explored through the analysis of the results.

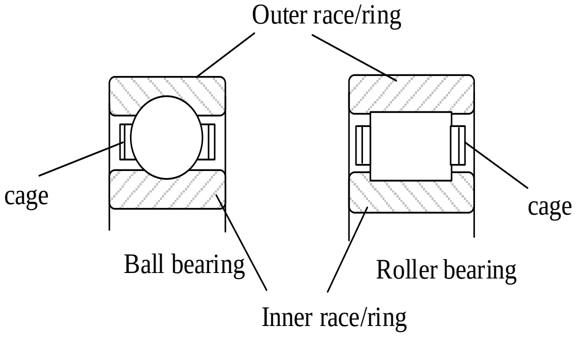


Fig. 1 Rolling element bearing (Adapted from [1]).

3 GENERAL GRAMMAR AND PREFERRED USAGE

3.1. Experimental Plan

The experimental test rig (“Fig. 2”) contains a rotating shaft that is supported by multiple bearings, including a self-aligned ball bearing SKF2206ETN9 (Third bearing), ball bearing SKF1206E (Second bearing) and a spherical roller bearing SKF22207E (Testing bearing), which is placed near the loading position. A three-phase A.C motor is used to allow speed and torque adjustment. The hydraulic system used in this study is presented in “Fig. 3”. Knowing that radius of the area of contact (r) and maximum applied pressure are 19 mm and 80 bars, the radial loads applied to the shaft are presented in “Table 1”. To extract the AE signal information, the AE sensor was coupled adjacent to the testing bearing (“Fig. 3”). To verify the adequacy of the proposed methodology, the pencil lead break test was manipulated. Within the verification tests, the pencil lead was placed adjacent to the testing bearing, and then it was broken to record the emitted energy. This procedure was repeated three times to respect the replications needed. The average values of experimental results were then recorded. Experimental results reveal that under similar operating conditions, higher levels of energy were recorded from testing bearing as compared to those recorded from the second and third bearings. This is in agreement with scientific assumptions. Therefore, the effects of both bearings with a lower level of emitted energies were neglected in subsequent studies.

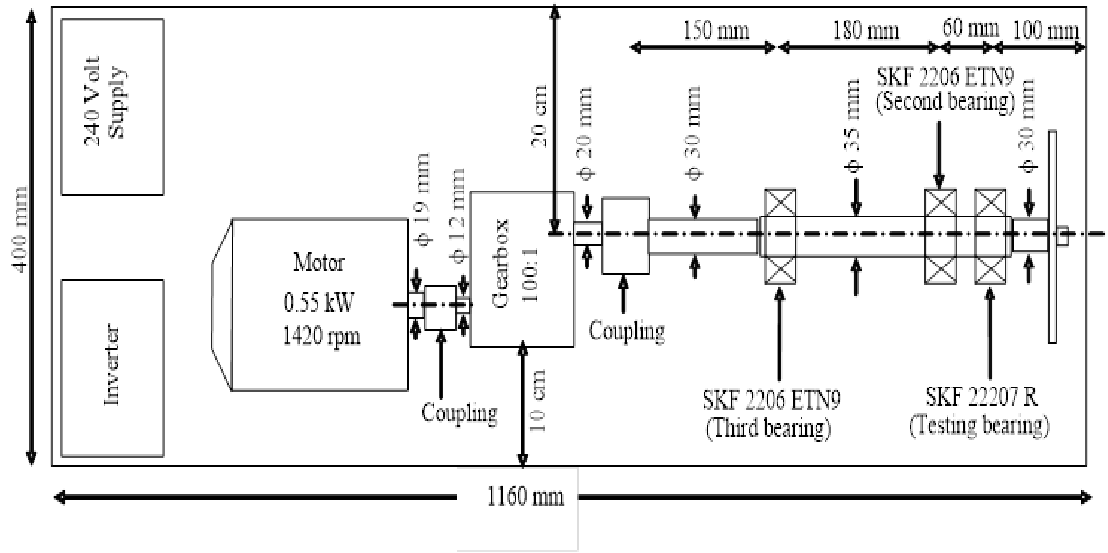


Fig. 2 Overview of the test rig (Adapted from [1]).

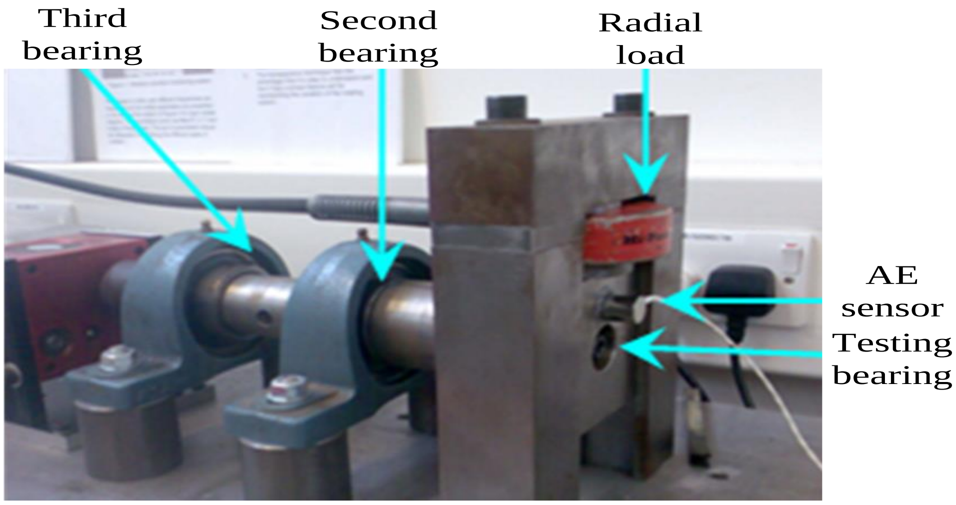


Fig. 3 Experimental test rig (Adapted from [32]).

Table 1 The statistically significant AE parameters

Tests	Rotational Speed (rpm)	Radial Load (N)	Lubricated bearing			Dry bearing		
			Mean (V)	Std	Max (V)	Mean (V)	Std	Max (V)
1	1800	2268	0.65	0.70	0.71	7.01	7.99	11.51
2	2400	2268	0.73	0.77	0.78	9.85	10.62	13.27
3	3000	2268	4.26	4.29	4.56	6.57	6.40	8.68
4	3600	2268	3.94	3.80	4.32	1.95	2.46	2.52
5	4200	2268	5.28	5.07	6.57	4.17	4.83	5.26
6	4800	2268	3.96	3.97	4.53	0.61	1.61	0.97
7	5400	2268	2.45	2.52	2.81	2.39	2.69	2.78
8	6000	2268	2.08	2.38	2.49	0.75	0.97	0.96
9	1800	4537	0.60	0.62	0.62	8.48	10.34	8.75
10	2400	4537	0.88	0.91	1.00	10.96	9.35	13.25
11	3000	4537	7.79	8.11	9.37	7.77	6.83	7.25
12	3600	4537	4.83	4.40	6.13	1.68	2.64	2.59
13	4200	4537	0.41	4.21	4.66	3.70	4.32	4.57
14	4800	4537	4.54	4.76	5.68	0.59	1.57	0.80
15	5400	4537	3.64	3.72	4.08	2.01	2.85	2.27
16	6000	4537	2.60	2.82	3.44	0.75	0.98	0.93
17	1800	6805	0.57	0.65	0.80	7.02	8.56	9.46
18	2400	6805	0.63	0.69	0.83	9.36	11.01	12.33
19	3000	6805	6.87	6.56	11.78	6.13	6.26	7.88
20	3600	6805	4.71	4.33	5.34	2.15	2.48	2.52
21	4200	6805	0.01	0.00	0.01	3.45	4.06	4.53
22	4800	6805	4.52	4.96	0.05	0.93	1.63	1.10
23	5400	6805	3.68	3.64	4.66	2.11	3.12	3.20
24	6000	6805	1.87	2.39	3.06	1.87	2.39	2.76
25	1800	9073	0.51	0.56	0.55	7.32	7.87	9.18
26	2400	9073	0.65	0.66	0.63	8.79	8.79	12.25
27	3000	9073	7.97	7.15	7.95	5.89	7.33	6.63
28	3600	9073	4.54	4.18	5.23	2.31	2.57	2.53
29	4200	9073	3.43	0.01	4.59	2.77	3.87	3.78
30	4800	9073	3.74	3.83	4.92	0.85	1.65	1.17
31	5400	9073	3.19	3.43	3.44	1.87	2.75	2.48
32	6000	9073	2.89	3.08	3.27	0.46	1.22	0.77

3.2. Measurement Tools

The following systems and devices were applied using signal processing and condition monitoring of the tested bearings:
1- Transducers, filter, and preamplifiers.
2- The experimental test rig.
3- Data acquisition systems.
A preamplifier (model 2100/PA 60) with a gain of 60dB, and built-in bandpass filter set at 100 kHz –1 MHz was connected to the transducer via a short cable. The main function of the band-pass filter is to eliminate the frequency components lying outside the window. A wideband transducer (model WD, PAC) with a frequency range of 100-1000 kHz was operated. The sensor is located in a metallic case; made from stainless steel with ceramic sensing disc that is coated to minimize EMI interference. The signal processing was performed using a sampling frequency of 3 MHz. An algorithm was written to automatically calculate the standard deviation (σ) of computed values. As mentioned earlier, to eliminate the noise effect, a floating threshold of 4σ was used, and only those six AE events that could pass from the assigned threshold were used in the result analysis. This could enable the system to provide the time duration of AE events when passing the threshold. The adjusted threshold value was determined following multiple preliminary tests. In fact, the floating threshold of 3σ was used in preliminary tests and no accurate results were obtained. No work was found in this domain to define an automatic threshold, capable of purifying the extracted features and also statistical methods for evaluation of the bearing lubrication conditions. The aforementioned real-time signal processing and data analysis assignments were conducted on commercial operating software LABVIEW (version 5.1). Following signal processing, the recorded signals were then converted into digital format and were then transferred to the intelligent graphics terminal (IGT) where a manipulator was used to observe a graphical demonstration of anticipated AE data.

The computed AE parameters from an individual AE event are:

Max= AE_{Max} or Maximum value or amplitude of the signal

Min= AE_{Min} or Minumum value of the signal

Mean (μ)= AE_{μ} mean value of the signal

$$Mean = \frac{\sum_{i=1}^{N} x_i}{N-1} \tag{1}$$

Standard deviation (σ)= Std

$$Std = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \bar{x})^2}{N-1}} \tag{2}$$

Variance = σ^2 or AE_{Var}

$$Var = \frac{\sum_{i=1}^{N} (x_i - \bar{x})^2}{N-1} \tag{3}$$

Kurtosis or AE_{Kurt}

$$Kurt(x) = E\left[\left(\frac{X-\mu}{\sigma}\right)^4\right] \tag{4}$$

Skewness or $AE\gamma_1$

$$\gamma_1(x) = E\left[\left(\frac{X-\mu}{\sigma}\right)^3\right] \tag{5}$$

4 RESULTS

The results are presented in two categories, one based on using statistical analysis to define the sensitive AE signals information to bearing lubrication modes, followed by proposing an innovative AE parameter which is sensitive to the variation of lubrication mode in bearing surfaces.

4.1. AE Signal Parameters and Statistical Analysis

Under the similar experimental conditions as aforementioned, the statistical results of recorded AE responses are depicted in “Table 1”. The statistical results exhibit that several AE parameters including, Max, Std, Variance and Mean are sensitive to the variation of experimental parameters ($R^2 > 0.75$) under the dry bearing. It can be indicated that the difference in computed values of time series AE parameters as well as the sensitivity of the aforementioned AE parameters to experimental parameters can be considered as an index for bearing condition and health monitoring, specifically when lack of lubricant is observed in the bearing surfaces. According to “Table 1”, despite lubrication mode, the direct effect of rotational speed (A) as well as interaction effects between rotational speeds (AA) have significant influences on all AE parameters. Furthermore, radial load (B) is not a significant element on all computed AE signal parameters in both lubrication modes. As noted earlier, using the abovementioned statistically significant AE parameters, it becomes possible to distinguish between the lubricated modes in the bearing surfaces.

To better describe the sensitive AE parameters under various experimental conditions, the 3D surface response of AE_{Std}, and AE_{Max} which were classified as the most sensitive AE parameters (“Table 1”) are presented in “Fig. 4”. It can be underlined that under dry bearing, the computed AE parameters could achieve their maximum values at 1800 rpm (“Fig. 4b”), while, despite the radial load applied, under both dry and lubricated conditions, increased rotational speed (1800-6000 rpm) led to reduced values of both AE parameters. Under lubricated bearing, the maximum value of all AE parameters was obtained at 4200 rpm. Increased rotational speed (4200-6000 rpm) led to lower resulting values in all AE parameters (“Fig. 4”). This observation, however, denotes the presence of interaction effects between rotational speed (AA) as clearly presented in “Table 2”.

Table 2 The computed values of μ/σ in dry bearing

Parameters/ lubrication	Radial load kN	Mean value of μ/σ							
		30Hz	40Hz	50Hz	60Hz	70Hz	80Hz	90Hz	100Hz
Dry bearing	2.27	0.91	0.92	1.06	0.79	0.88	0.37	0.91	0.78
	4.54	0.82	1.21	1.14	0.63	0.87	0.37	0.71	0.77
	6.81	0.83	0.85	0.99	0.88	0.86	0.58	0.68	0.73
	9.07	0.93	1.02	0.8	0.90	0.72	0.52	0.69	0.38
Lubricated Bearing	2.27	0.93	0.94	1.05	1.04	1.04	1.00	0.99	0.88
	4.54	0.97	0.97	0.96	1.11	0.98	0.96	0.998	0.93
	6.81	0.89	0.92	1.05	1.11	0.98	0.93	1.03	0.73
	9.07	0.92	0.99	1.14	1.11	0.95	1.00	0.94	0.94

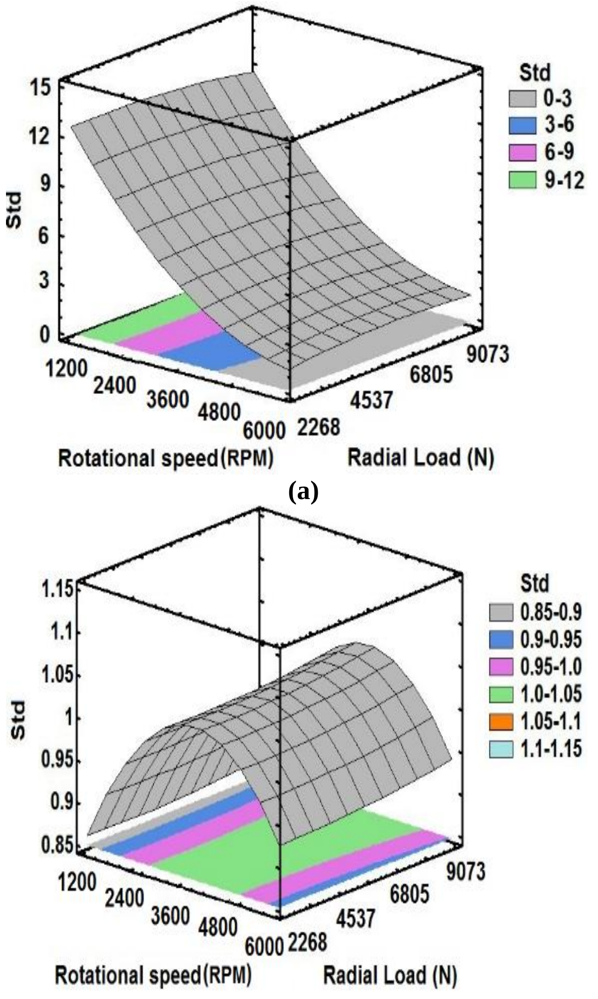


Fig. 4 The 3D plot of std under: (a): lubricated bearing and (b): dry bearing.

According to “Fig. 4 and Fig. 5”, under similar experimental conditions, a nonlinear behavior is observed from detected AE parameters from the lubricated bearing, while contrary, a linear relationship can be constructed among sensitive AE parameters when various levels of experimental parameters are used under the dry bearing. Moreover, a noteworthy difference can be observed between AE parameters' magnitude under rotational speed 1800-3600 rpm in both lubrication modes (“Fig. 4 and Fig. 5”). The absence of lubricant within the operating surfaces of the tested bearings is known as the main reason for the abrupt change in the magnitude of AE parameters. This is a remarkable phenomenon that can be used to distinguish between bearing lubrication modes in real-time condition monitoring and health diagnosis assignments.

Based on using similar process parameters and experimental tools as aforementioned and according to statistically significant AE parameters indicated in “Table 2”, an innovative parameter based on arithmetic relationship between standard deviation (σ) and mean (μ) values of AE signals denoted as μ/σ is prepared as an index for real-time distinguish between lubrication modes in bearing surfaces. The computed values of μ/σ in all experimental conditions in both bearing lubrication modes are presented in “Table 2”. As depicted in “Fig. 6”, regardless of applied radial loads under rotational speeds 30-50 Hz, no clear discussion can be made concerning the variation of μ/σ values on the basis of the confidence interval of 95%. In this interval, the proposed parameter is not capable of distinguishing between lubricated and dry bearings. Regardless of applied radial loads used at 60-100 Hz, larger μ/σ values resulted in the lubricated bearing (“Fig. 6”). Moreover, it could be inferred that under maximum radial load (F=9076 N), the difference between resulted values of μ/σ under both lubrication modes is not within error limits. This reveals that within the range of 60-100 Hz, the proposed parameter (μ/σ) can be used to differentiate between both bearing modes used.

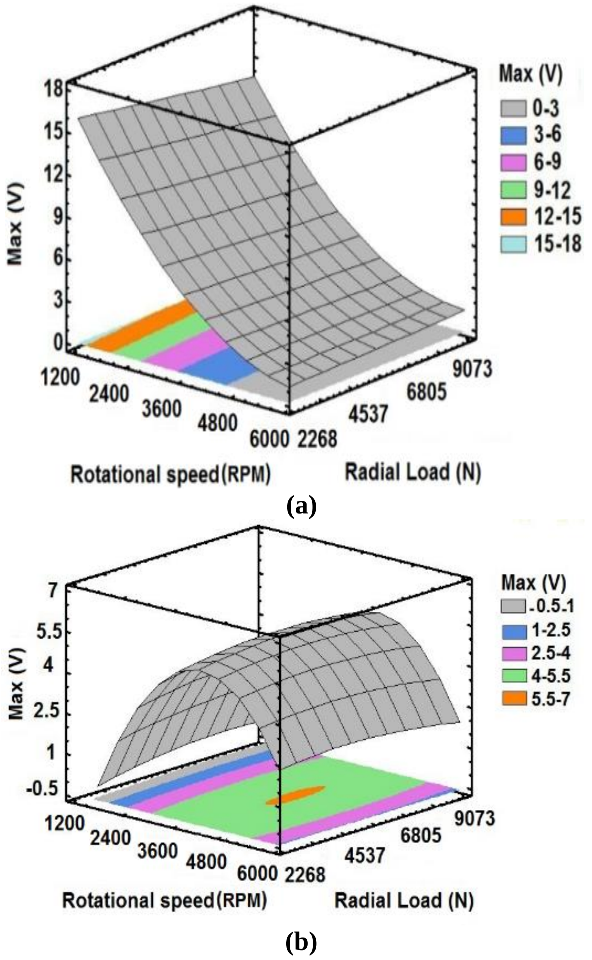
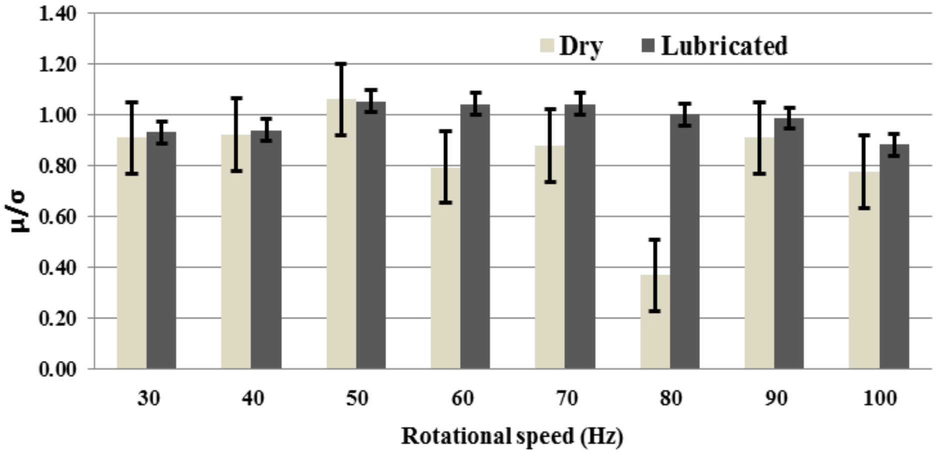
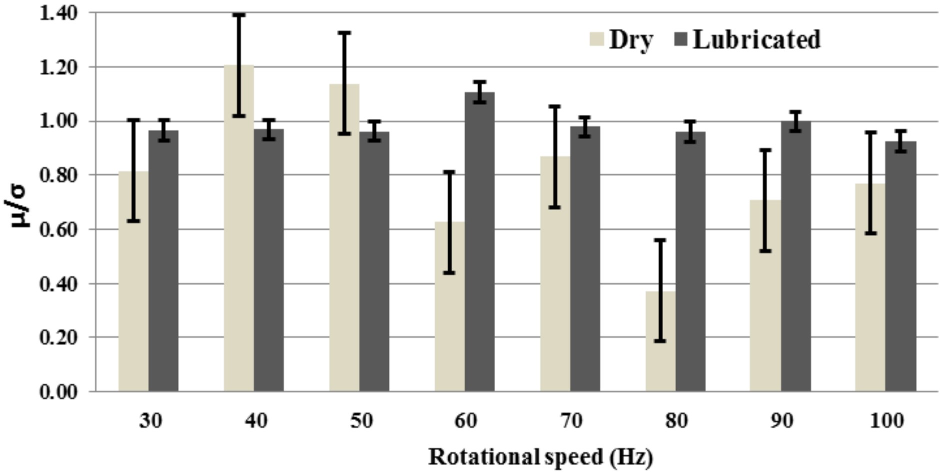


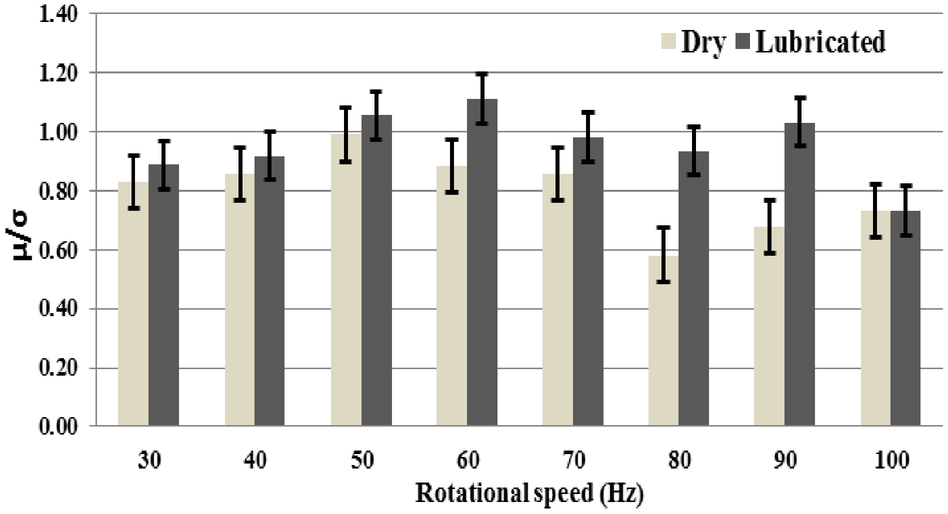
Fig. 5 The 3D plot of Max under: (a): lubricated bearing and (b): dry bearing.


Dry
Lubricated
μ/σ
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
30
40
50
60
70
80
90
100
Rotational speed (Hz)

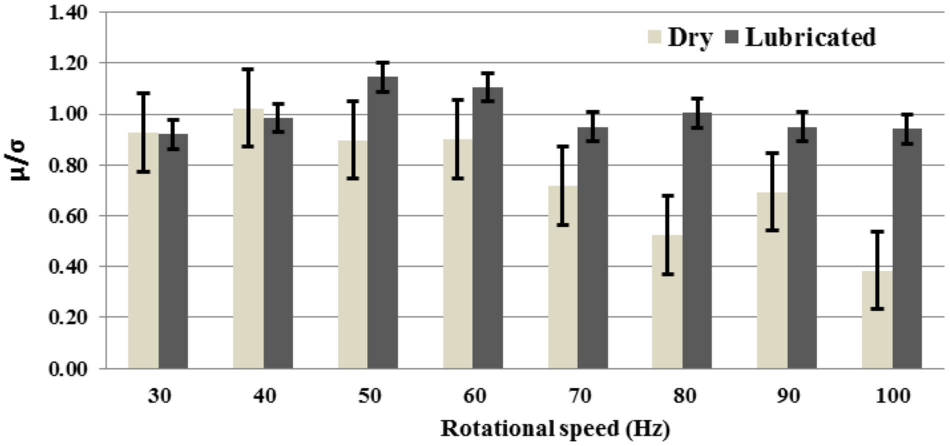
(a)


Dry
Lubricated
μ/σ
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
30
40
50
60
70
80
90
100
Rotational speed (Hz)

(b)


Dry
Lubricated
μ/σ
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
30
40
50
60
70
80
90
100
Rotational speed (Hz)

(c)



(d)

Fig. 6 μ/σ versus rotational speeds at various radial loads as follows: (a): 4.54 kN, (b): 4.54 kN, (c): 6.81 kN and (d): 9.07 KN.

In aforementioned experimental conditions, and due to lack of lubrication in beating surfaces and surface frictions, in particular when the test rig shaft is rotated with 60-100 Hz, a large difference can be observed between detected values of μ/σ in dry and lubricated bearings. Consequently, decreased values of μ/σ are obtained under the dry bearing. Except for few cases at lower levels of radial load, a similar conclusion can be made. According to "Fig. 6(a)", when rotational speed varies in the range of 50-100 Hz, the computed values of μ/σ from lubricated and dry bearings are not within error limits. As depicted in "Fig. 6", the lower sensitivity of μ/σ is observed under lower levels of radial load. Also, as shown in "Fig. 6(d)", when rotational speeds 60 and 80 Hz are in operation, the difference between computed values of μ/σ under both lubrication modes are outside of error limits [20]. The proposed AE parameter in this work seems to be sensitive to a broad range of experimental parameters, in particular, increased loads and speed where high surface tension and friction appear due to lack of lubricant. Therefore, the proposed parameters could be useful to distinguish between lubricated and dry bearing at higher levels of experimental parameters, where other aforementioned parameters are not very sensitive. However, subsequent studies on real-time condition and health monitoring of bearings are still demanded to ascertain the adequacy of the proposed parameter in wider scopes.

5 CONCLUSION

Through presenting results in this work, the following conclusions are drawn:

- Signal processing and statistical analysis conducted in this study led us to conclude that several time series AE parameters, in particular, Std (σ), Max, Mean (μ), and Variance (σ^2) are sensitive to the variation of experimental parameters, in particular, radial load and rotational speed. Among experimental parameters, the radial load (B) has non-significant effects on computed values of AE parameters from both bearing modes. The statistical analysis revealed that rotational speed (A) has a significant effect on all computed AE parameters from the dry bearing.
- The computed values of AE parameters under different lubrication modes can be distinguished from other elements when rotational speeds vary from 1800-3600 rpm. This phenomenon can be correlated to the lack of lubricant in dry bearing surfaces which may lead to the presence of friction in the bearing surfaces.
- The 3D plots presented in this work can indicate that under standard operating conditions, computed AE parameters from lubricated bearing can be recognized from those recorded from the dry bearing.
- According to experimental observations, despite radial load applied, at higher levels of rotational speeds (60-100 Hz), μ/σ tends to increase under the lubricated bearing. In other words, it can be exhibited that μ/σ is capable of differentiating between bearing lubrication modes at higher radial load and rotational speed (60-100 Hz), whereas less sensitivity was observed under lower values of radial loads. This observation can be related to the effects of frictions at higher levels of radial load and rotational speed.
- When using increased radial load and the rotational speed of 60-100 Hz, the lubricated and dry bearings were successfully distinguished from others when the proposed parameter (μ/σ) was used. This can be related to friction higher which tends to increases at high levels of rotational speed and radial load.
- Although the presented results are thought to be valid according to experimental apparatus and conditions used, however, to verify the consistency of

proposed methodology, the presented work needs to be expanded in broader levels through further experimental and theoretical investigations. For instance, since the rotational speed is limited to 100 Hz, additional experimental studies at higher levels of rotational speed and various bearing operating modes (e.g., inner and outer surface damage) are proposed to better validate the competency of the proposed AE signal parameters and condition monitoring methodology.

The present study is thought to have a good capability for a wider range of applications in real-time condition monitoring of bearing failures under various lubrication modes, including dry, lubricated and semi lubricated. To this end, incorporating certain levels of modifications to the experimental test rig and analysis approach are recommended. One solution is to integrate the use of the recorded data in frequency as well as time domains with artificial intelligence (AI) methods based pattern recognition technique.

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7 APPENDIX OR NOMENCLATURE

Method of analysis

In order to evaluate the effects of cutting parameters on computed values of AE parameters, the following experimental techniques and parameters were used. The complete overview of the statistical terms used are presented in [33]:

1. ANOVA: The analysis of variance (ANOVA) examines the effects of controllable experimental parameters and their combined effects at 95% confidence interval (CI).

❖ The coefficient of determination (R^2) presents a degree of variability of the observed response as a function of controllable parameters and their interactions. A $R^2 > 0.75$ indicates that the anticipated model is sensitive to the variation of experimental parameters, while if $R^2 < 0.75$, the predicted models is considered insignificant to the variation of experimental parameters.

❖ R^2_{adj} is an appropriate term used to compare the models with dissimilar independent parameters. R^2_{adj} is in general smaller or equivalent to R^2.

❖ P-value: This term is used to determine if each individual experimental variable as well as the presented model in either second order degree, linear or 2-factor interactions are either significant, mid significant or insignificant. To that end, the following assessment criteria are used;

- P-value > 0.10, the experimental variable/model is insignificant
- $0.05 \leq$ P-value ≤ 0.10, the experimental variable/model is mildly significant
- P-value < 0.05, the experimental variable/model is significant

2. Pareto chart: This chart applies statistical analysis to demonstrate the distinction of the main and interaction effects between experimental parameters and their combined effects on the responses by means of decreasing contribution.

The significant and insignificant variables were identified using statistical parameters, including P-value, R^2 and R^2_{adj}. The input variables, in principle cutting parameters and their interaction effects with the P-value smaller than 0.05 are considered as a statistically significant response. Therefore, the AE responses with corresponding values of R^2 smaller than 0.75 were also considered as the insignificant responses to the variation of cutting parameters. .

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