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STUDY OF DAMAGE IN SPUR GEAR USING ACOUSTIC EMISSION SIGNAL ANALYSIS

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Abstract

Objective of this research is to study how to use acoustic emission in condition monitoring of spur gear defect diagnosis which was calculated by using the statistical parameter analysis technique. Acoustic emission is defined as defect propagation rate in the microscopic and macroscopic of rotating machinery which has spur gear as the main part of power transmission system. This experiment was set up based on motorcycle spur gear with torque loading in various conditions such as defect free, a 25% crack tooth, a 50% crack tooth, a 50% broken tooth, a 100% broken tooth, one gear has a 50% broken tooth and a 100% broken tooth. Result of this experiment showed that acoustic emission signal analysis with two statistical parameters could be meaningfully used for defect identification.

1. Introduction

Condition monitoring technique is an essential method in nuclear, aviation and petrochemical industries in order to ensure product integrity and in turn reliability, avoid failures, prevent accidents and save human life, and lower manufacturing costs [1]. Furthermore, gearboxes are the key parts in any rotating machines and also used for transferring the power and rotational speed from a mechanical source which we do not expect any failures or shutdown. Recent years, acoustic emission (AE) is one of many technologies for health monitoring of rotating machines for the early diagnosis of various defect conditions and low cost.

In fact, AE is defined as the elastic wave spontaneously released by materials when they undergo deformation and fracture. The principal advantage of AE comes from its high sensitivity since AE microscopic level is developed from surface motion at dislocations, microcracks and phase transformations, particularly for those which involves in the annihilation formation of martensite [1].

AE is relatively new technique and has grown significantly over the last decade. AE in rotating machinery is defined as elastic wave generated by the interaction between two medias in motion such as a pair of gears. A source of AE in rotating machinery is in clued asperities contact, cyclic fatigue, friction, material loss cavitations, leakage, etc. The main reason that AE technique has drawn attention is it offers some advantages over classical method. Since AE is a non-directional technique, one AE sensor is sufficient in contrast to vibration monitoring which may require information from three-axis. Since AE is produced at microscopic level, it is highly sensitive and offers opportunities for identifying defects at an earlier stage when comparing to other condition monitoring techniques. As AE mainly detects high-frequency elastic waves, it is not affected by structural resonances and typical mechanical background noise (under 20 kHz) [2]. AE analysis technique is an attempt to correlate all possible failure modes of a gearbox during its useful life. Failures such as shaft misalignment, tooth breakage, scuffing and a worn tooth associated with the AE amplitude, root mean square, standard deviation and duration. It was concluded that the AE results could be correlated to various defect condition [3].

The interest for applications of AE and vibration is for condition monitoring in rotating machinery. Tandon et al [2] performed an experiment to prove correlate between AE parameters, such as peak amplitude, ringdown count and energy with gear defect size. The experimental set-up employed a back-to-back gearbox with a gear ratio of 15:16. An AE sensor with resonant frequency of 375 kHz and an accelerometer of natural frequency of 39 kHz were employed for experiment. The tests were performed at a rotational speed of 1000 rpm under different load conditions. Simulated pits on the pitch-line with constant depth (500m) and varying diameters from 250 to 2200 m were introduced by using the spark erosion technique. Tandon et al. observed hat of the monitored AE parameters increased with defect size (pit diameter) and load. Tandon et al. also concluded that AE has a better detection capability over vibration since it was able to detect smaller pit size. Chee Keong Tan et al. [4] presented interesting observation of AE and vibration activity due to large addendum defect. The test was performed at a rotational speed of 745 and 1460 rpm under 0, 55, 110, 183 and 220 load conditions on a back-to-back gearbox with a spur gear set of 49 and 65 teeth. The AE sensor used was a resonant type placed on the pinion. Chee Keong Tan et al. concluded that the main element contributing to the change in vibration level is the stiffness of the operating gear system. Hence, as long as the defect is able to alter the stiffness of the system, it will be detected by the accelerometer, as observed in the experiments reported. This is in contrast to the AE technique which was excited by asperity contacts. Toutountzakis et al. [5] investigated the influence of oil temperature and oil film thickness on AE activity and on AE signals captured during continuous running of a back-to-back gearbox test-rig. It was observed that the AE RMS varied with time as the gearbox reached a stabilized temperature and the variation in AE activity RMS could be as much as 33%

Although the development of AE in gear diagnosis is in its infancy, the literatures review has illustrated the potential and viability of AE that it becomes a useful diagnostic tool in condition monitoring of gears. However, in-depth investigations are still required to prove that this technique is robust and applicable for operational gearboxes. The purpose of this investigation was to determine an effective AE indicator for various defect conditions.

2. Experimental setup

Figure 1 shows the experimental setup used for the gear testing. The test-rig consists of two shafts of the gears which are supported by two ball bearings each. The entire system is settled in an oil basin in order to ensure proper lubrication. The gearbox is powered by a motor and consumes its power on a generator. Their characteristics are as follows:

1. A pinion gear has 20 teeth with 10 mm. and module 20 mm.
2. Two wheel gears have 25 and 28 teeth with 10 mm. and module 20 mm.
3. Three-phase half hp motor (220V, 2.0 A, 50 Hz, 1400 rpm) controlled by inverter.
4. Electric's brake with continuous power consumption control (torque loading fluctuation), 12 Nm 1800 rpm
5. the lubrication used is grade 15W-40

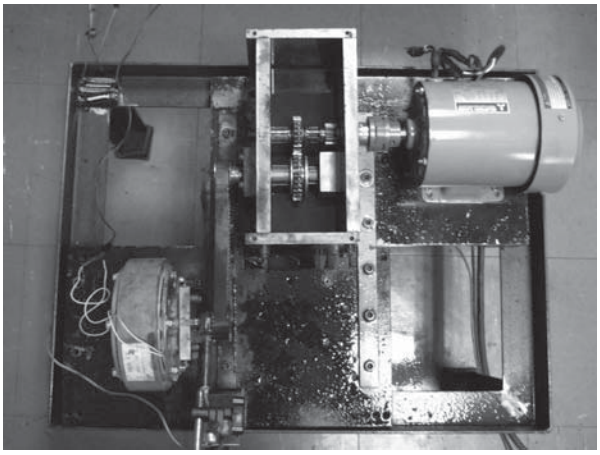


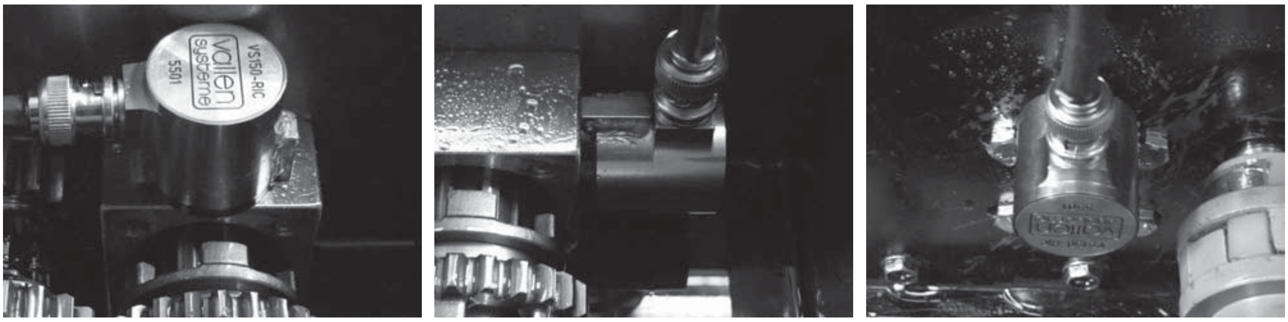
Figure 1 Test-rig gearbox used in this study

The AE sensors used for this experiment were broadband type sensors with a relative flat response in the region between 30 to 500 kHz (Model: VS-150-RIC, Vallen System GmbH). The output signal from AE sensor was amplifier at 34 dB. Tachometer measured rotational speed on wheel shaft. The recordings of all the above data coming form tachometer and AE sensors are realized by Advantech PCI-1714U data acquisition device and assisted by software developed in-house, recorded continuous of 1 second duration at a sampling rate of 1.5 MHz.

3. Test procedure

The actual experiment was carried out after the gearbox was run for 30 minutes at a rotational speed of 1400 rpm in order to allow the gearbox to be dynamically settled and reached at stabilized temperature. Prior to the start of the test, Nielson source tested [6] on the gearbox was undertaken in order to understand the characteristics of the test-rig, it was essential to record AE data

The test performed with 25 and 28 teeth gear, The AE sensors were placed on 3 position of the bearing casing of the wheel shaft such as vertical axis, horizontal axis and shaft axis as show in Figure 2. This procedure was repeated for the torque condition of 1 Nm.



(A) (B) (C)

Figure 2 AE sensor located on bearing casing (A).Vertical axis, (B).Horizontal axis, (C).Shaft axis

A total of six experimental combinations were undertaken such as:

1st condition is defect free.

2nd condition is tooth crack of 25% thickness.

3rd condition is tooth crack of 50% thickness (Figure 3).

4th condition is tooth breakage of 50% height (Figure 4).

5th condition is tooth breakage of 100% height.

6th condition is teeth breakage of 50% and 100% height opposite position

Two groups of AE data were recorded every experimental condition, first group recorded thirty sets for condition boundary and second group record twenty sets for accuracy test.

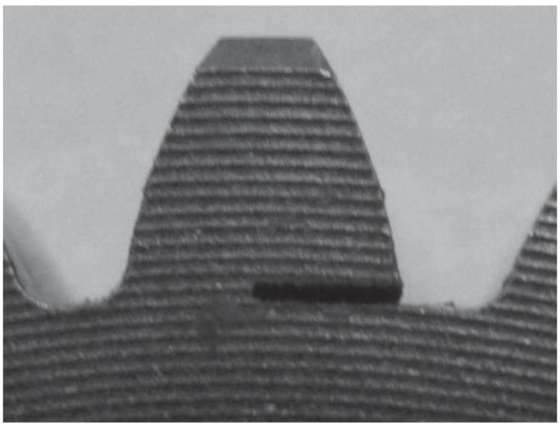


Figure 3 Tooth crack of 50% thickness

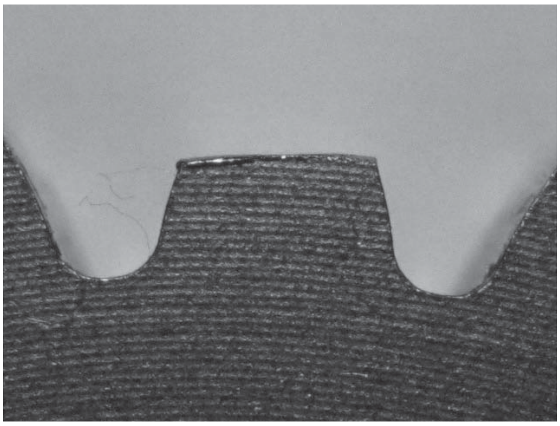


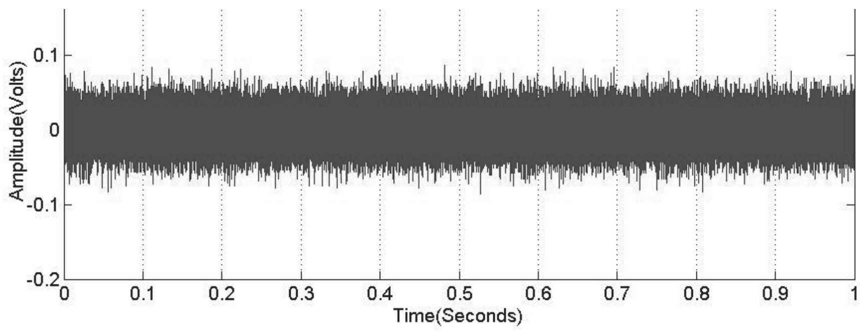
Figure 4 Tooth breakage of 50% height

4. Results and Discussion

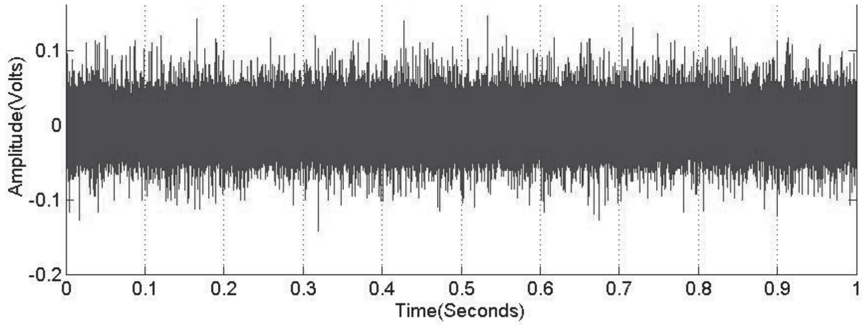
The best attenuation of AE signatures was observed on the shaft axis. A typical AE signature with a defect free condition in time domain as show in Figure 5 and AE signature in frequency domain could also be calculated form the time domain AE signal by using equation (1) as show in Figure 6

$$Y(t) = \int_0^t y(t)e^{-j\omega t}dt \qquad (1)$$

Where Y(t) is the amplitude in frequency axis
y(t) is the amplitude in time axis
t is the period
ω is the angular speed

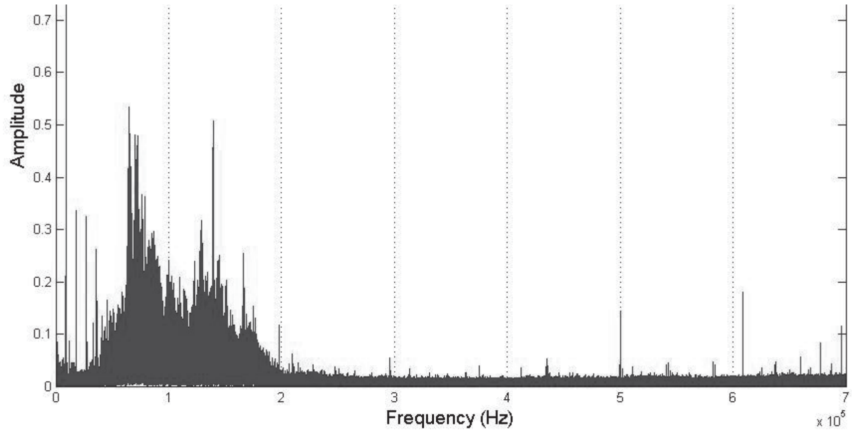


(A)

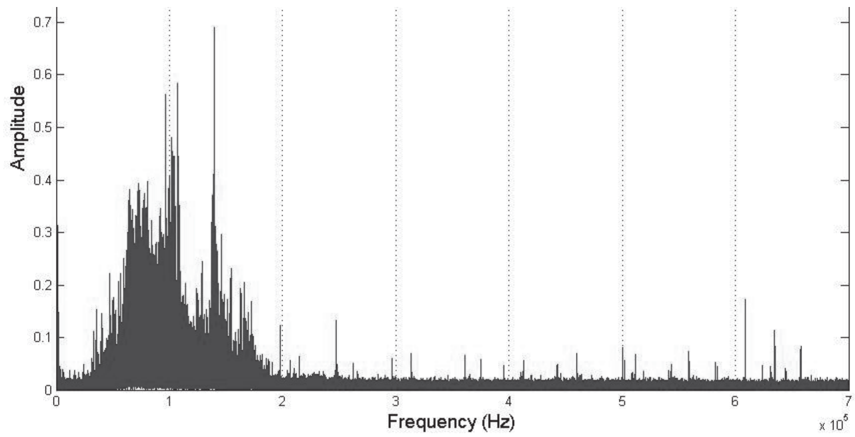


(B)

Figure 5 AE signal show in time domain for defect free condition (A).25 teeth gear, (B).28 teeth gear



(A)



(B)

Figure 6 AE signal showed in frequency domain for defect free condition (A).25 teeth gear, (B).28 teeth gear

The frequency rang of the transient and continuous AE signals associated with these tests ranged from 50 to 250 kHz. For analysis of AE data obtained from this experiment Energy, Root Mean Square (RMS), Mean and Kurtosis values were calculated to proven robustness of these parameters for machine health diagnosis by using equation (2) - (5). Table 1 - 4 presents the parameters every experimental condition.

$$Energy = \int_0^t x^2(t)dt \tag{2}$$

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2} \tag{3}$$

$$Mean = \frac{1}{T}\int_0^T |x(t)|dt \tag{4}$$

$$Kurtosis = \frac{1}{N}\sum_{i=0}^{N-1}\left(\frac{|x_i| - \bar{x}}{\sigma}\right)^4 \tag{5}$$

Where x(t) and x(i) are the amplitude in time axis
N is data numbers
T is the period

Table 1 Parameter of 25 teeth gear without torque

Condition	Energy (Joule)	RMS (Volt)	Mean (Volt)	Kurtosis
1st	401.2	0.01635	0.00077	3.075
2nd	1111.1	0.02721	0.00114	3.017
3rd	267.3	0.01334	-0.00014	3.279
4th	1151.8	0.02768	0.00025	46.3
5th	29790.6	0.14057	0.00173	441.7
6th	18182.7	0.10989	0.00066	321.6

Table 2 Parameter of 25 teeth gear with torque

Condition	Energy (Joule)	RMS (Volt)	Mean (Volt)	Kurtosis
1st	580.5	0.01967	0.00102	3.050
2nd	1438.2	0.03096	0.00169	3.011
3rd	369.0	0.01568	0.00051	3.171
4th	3105.2	0.04539	0.00115	189.9
5th	77853.6	0.22756	0.00188	205.4
6th	54323.4	0.18991	0.00121	177.7

Table 3 Parameter of 28 teeth gear without torque

Condition	Energy (Joule)	RMS (Volt)	Mean (Volt)	Kurtosis
1st	541.6	0.01898	-0.00013	3.231
2nd	292.1	0.01392	0.00055	3.811
3rd	157.7	0.01024	0.00112	5.506
4th	572.0	0.01952	-0.00054	22.5
5th	1929.5	0.03565	0.00024	249.1
6th	961.7	0.02512	-0.00005	177.8

Table 4 Parameter of 28 teeth gear with torque

Condition	Energy (Joule)	RMS (Volt)	Mean (Volt)	Kurtosis
1st	484.3	0.02214	0.00018	3.127
2nd	205.6	0.01796	0.00129	3.278
3rd	735.6	0.01170	0.00136	4.297
4th	1586.9	0.03249	-0.00057	79.6
5th	18222.2	0.10946	0.00057	187.5
6th	8901.2	0.07691	-0.00076	214.2

AE signal analysis with one parameter could not be clearly used for defect detection form rotating machine.

AE signal analyzed two statistical parameters plot boundary by using x-axis as Kurtosis and y-axis as RMS and boundary radius equal double standard deviation for 30 sets parameter every condition. Plot between 25 and 28 teeth gear boundary was separated into 2 groups such as first group is defect free and crack condition as show Figure 7 – 8 and the second group is breakage condition as shown in Figure 9 – 10

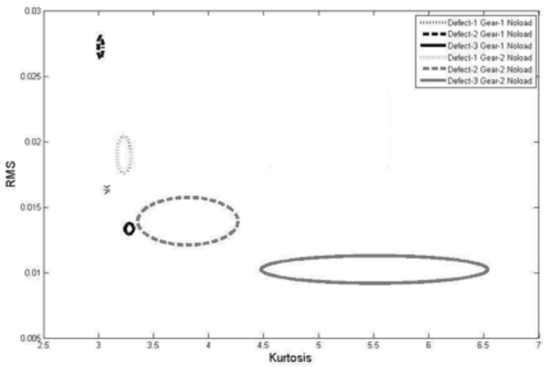


Figure 7 Boundary of 25 and 28 teeth gears shows 1st, 2nd and 3rd condition without torque

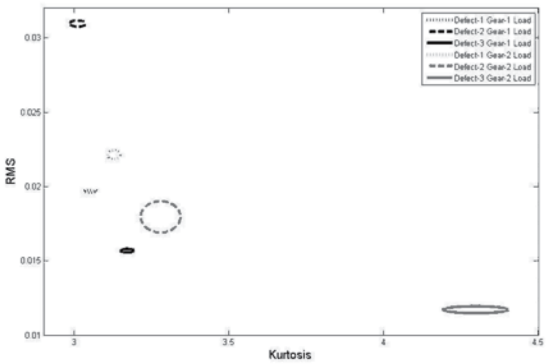


Figure 8 Boundary of 25 and 28 teeth gears shows 1st, 2nd and 3rd condition with torque

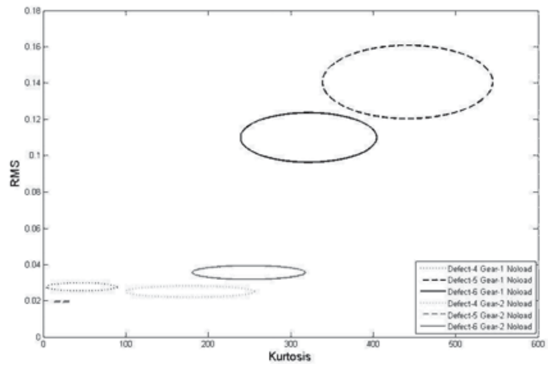


Figure 9 Boundary of 25 and 28 teeth gears shows 4th, 5th and 6th condition without torque

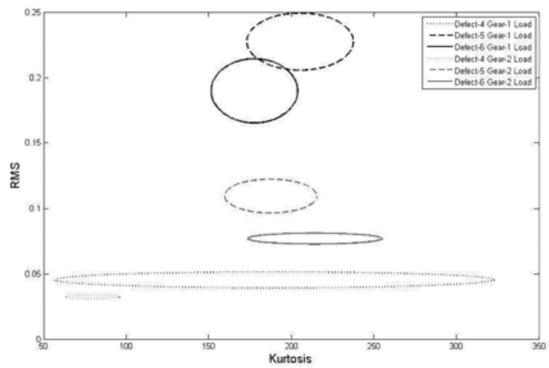


Figure 10 Boundary of 25 and 28 teeth gears shows 4th, 5th and 6th condition with torque

Accuracy test of condition boundary used 20 sets in other groups to prove condition boundary. Test parameter was in the condition boundary as show in Figure 11 - 18. Table 5 summarizes accuracy of condition monitoring with acoustic emission analysis

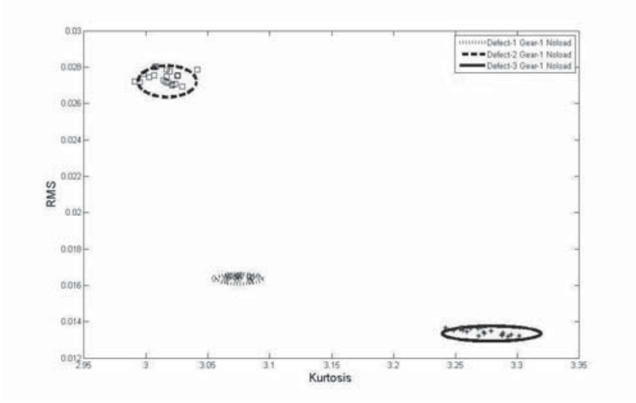


Figure 11 Accuracy testing of 25 teeth gear shows 1st, 2nd and 3rd condition without torque

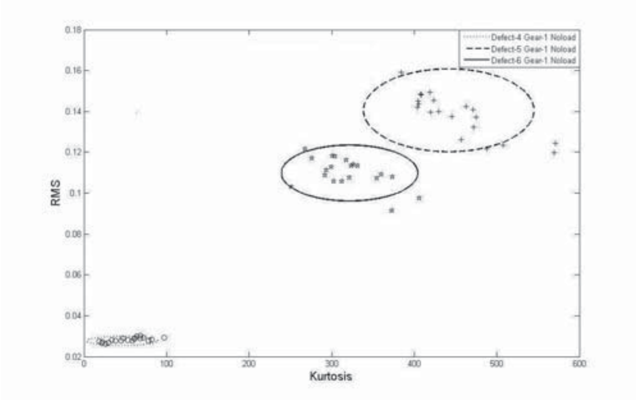


Figure 12 Accuracy testing of 25 teeth gear shows 4th, 5th and 6th condition without torque

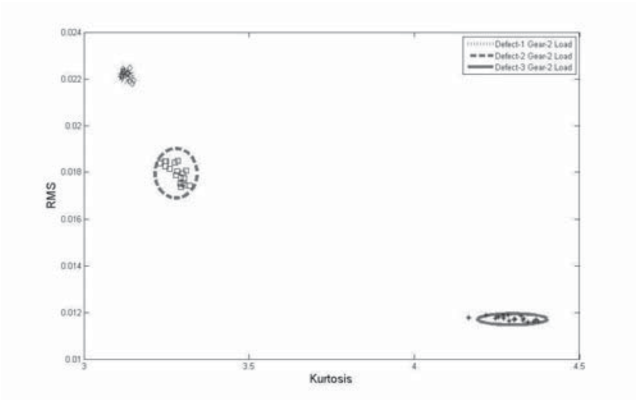


Figure 13 Accuracy testing of 25 teeth gear shows 1st, 2nd and 3rd condition with torque

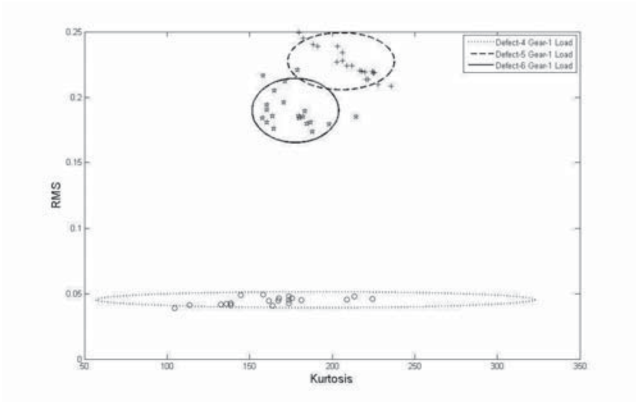


Figure 14 Accuracy testing of 25 teeth gear shows 4th, 5th and 6th condition with torque

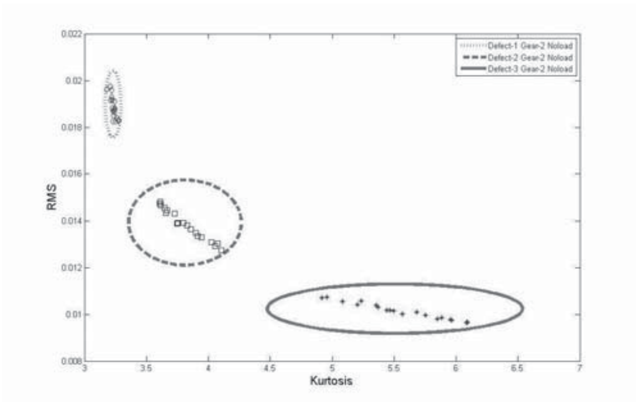


Figure 15 Accuracy testing of 28 teeth gear shows 1st, 2nd and 3rd condition without torque

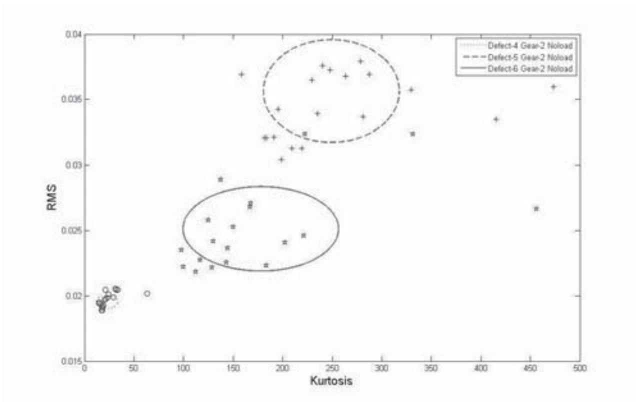


Figure 16 Accuracy testing of 28 teeth gear shows 4th, 5th and 6th condition without torque

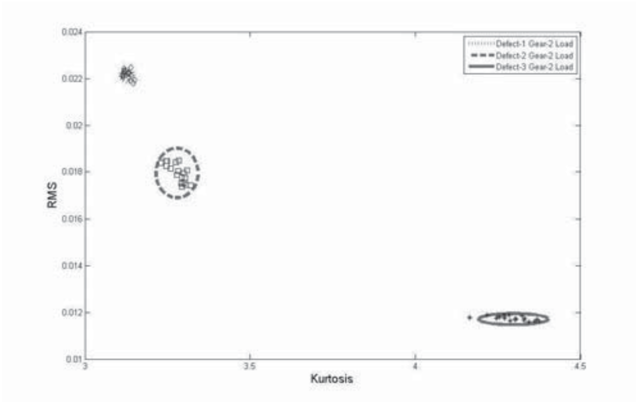


Figure 17 Accuracy testing of 28 teeth gear shows 1st, 2nd and 3rd condition with torque

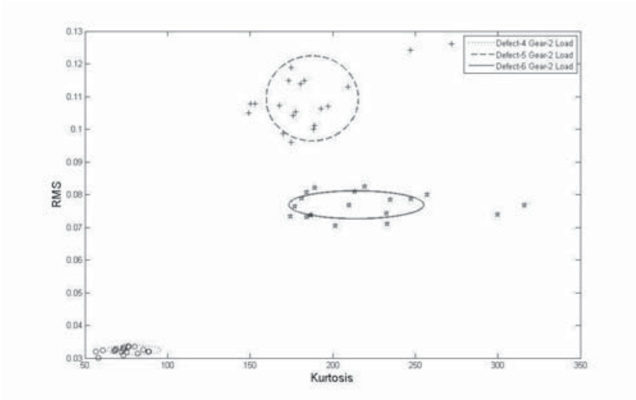


Figure 18 Accuracy testing of 28 teeth gear show 4th, 5th and 6th condition with torque

Table 5 Accuracy of condition monitoring with acoustic emission analysis

condition	25 teeth without torque	25 teeth with torque	28 teeth without torque	28 teeth with torque
1st	95%	80%	100%	80%
2nd	90%	85%	100%	100%
3rd	95%	95%	100%	95%
4th	90%	95%	65%	80%
5th	75%	80%	65%	75%
6th	85%	85%	70%	50%

5. Conclusion

The results from this study can be concluded that two statistical parameters with x-axis as Kurtosis and y-axis as RMS are able to plot the boundary radius equal to double standard deviation and can be evidently used for defect identification of the six defects with defect identification was performed with 84.5% accuracy within the condition boundary.

When conducting AE signal analysis for condition monitoring with one gear, it provided better result than conducting with several gears at a time. AE signal should be recorded when the gearbox is dynamically settled and stabilized signal variance.

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