

A comparative experimental study on the use of Acoustic Emission and vibration analysis for bearing defect identification and estimation of defect size

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Abstract

Vibration monitoring of rolling element bearings is probably the most established diagnostic technique for rotating machinery. The application of Acoustic Emission (AE) for bearing diagnosis is gaining ground as a complementary diagnostic tool, however, limitations in the successful application of the AE technique have been partly due to the difficulty in processing, interpreting and classifying the acquired data. Furthermore, the extent of bearing damage has eluded the diagnostician. The experimental investigation reported in this paper was centered on the application of the Acoustic Emission technique for identifying the presence and size of a defect on a radially loaded bearing. An experimental test-rig was designed such that defects of varying sizes could be seeded onto the outer race of a test bearing. Comparisons between AE and vibration analysis over a range of speed and load conditions are presented. In addition, the primary source of AE activity from seeded defects is investigated. It is concluded that AE offers earlier fault detection and improved identification capabilities than vibration analysis. Furthermore, the AE technique also provided an indication of the defect size, allowing the user to monitor the rate of degradation on the bearing; unachievable with vibration analysis.

Keywords: Acoustic Emission, bearing defect, condition monitoring, defect size, vibration analysis.

1. Introduction

Acoustic emissions (AE) are defined as transient elastic waves generated from a rapid release of strain energy caused by a deformation or damage within or on the surface of a material [1]. In this particular investigation, AE's are defined as the transient elastic waves generated by the interaction of two surfaces in relative motion. The interaction of surface asperities and impingement of the bearing rollers over the seeded defect on the outer race will generate AE's. Due to the high frequency content of the AE signatures typical mechanical noise (less than 20kHz) is eliminated.

2. Bearing defect diagnosis and Acoustic Emissions

There have been numerous investigations reported on applying AE to bearing defect diagnosis. Roger [2] utilised the AE technique for monitoring slow rotating anti-friction slew bearings on cranes employed for gas production. In addition, successful applications of AE to bearing diagnosis for extremely slow rotational speeds have been reported [3, 4]. Yoshioka and Fujiwara [5, 6] have shown that selected AE parameters identified bearing defects before they appeared in the vibration acceleration range. Hawman et al [7] reinforced Yoshioka's observation and noted that diagnosis of defect bearings was accomplished due to modulation of high frequency AE bursts at the outer race defect frequency. The modulation of AE signatures at bearing defect frequencies has also been observed by other researchers [8, 9, 10]. Morhain et al [11] showed successful application of AE to monitoring split bearings with seeded defects on the inner and outer races.

This paper investigates the relationship between AE r.m.s, amplitude and kurtosis for a range of defect conditions, offering a more comparative study than is presently available in the public domain. Moreover, comparisons with vibration analysis are presented. The source of

AE from seeded defects on bearings, which has not been investigated to date, is presented showing conclusively that the dominant AE source mechanism for defect conditions is asperity contact. Finally a relationship between the defect size and AE burst duration is presented, the first known detailed attempt.

3. Experimental Test Rig and Test Bearing

The bearing test rig employed for this study had an operational speed range of 10 to 4000rpm with a maximum load capability of 16kN via a hydraulic ram. The test bearing employed was a Cooper split type roller bearing (01B40MEX). The split type bearing was selected as it allowed defects to be seeded onto the races, furthermore, assembly and disassembly of the bearing was accomplished with minimum disruption to the test sequence, see figure 1. Characteristics of the test bearing (Split Cooper, type 01C/40GR) were:

- Internal (bore) diameter, 40mm
- External diameter, 84mm
- Diameter of roller, 12mm
- Diameter of roller centers, 166mm
- Number of rollers, 10

Based on these geometric properties the outer race defect frequency was determined at '4.1X' (4.1 times the rotation shaft speed). The layout of the test rig is illustrated in figure 2, with the load zone at top-dead-centre.

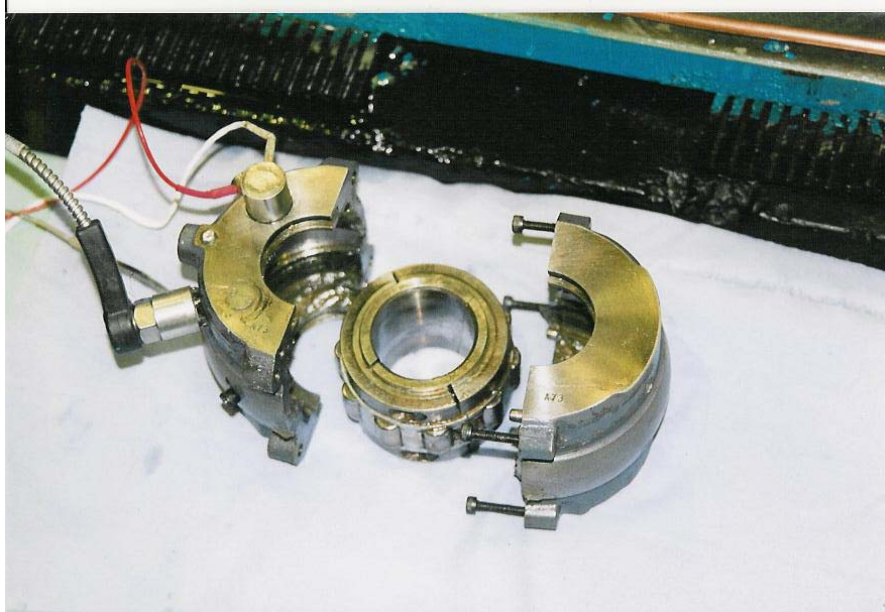


Figure 1 Bearing Test Rig

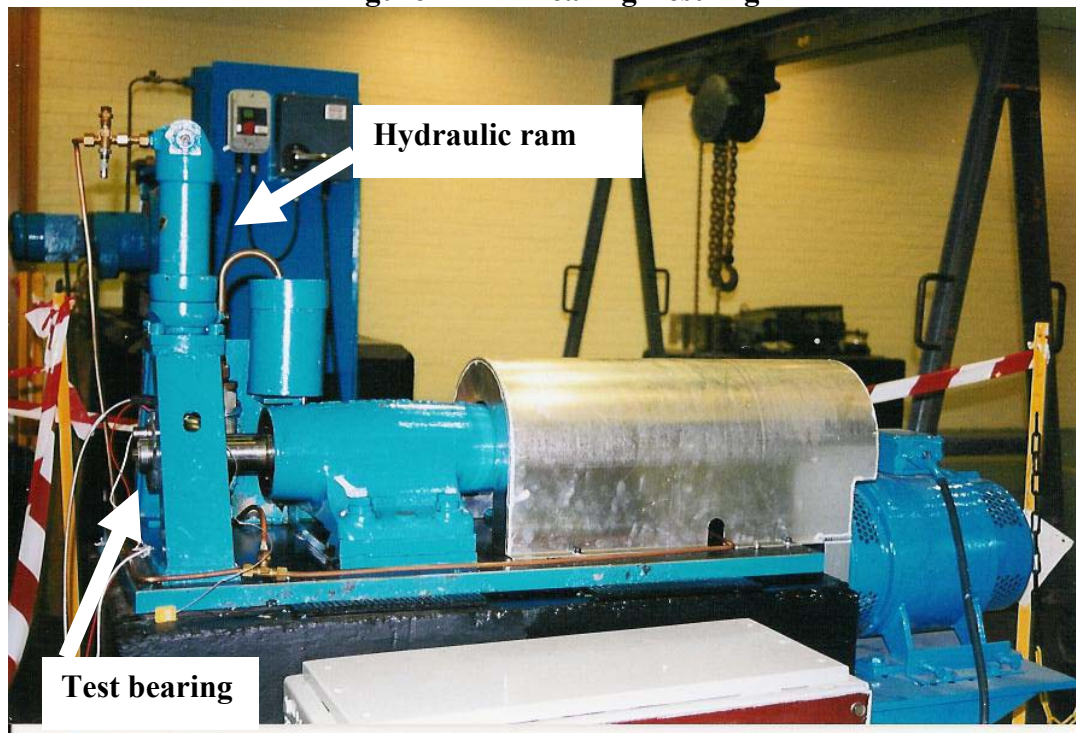


Figure 2 Test rig layout

4. Data Acquisition System and signal processing

The transducers employed for vibration and AE data acquisition were placed directly on the housing of the bearing, see figure 1. A piezoelectric type AE sensor (Physical Acoustic Corporation type WD) with an operating frequency range of 100 kHz – 1000 kHz was employed whilst a resonant type accelerometer, with a flat frequency response between 10 Hz and 8000 Hz (Model 236 Isobase accelerometer, ‘Endevco Dynamic Instrument Division’) was used for vibration measurement. Pre-amplification of the acoustic emission signal was set at 40dB. The signal output from the pre-amplifier was connected (i.e. via BNC/coaxial cable) directly to a commercial data acquisition card. The broadband piezoelectric transducer was differentially connected to the pre-amplifier so as to reduce electromagnetic noise through common mode rejection. This acquisition card provided a sampling rate of up to 10MHz with 16-bit precision giving a dynamic range of more than 85 dB. In addition, anti-aliasing filters (100 KHz to 1.2MHz) were built into the data acquisition card. A total of 256,000 data points were recorded per acquisition (data file) at a sampling rates of 2MHz, 8MHz and 10MHz, dependent on simulation. Twenty (20) data files were recorded for each simulated case, see experimental procedure. The acquisition of vibration data was sampled at 2.5 KHz for a total of 12,500 data points.

Whilst numerous signal processing techniques are applicable for the analysis of acquired data, the authors have opted for simplicity in diagnosis, particularly if this technique is to be readily adopted by industry. The AE parameters measured for diagnosis in this particular investigation were amplitude, r.m.s, and kurtosis. These were compared with identical parameters from vibration data. It is worth stating that the selected parameters for AE diagnosis are also typical for vibration analysis.

The most commonly measured AE parameters for diagnosis are amplitude, r.m.s, energy, counts and events [12]. Counts involve determining the number of times the amplitude exceeds a preset voltage (threshold level) in a given time and gives a simple number characteristic of the signal. An AE event consists of a group of counts and signifies a transient wave. Tan [13] cited a couple of drawbacks with the conventional AE count technique. This included dependence of the count value on the signal frequency. Secondly, it was commented that the count rate was indirectly dependent upon the amplitude of the AE pulses.

By far the most prominent method for vibration diagnosis is the Fast Fourier Transform. This has the advantage that a direct association with the characteristics of rotating machine can be obtained. Other vibration parameters include ‘peak-to-peak’, ‘zero-to-peak’, r.m.s, crest factor and kurtosis. The drawback with amplitude parameters is that they can be influenced by phase changes and spurious electrical spikes. The kurtosis value increases with bearing defect severity however, as severity worsens the kurtosis value can reduce. The r.m.s parameter is a measure of the energy content of the signal and is seen as a more robust parameter. However, whilst r.m.s may show marked increases in vibration with degradation, failures can occur with only a slight increase or decrease in levels. For this reason r.m.s measurement alone is sometimes insufficient.

5. Experimental procedure

Two test programmes were undertaken.

- An investigation to ascertain the primary source of AE activity from seeded defects on bearings was undertaken, in addition to determining the relationship between defect size, AE and vibration activity. In an attempt to identify the primary source of

AE activity, a surface topography (Form Talysurf 120L; stylus used had a 2 μ m radius diamond tip) of the various defects was taken. Furthermore, two types of defect conditions were simulated; firstly, a seeded defect with a surface discontinuity that did not result in material protruding above the average surface roughness of the outer race. The second defect type resulted in material protrusions that were clearly above the average surface roughness.

- The second test programme aimed to establish a correlation between AE activity with increasing defect size. This was accomplished by controlled incremental defect sizes at a fixed speed.

Prior to defect simulations for all test programmes, baseline, or defect free, recordings were undertaken for twelve running conditions; four speed (600, 1000, 2000 and 3000 rpm) and three load conditions (0.1, 4.43KN and 8.86KN). Defects were simulated with the use of an engraving machining employing a carbide tip.

6. Test programme-1; AE source identification and defects of varying severities

Five test conditions of varying severities were simulated on the outer race of the test bearing which was positioned in the load zone; top-dead-centre for this particular test-rig configuration, see table 1. In addition, the nomenclature used to label all test conditions is detailed in table 1. The test conditions were:

- Baseline or defect free condition in which the bearing was operated with no defect on the outer-race. Figure 3 shows a visual condition of the race and a surface roughness map (maximum 0.5 μ m).
- A point defect engraved onto the outer race which was approximately 0.85 x 0.85mm, see figure 4. This defect condition had material of the outer race protruding approximately 4

μm above the bearing maximum surface roughness.

- A line defect, approximately 5.6 x 1.2 mm, see figure 5.
- A rough defect, approximately 17.5 x 9.0 mm, see figure 6.
- A smooth defect in which a surface discontinuity, not influencing the average surface roughness, was simulated. In this particular instance a grease hole on the outer race matched the requirements, see figure 7. From figure 7 it is evident that the point of discontinuity of the surface does not have a protrusion above the surface roughness as evident for the 'point' or 'line' defect conditions. The main purpose of this simulation is to observe if any changes in the load distribution will lead to generation or changes in AE activity in comparison to a defect free condition.

All defects were run under four speeds (600, 1000, 2000 and 3000 rpm) and three different loads (0.1, 4.43 and 8.86 KN). It must be noted that the defect length is along the race in the direction of the rolling action and the defect width is across the race.

Table 1 **Notation for test programme-1 with seeded defect dimensions**

Test programme -1: Defects of Different Severities	Defect Type (W x L) mm		Speed (rpm)		Load (kN)	
	N	Noise (No Defect)	S1	600	L0	0.1
	SD	Smooth Defect	S2	1000	L1	4.43
	PD	Point Defect (0.85x0.85) mm	S3	2000	L2	8.86
	LD	Line Defect (5.6x1.2) mm	S4	3000		
	RD	Big Rough Defect (17.5x9.0) mm				

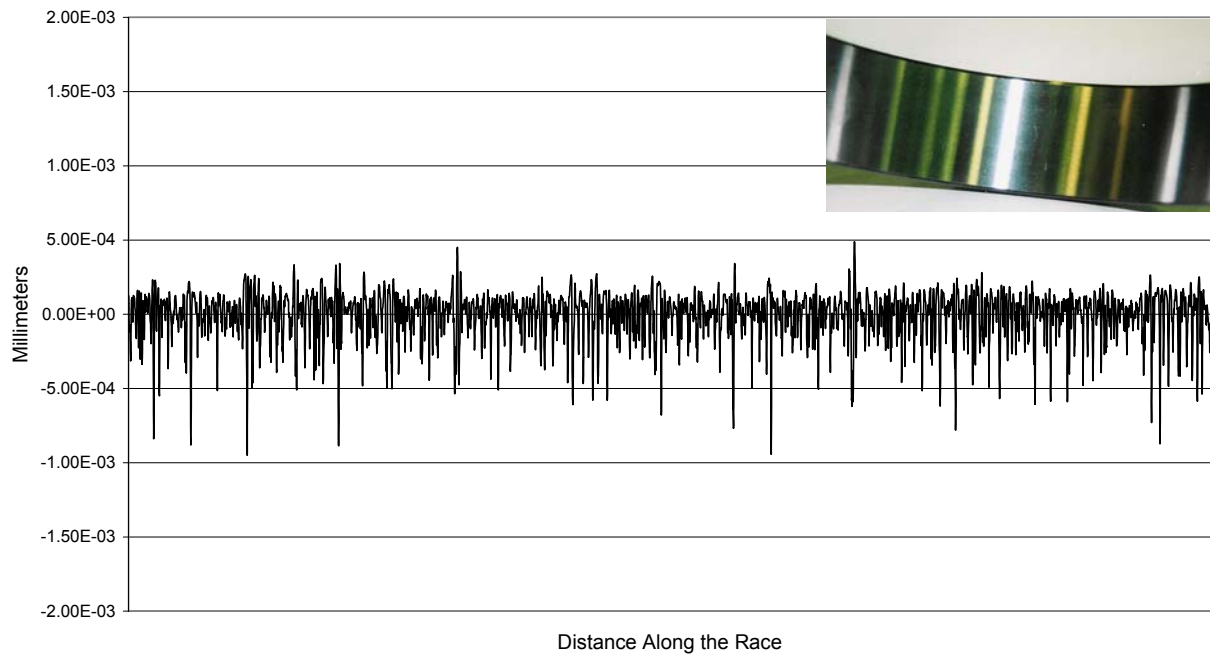


Figure 3 **Surface profile of defect free condition**

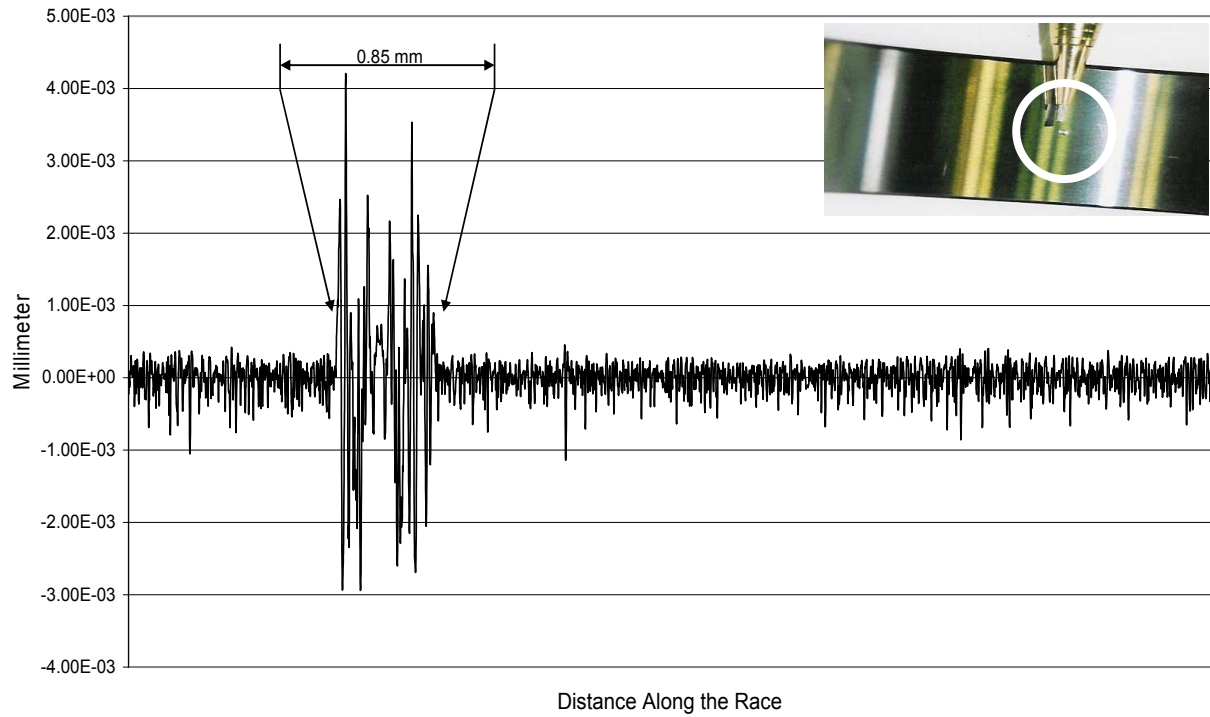


Figure 4 Surface profile of point defect condition

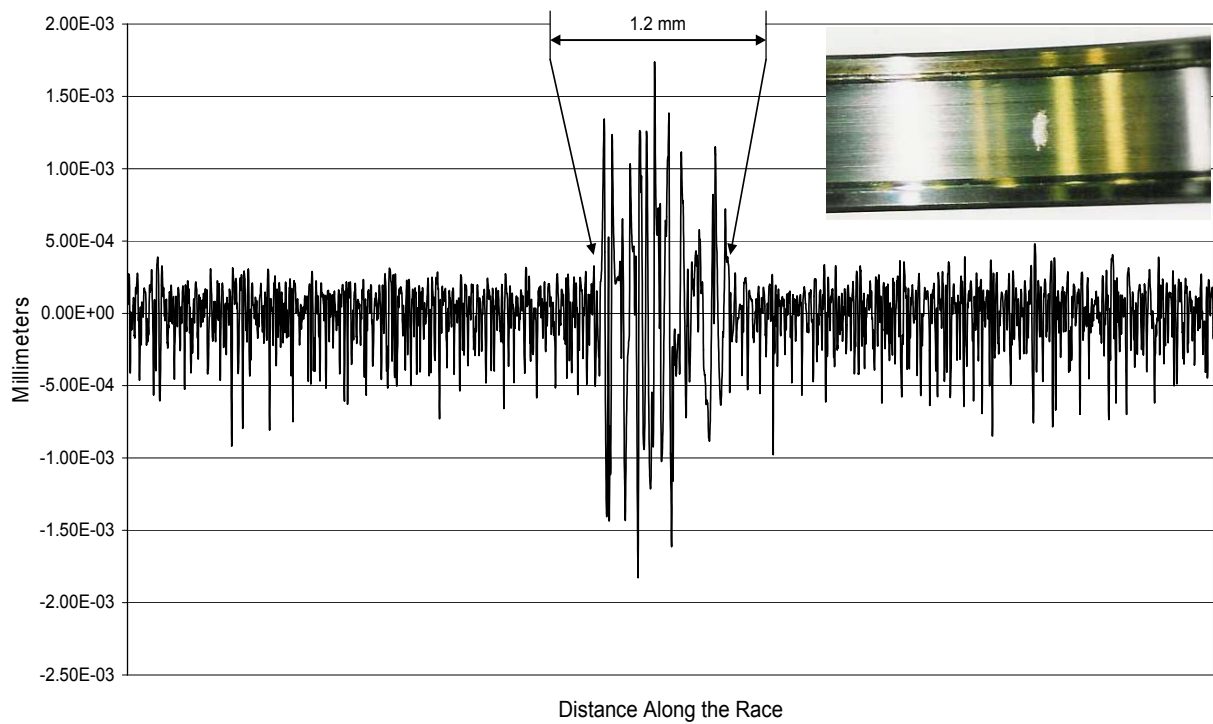


Figure 5 Surface profile of a line defect condition



Figure 6 **Rough defect condition**

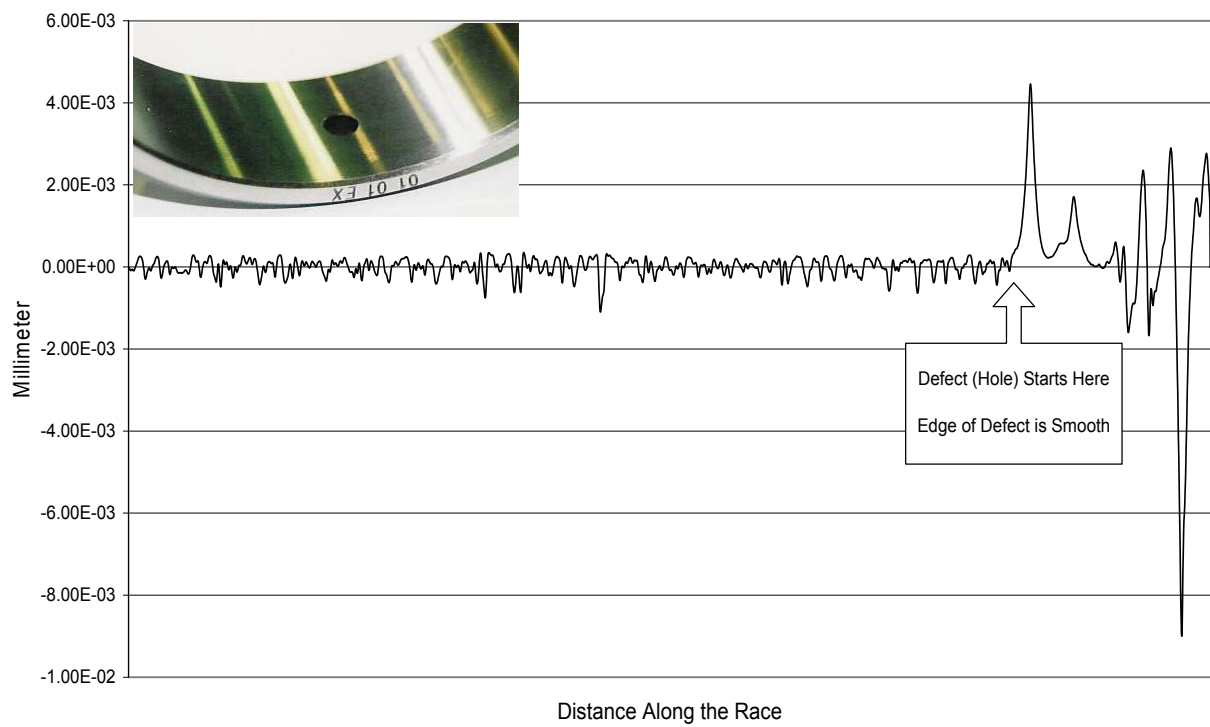


Figure 7 **Surface profile of a smooth defect condition**

7. Test programme-2; Defects of varying size

For this particular test programme, two experiments (E1 and E2) were carried out to authenticate observations relating AE to varying defect sizes. Each experiment included seven defects of different lengths and widths, see table 2. A sample defect is shown in figure 8. In experiment-1 (E1), a point defect (D1) was increased in length in three steps (D2 to D4) and then increased in width in three more steps (D5 to D7). However, in experiment-2 (E2), a point defect was increased in width and then in length interchangeably from D1 to D7. Both experiments were run at 2000 rpm and at a load of 4.4kN. The AE sampling rates for the first and second experiments are 8MHz and 10 MHz respectively. In experiment-2, vibration was acquired in addition to AE for comparative purposes.

Table 2 Notation for test programme-2 with seeded defect dimensions

Test Programme 2: Defects of Different Sizes	Experiment 1		Experiment 2	
	Defect Size, (width x length) mm		Defect Size, (width x length) mm	
	E1-D0	No defect	E2-D0	No defect
	E1-D1	0.85 x 0.85 mm	E2-D1	0.85 x 1.35 mm
	E1-D2	1 x 2.95 mm	E2-D2	2. x 1.35 mm
	E1-D3	1 x 7.12 mm	E2-D3	2 x 4 mm
	E1-D4	1 x 15.83 mm	E2-D4	4 x 4 mm
	E1-D5	3.98 x 15.83 mm	E2-D5	8 x 4 mm
	E1-D6	8.66 x 15.83 mm	E2-D6	13 x 4 mm
	E1-D7	13.6 x 15.83 mm	E2-D7	13x 10 mm

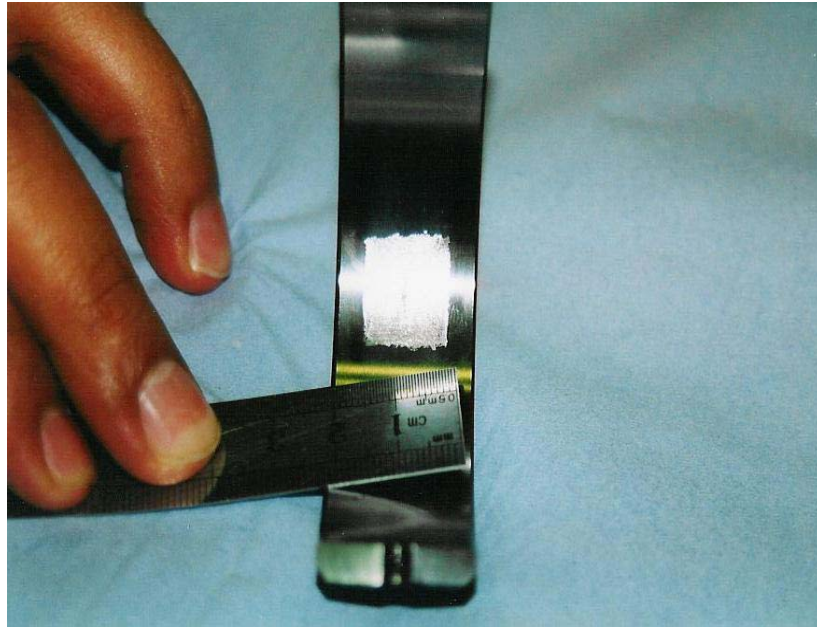


Figure 8 The largest seeded defect, E1-D7, 13.6 x 15.83 mm

8. Analysis Procedure

If the defects simulated were to produce AE transients, as each rolling element passed the defect, it was envisaged that the AE bursts would be detected at a rate equivalent to the outer race defect frequency ('4.1X'). In addition, it was also anticipated that the defect frequency would be observed in the vibration frequency range.

For test programme 1 (defects of different severities) AE in time domain and vibrations in frequency domain were analysed. Furthermore, the AE and vibration r.m.s, maximum amplitude and kurtosis values were calculated. Approximately twenty AE data files were captured per fault simulated. Each data file was equivalent to one, two, four and six revolutions at speeds of 600, 1000, 2000 and 3000rpm respectively. Every AE data file (for all simulations) was broken into sections equivalent to one revolution. For instance, at 2000rpm the AE data was split into four equal sections, each representing one shaft revolution.

The diagnostic parameters of r.m.s, etc, were calculated for each shaft revolution and averaged for all data files. This implied that at 2000rpm, and for twenty data files, a total of eighty AE r.m.s values were calculated and the value presented is the average of the eight values. For vibration analysis, two data files were acquired for each simulation. This was equivalent to 50, 83, 166 and 250 revolutions per data file at speeds of 600, 1000, 2000 and 3000rpm respectively. The exact procedure for calculating the AE parameters was employed on the vibration data.

For test programme-2 observations of AE burst duration, r.m.s and amplitude for the various defect sizes were undertaken. The burst duration was obtained by calculating the duration from the point at which the AE response was higher than the underlying background noise level to the point at which it returned to the underlying noise level. This procedure was undertaken for every data file and the average value for each simulated case is presented.

9. Data Analysis; Test Programme-1

9.1 Observations of AE time waveform

As already stated the outer race defect frequency was calculated for the various test speeds; 41, 69, 137 and 205Hz at 600, 1000, 2000 and 3000rpm respectively. Typical AE and vibration time waveforms for two different conditions are displayed in figures 9 and 10. It was noted that for all defects conditions, other than the smooth defect, AE burst activity was noted at the outer race defect frequency. Observations of AE time waveforms from noise and smooth defect conditions showed random AE bursts that occurred at a rate which could not be related to any machine phenomenon. Correspondingly, such transient bursts associated with the presence of the defect were not observed on vibration waveforms, but more

interestingly, the outer race defect frequency was not observed on the frequency spectra of most vibration data, except at one defect condition; rough defect, 3000rpm, load 0.1kN, see figure 11.

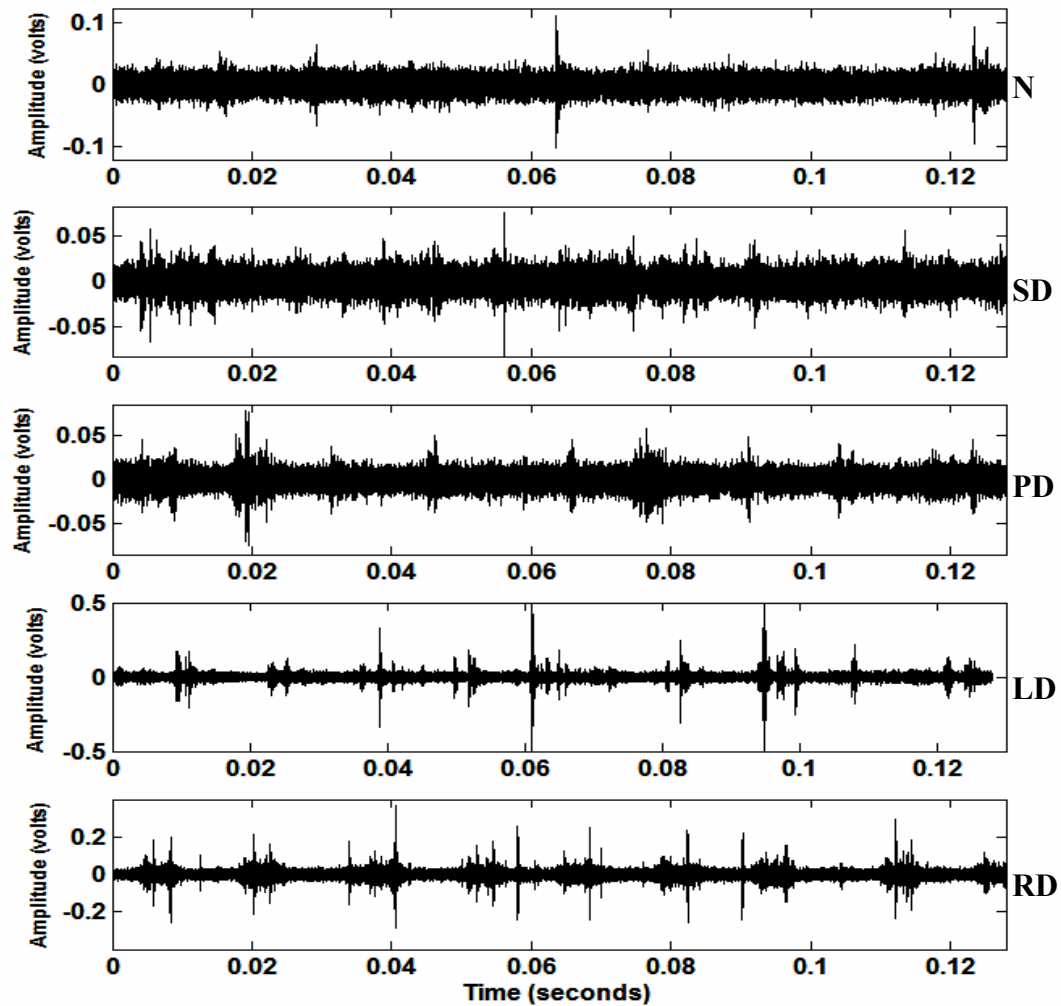


Figure 9 AE time waveforms for all defects at a speed of 1000 rpm and a load 4.43kN

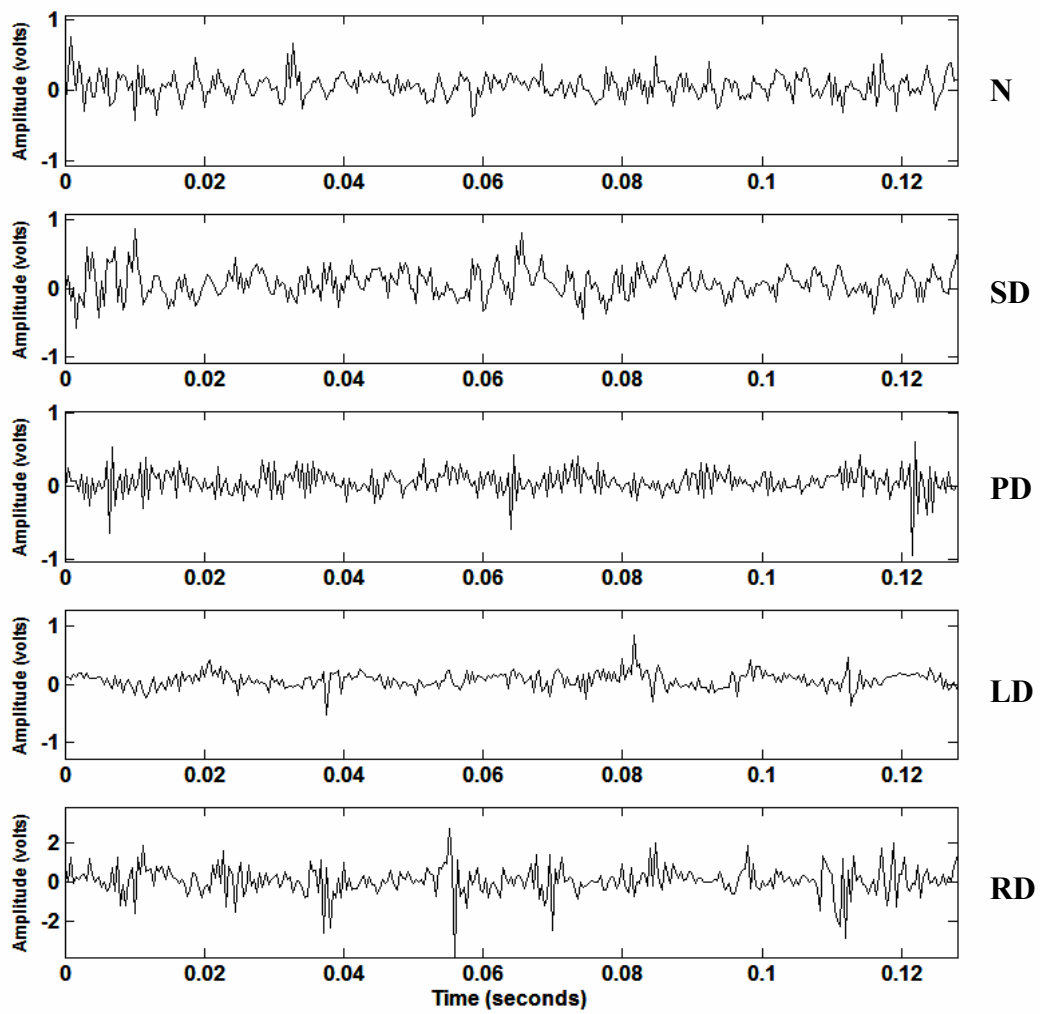


Figure 10 **Vibration time waveforms for all defects at a speed of 1000 rpm and a load 4.43kN**

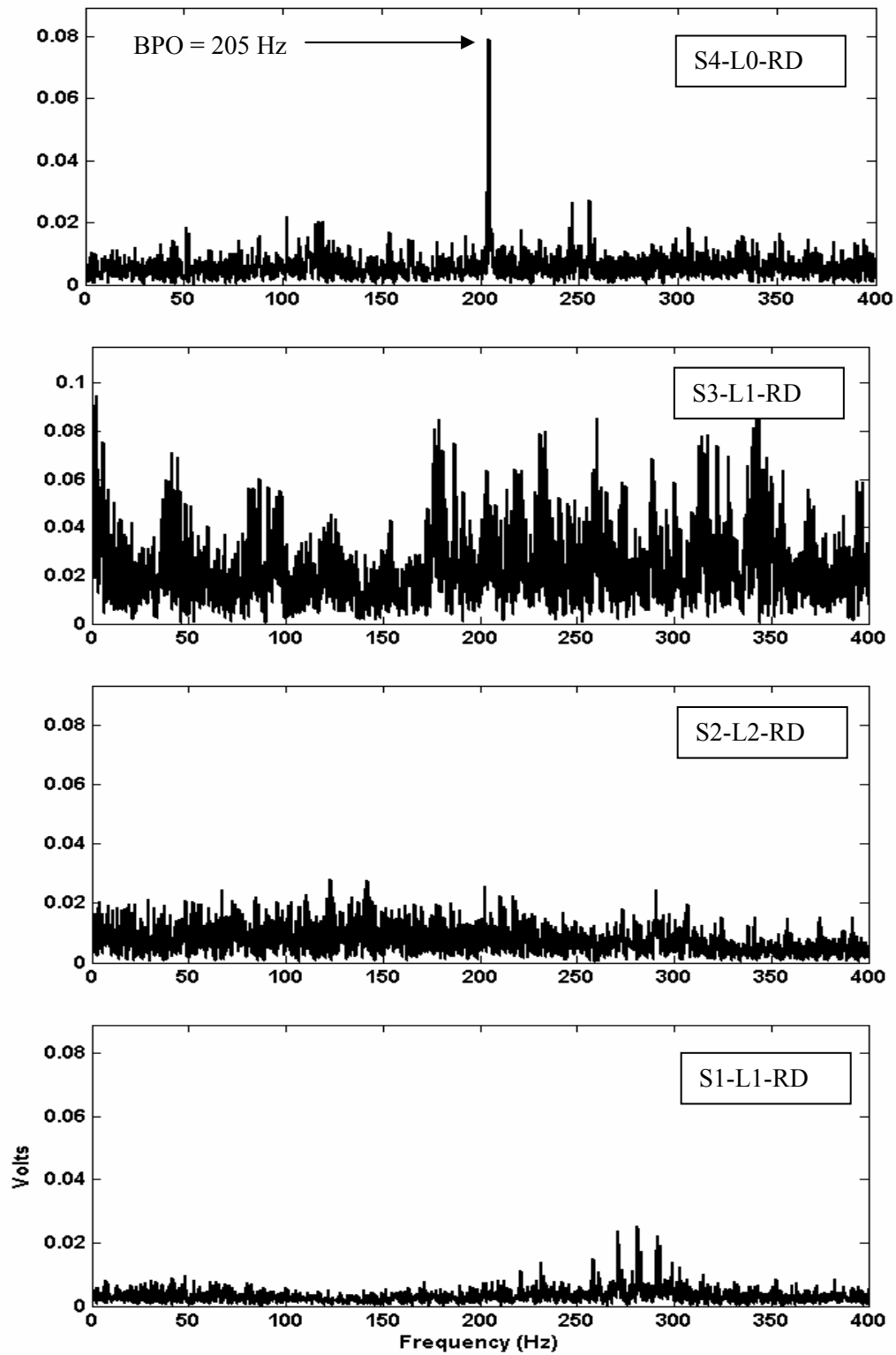


Figure 11 Sample vibration data in the frequency domain

9.2 Observations of r.m.s values

The r.m.s values of AE and vibration signatures for all defect and defect free conditions were compared for increasing speeds, see figures 12 and 13. For all test conditions, the AE r.m.s value increased with increasing the speed at a fixed load. It was also noted that the AE r.m.s values of noise and smooth defect were similar while AE r.m.s values increased with increased defect severity; point, line and rough defects respectively. For a fixed speed and variable load it was observed that in general AE r.m.s increased with load, which increased also with increasing defect severity, see figure 1 of appendix B. The vibration r.m.s values showed a relatively small increase with increasing defect size, however, a clear increase in vibration r.m.s was observed for the rough defect, see figure 13. Table 1 in appendix A highlights the percentage change of r.m.s values for different defect sizes, emphasising the sensitivity of AE to defect size progression, see figures 14 and 15. The percentage values presented in Appendix A and figures 14 and 15 were obtained by relating all speed and load defect simulations to the corresponding speed and load condition for the defect free (noise) simulation. Figures 1 and 2 of appendix B show the vibration and AE r.m.s values for increasing loads at fixed speeds.

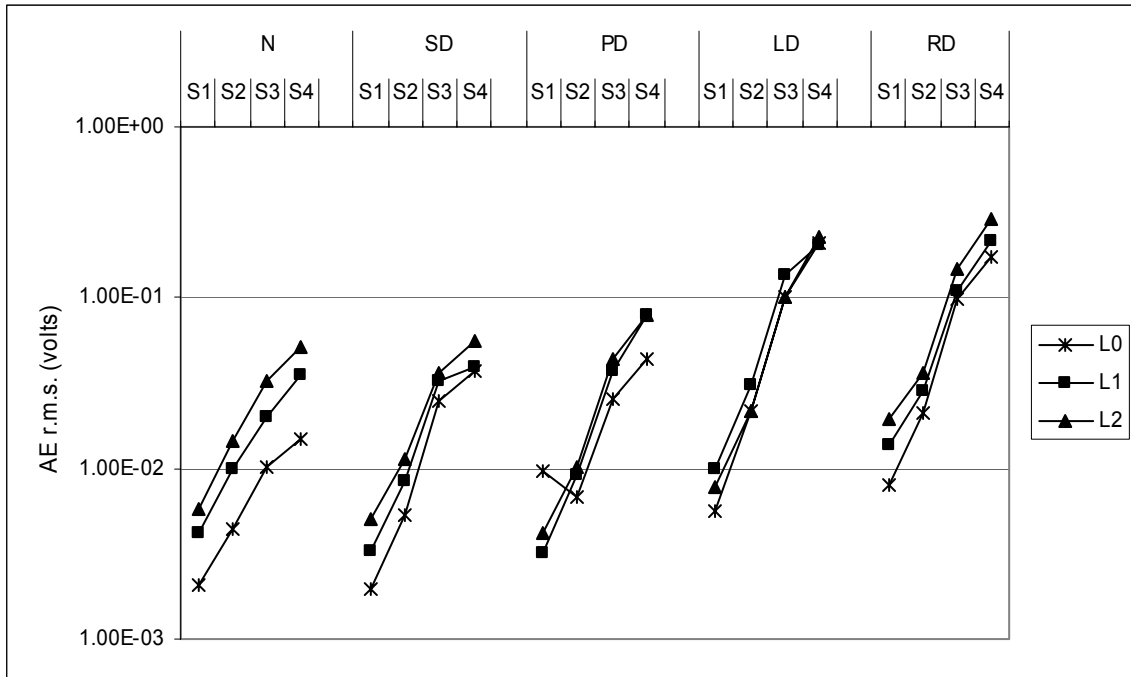


Figure 12 AE r.m.s of different defects; increasing speeds at a fixed Load

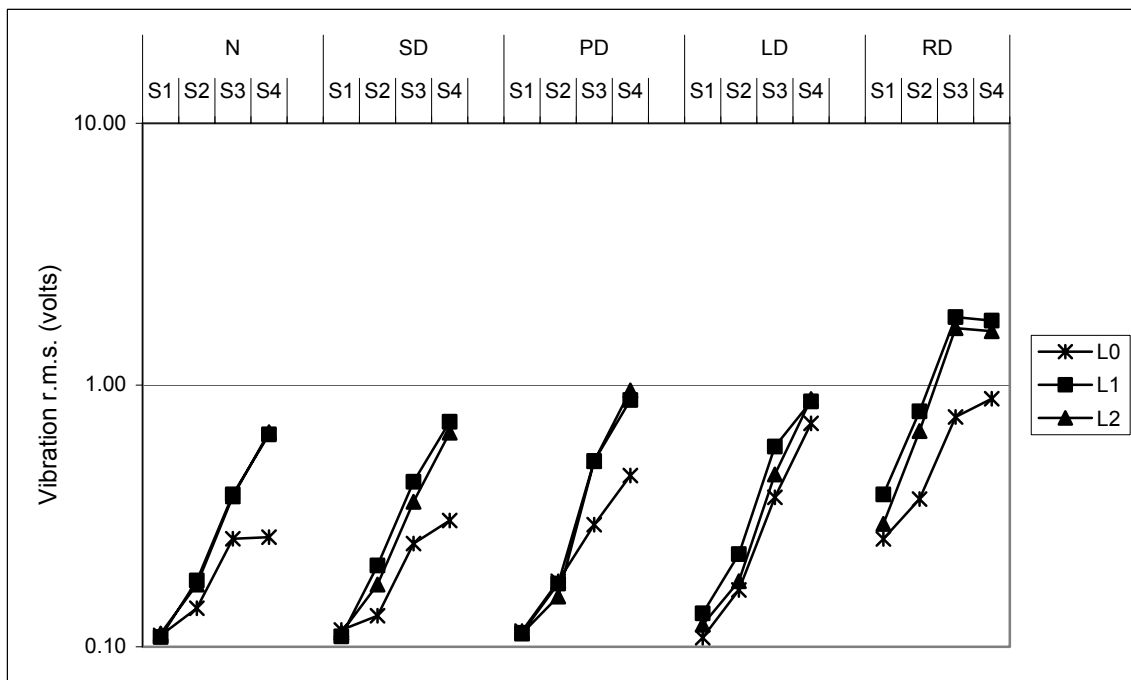


Figure 13 Vibration r.m.s of different defects; increasing speeds at a fixed Load

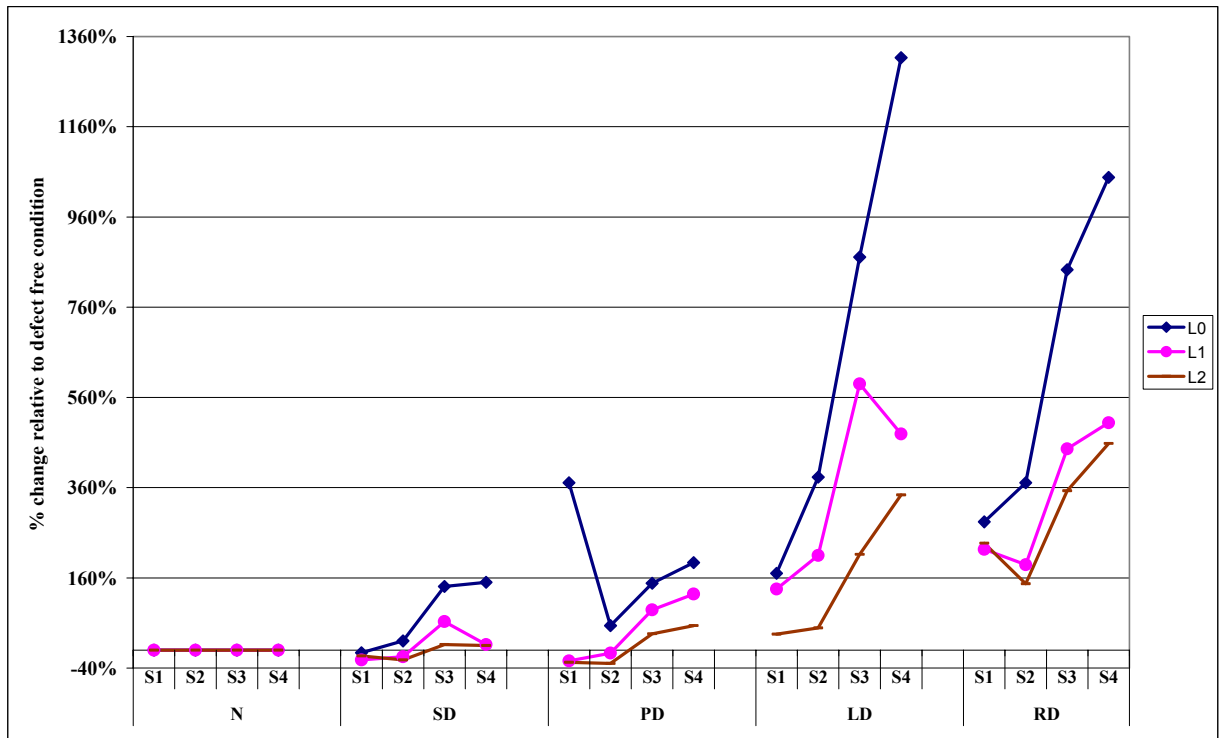


Figure 14 Percentage change in AE r.m.s

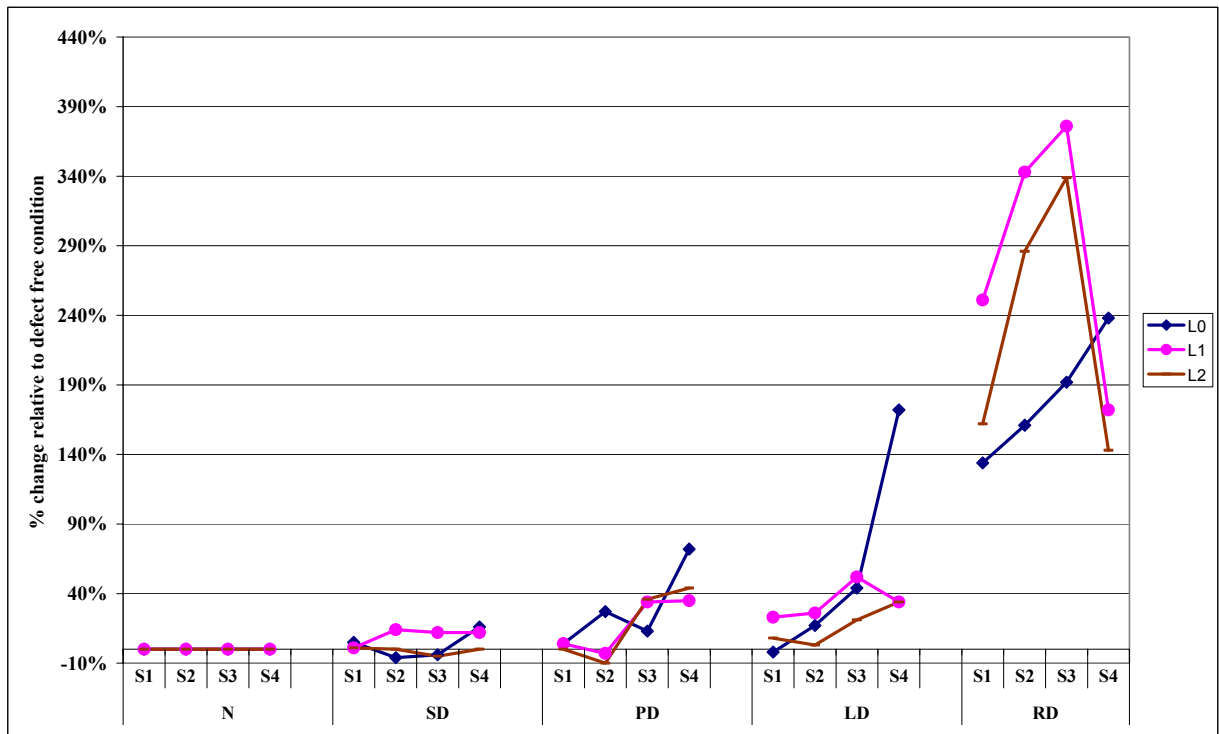


Figure 15 Percentage change in vibration r.m.s

9.3 Observations of maximum amplitude

It was noted that AE max amplitude increased with increasing speed for a fixed load, see figure 16. Also it was evident that as the defect size was increased, the maximum AE amplitude increased. The maximum AE amplitude increased from noise condition to the point defect and increased further for the line defect. The maximum amplitude for the rough defect was comparable to the ‘line’ defect. Again it was noted that values for ‘noise’ and ‘smooth’ conditions were similar. Vibration amplitude values were similar for all defect conditions except for the rough defect, see figure 17. Table 2 in appendix A highlights the percentage changes of maximum amplitude values for different defect sizes. These were determined as detailed in the previous section. Figures 3 and 4 of Appendix B show the vibration and AE maximum amplitude values for increasing loads at fixed speeds.

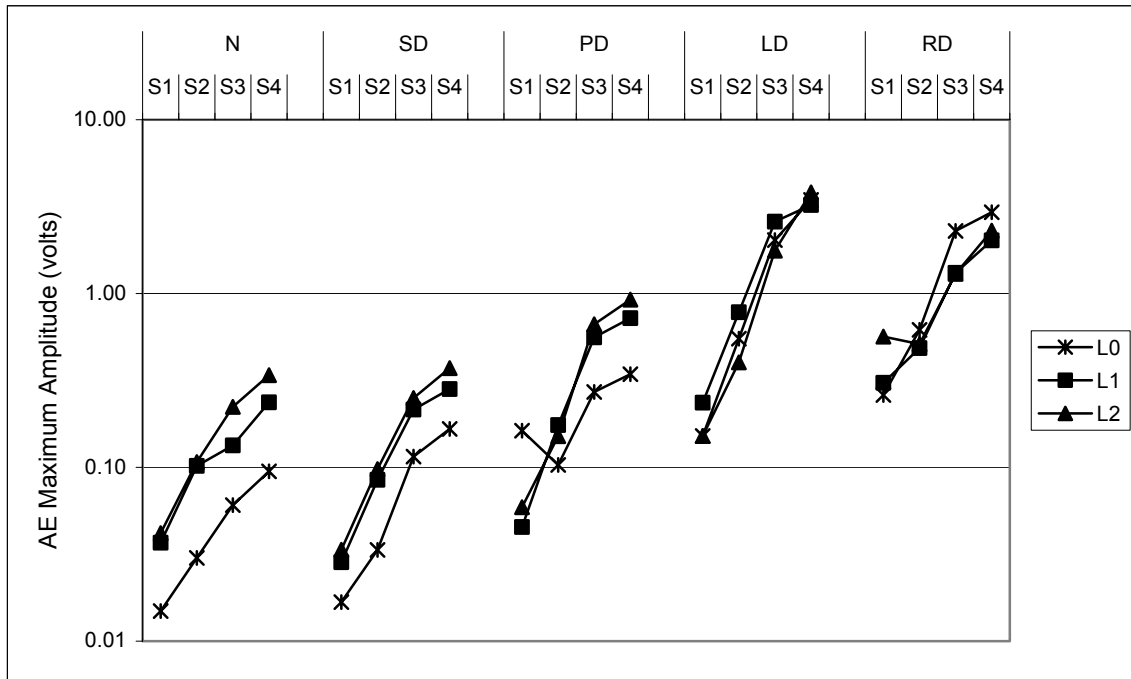


Figure 16 AE max amplitude of different defects at increasing speeds and fixed load

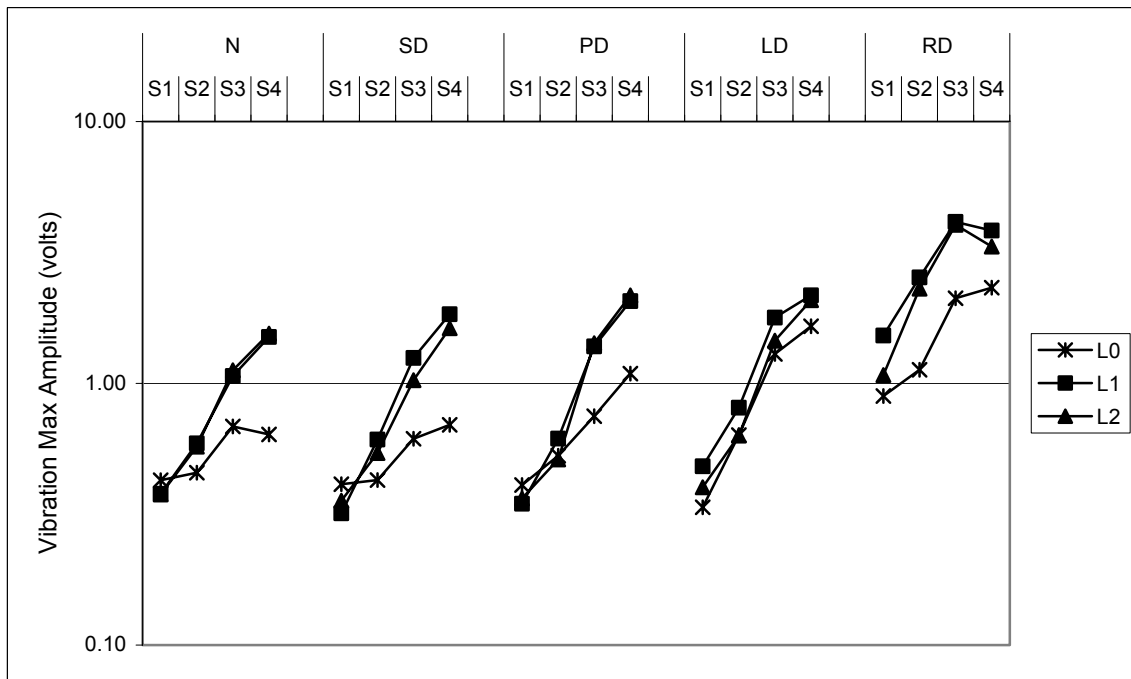


Figure 17 Vibration max amplitude of different defects at increasing speeds and fixed load

9.4 Observations of Kurtosis

Kurtosis is a measure of the peakness of a distribution and is widely established as a good indicator of bearing health for vibration analysis. For a normal distribution, kurtosis is equal to 3. The AE kurtosis values for the noise signal (N) and the smooth defect (SD) were approximately '3', see figure 18, as expected for a random distribution. It was noted that as defect size increased from 'noise' to 'point' to 'line', the kurtosis values increased accordingly. For the worst defect condition it was observed that the kurtosis values were lower than for the preceding defect condition (line defect). This was not unexpected because as the defect condition worsens it is known that kurtosis values will decrease; figure 18 depicts this observation. Kurtosis results for vibration showed similar values for all defect simulations apart from the rough defect where a relative increase was noted, see figure 19 Table 3 in appendix A highlights the change of kurtosis values for different defect sizes, emphasising the sensitivity of AE to defect size progression. Figures 5 and 6 of Appendix B show the vibration and AE kurtosis values for increasing loads at fixed speeds.

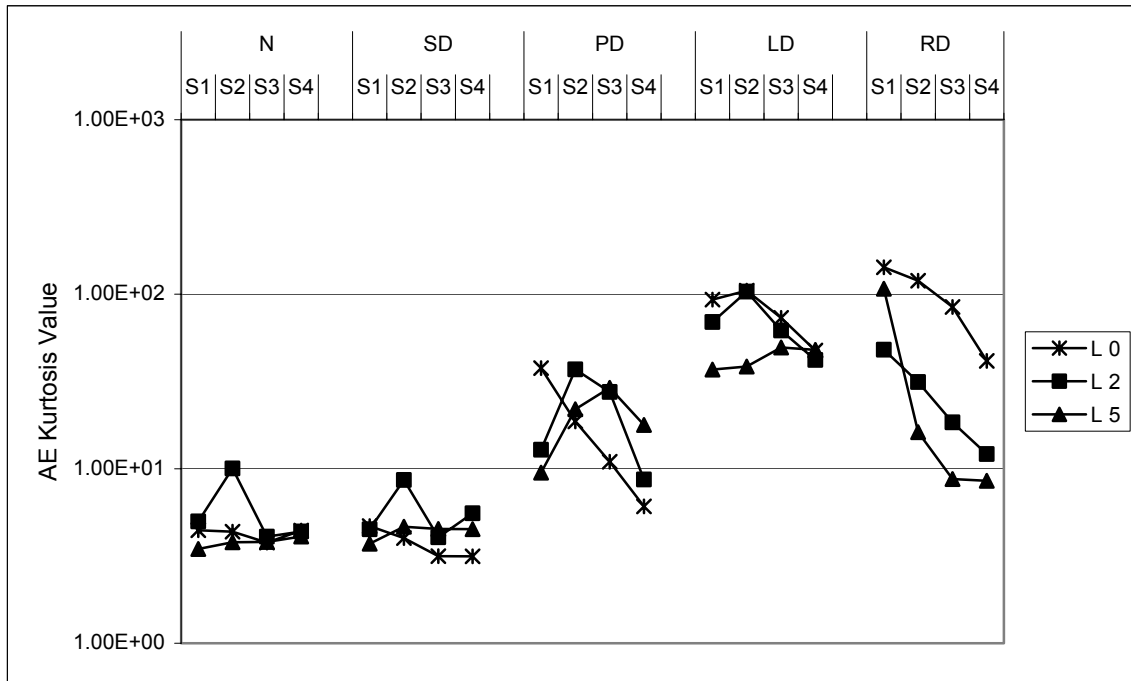


Figure 18 AE kurtosis of different defects at increasing speeds and fixed load

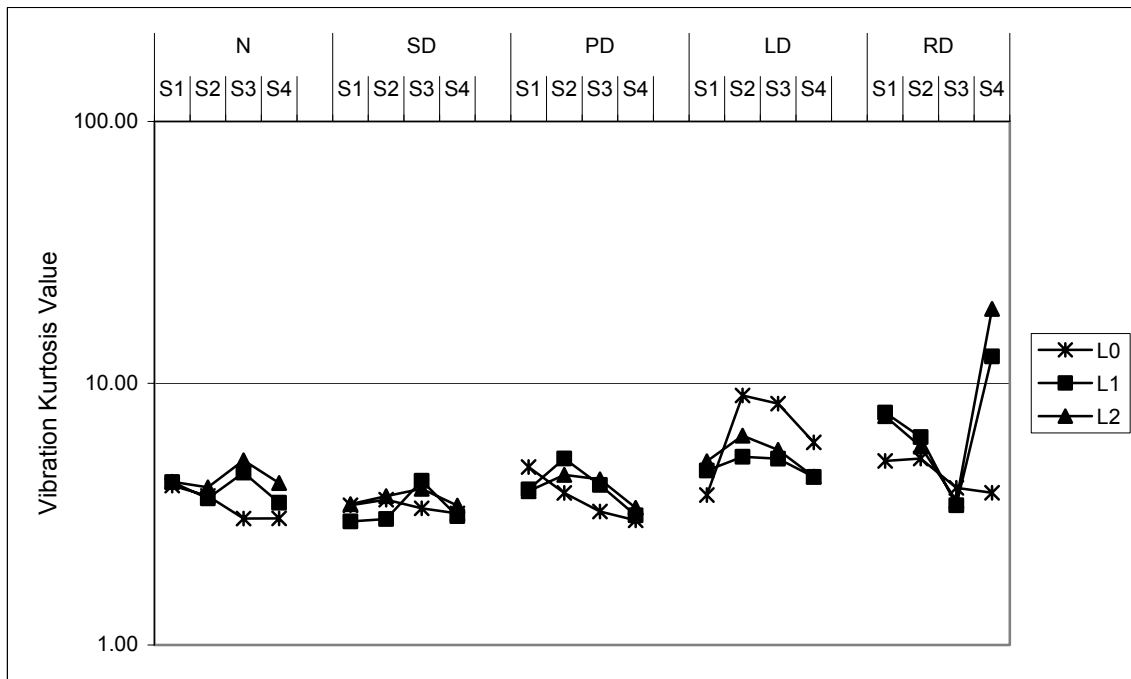


Figure 19 Vibration kurtosis of different defects at increasing speeds and fixed load

10. Data analysis: Test programme-2

The analysis of this test program was centered on AE time domain observations.

10.1. Observations of experiment-1 (E1)

This experiment included seven defect conditions; D1 to D4 had a fixed width with increasing length while defects D4 to D7 had a fixed length with increasing width; see table 2. From observations of the AE time waveforms, AE bursts were clearly evident from defects D4 to D7, see figure 20. The x-axis in these figures corresponds to one shaft revolution at 2000rpm. For defects D4 to D7 the width of associated defect AE burst was measured in an attempt to relate the AE burst duration to the defect size. Interestingly, the bursts with equal defect length D4 to D7 had near identical burst durations, see figure 21. For the other defects (D1 to D3), the burst duration could not be separated from underlying background noise, most probably due to the size of the seeded defect. Also it was observed that the ratio of amplitude of the AE burst to underlying operational background noise increased incrementally from D4 through to D7, as the defect increased in width, see table 3.

Table 3 Burst to noise ratio's for defects of fixed defect length (15.8mm)

Defect	Burst duration (second)	Burst amplitude (volt)	Noise amplitude (volt)	Burst to noise ratio
D4	0.0061	0.13	0.09	1.4:1
D5	0.0056	0.18	0.09	2.0:1
D6	0.0056	0.33	0.11	3.0:1
D7	0.0056	0.46	0.10	4.6:1

Two conclusions can be drawn, firstly, increasing the defect width increased the ratio of burst amplitude to operational noise (i.e., the burst signal was increasingly more evident above the operational noise levels, see figure 20). Secondly, it was deduced that increasing the defect length increased the burst duration. To confirm this, a second experiment was performed utilizing the same running conditions but with different defect size combinations.

Furthermore, the second test was undertaken to ensure repeatability, and a new bearing of identical type to that used in experiment-1 was employed.

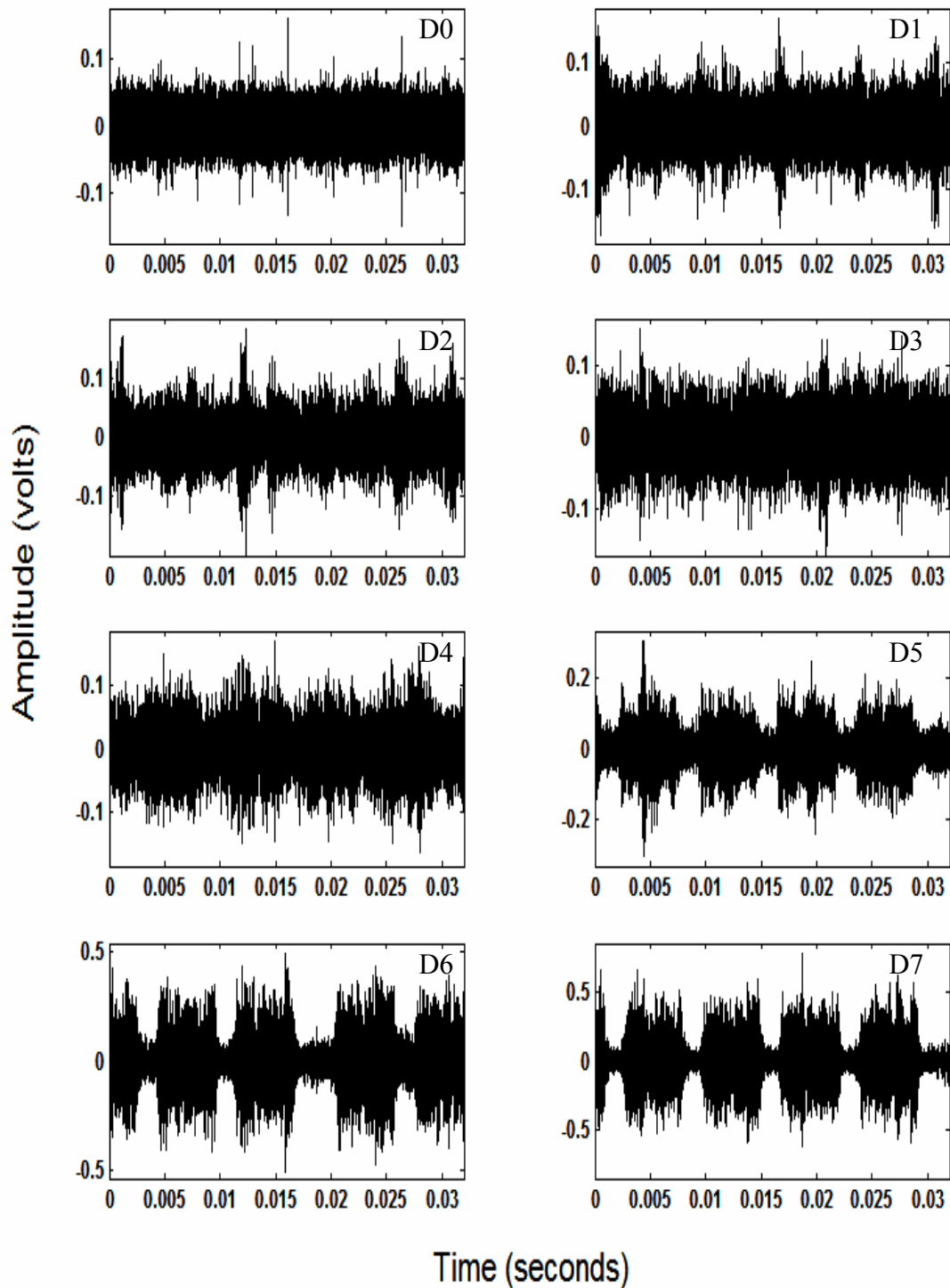


Figure 20 Sample AE time wave forms for defects D0 to D7 (Experiment-1)

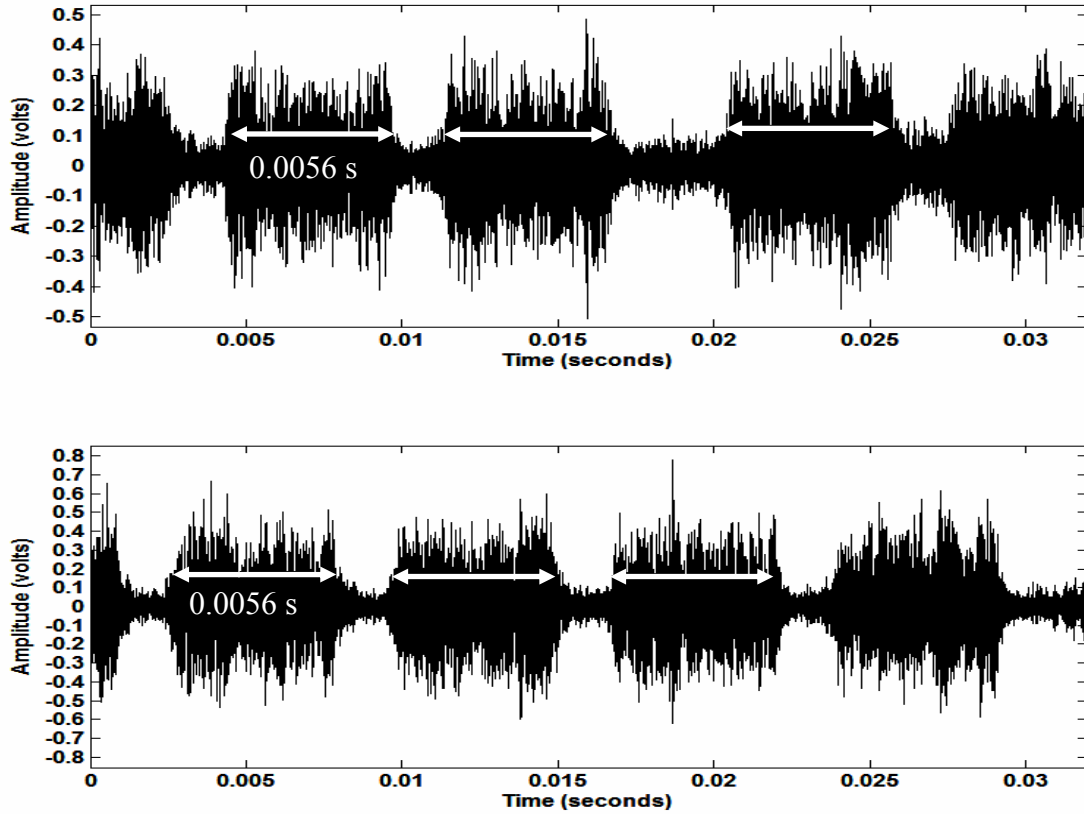


Figure 21 Burst duration for defect D6 & D7 (Experiment-1)

10.2. Observations of experiment 2 (E2):

The difference between this experiment and that reported in the previous section is two fold. Firstly, the defect size and arrangement of the seeded defect progression was different from experiment-1 and secondly, the AE data captured was sampled at 10 MHz.

Observations of the bursts durations for defects D1 to D7, see figure 22, identified that for defects D3 to D7, the burst duration was discernable; these defects had widths of at least 2 mm. It was also observed that the AE bursts for defects D3 to D6 (figure 23) were similar; these defects had the same length of 4 mm. Clearly when the defect was increased in length from 4mm to 10mm (D6 to D7) the burst duration increased dramatically, see figures 23 and 24.

Table 4 Burst to noise ratio's for defects with a fixed length (4mm) and a defect (D7) with an increased length (10mm)

Defect	Burst duration (second)	Burst amplitude (volt)	Noise amplitude (volt)	Signal to noise ratio
D3	0.0018	0.17	0.10	1.7:1
D4	0.0018	0.24	0.09	2.7:1
D5	0.0019	0.32	0.10	3.2:1
D6	0.0019	0.43	0.11	3.9:1
D7	0.0036	0.42	0.11	3.8:1

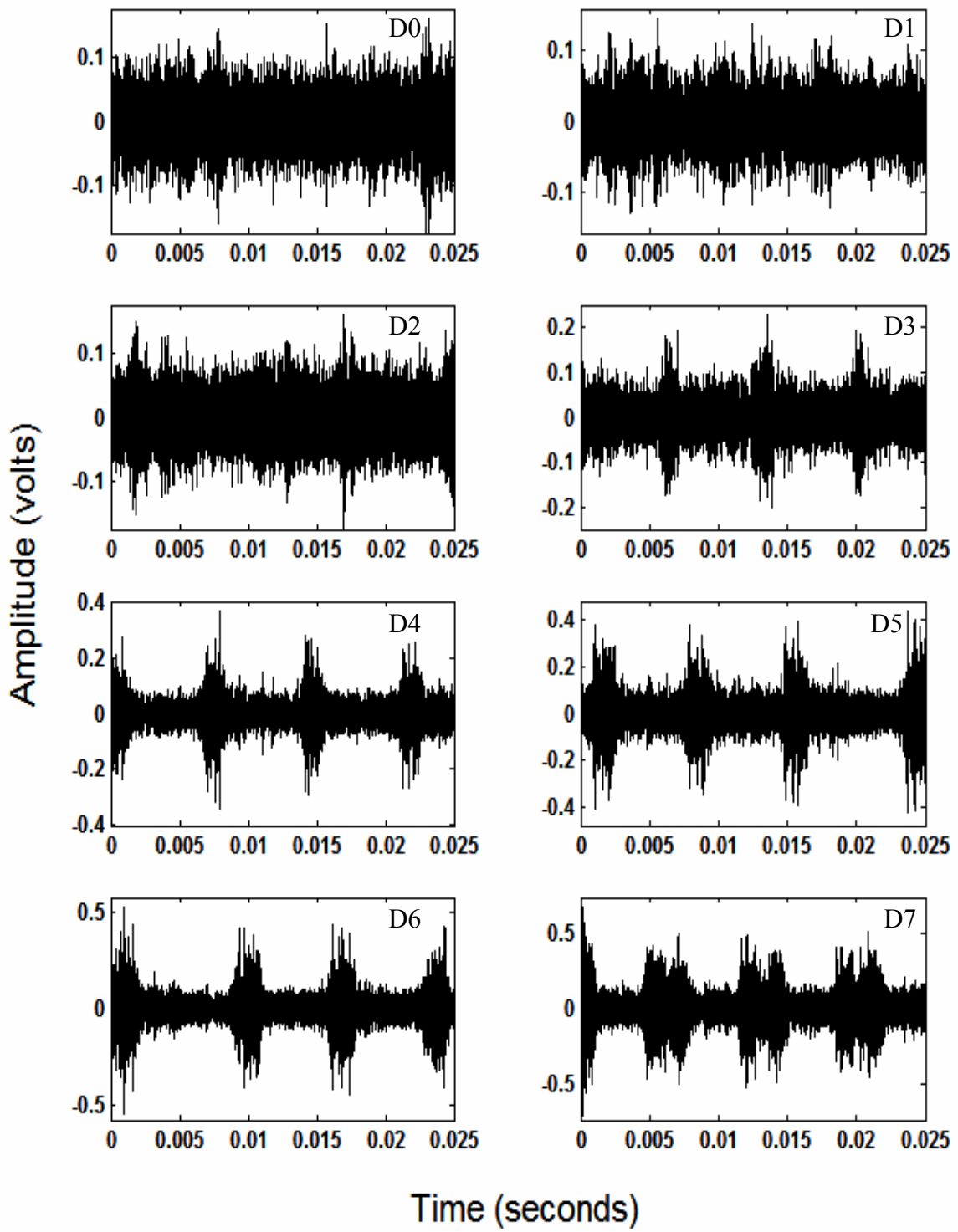


Figure 22 Sample AE time wave-forms for defects D0 to D7 (Experiment-2)

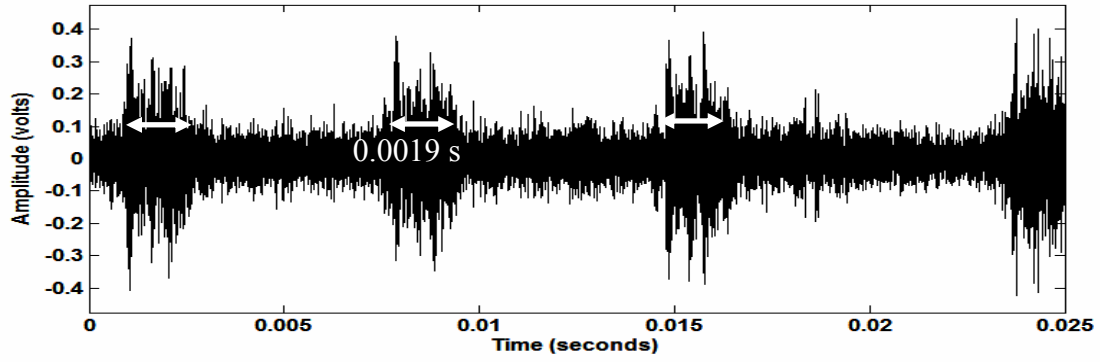
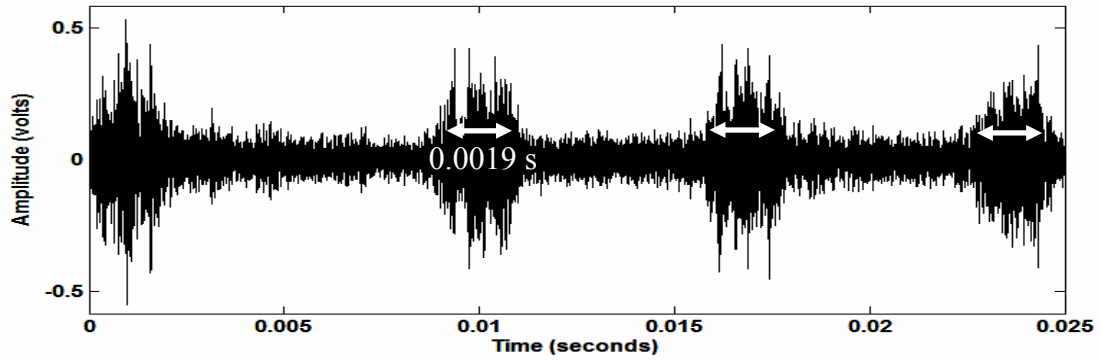


Figure 23 AE waveform bursts for defects D5-D6 (Experiment-2)

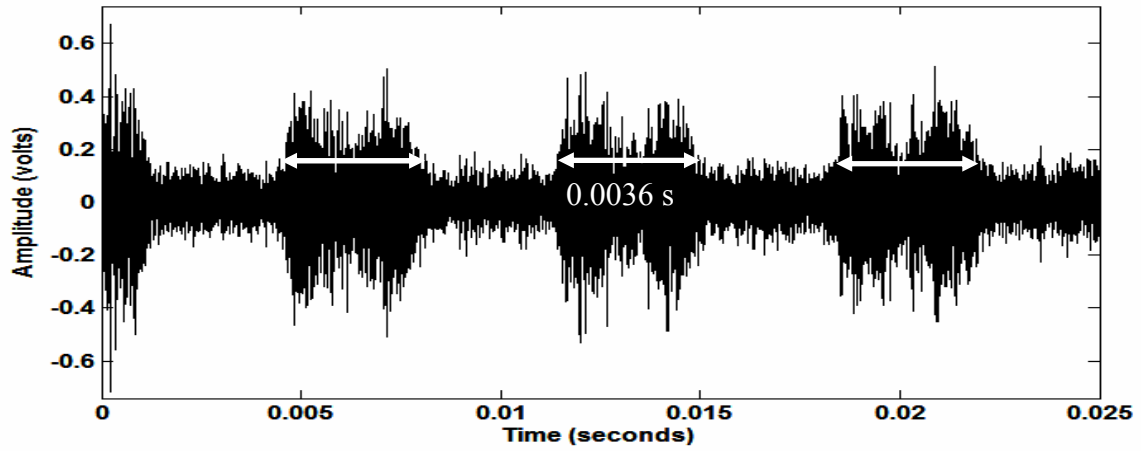
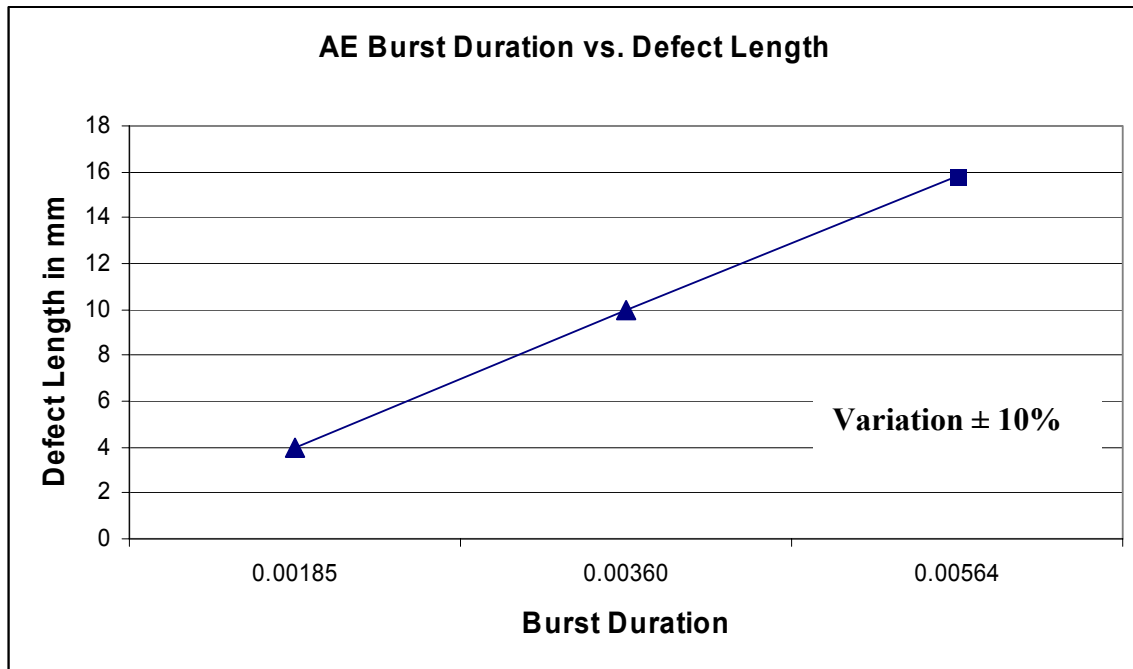


Figure 24 AE waveform burst for defect D7 (Experiment-2)

A summary of AE burst duration for experiments-1 and -2 are detailed in table 5. From table 5 a linear relation between the burst duration and the defect length is observed, see figure 25. The variation of this data about the mean was approximately $\pm 10\%$.

Table 5 Defect length and width vs. burst duration from experiments 1 and 2

Exp.	Defect	Length in mm	Width in mm	Burst Duration in seconds
2	D3 to D6	4	4, 8 and 13	0.00185
2	D7	10	13	0.00360
1	D5 to D7	15.83	4, 9 and 14	0.00564

**Figure 25 AE burst duration vs. defect length**

Observations of vibration measurements in experiment-2 of test programme 2 failed to locate the defect source under all simulations but one condition, D3-L1. This was in contrast to AE. The r.m.s and maximum amplitude values for AE and vibrations obtained in test programme-2, experiment-2, are detailed in figures 26 and 27. These were calculated per data file. Again as reported in test programme-1, AE r.m.s increased from defect size 'D1' onwards whilst AE maximum amplitude values increased from defect size 'D3', see figure 26 and 27. In contrast vibration r.m.s and maximum amplitude values have increased for defects D4 onwards, see figures 26 and 27.

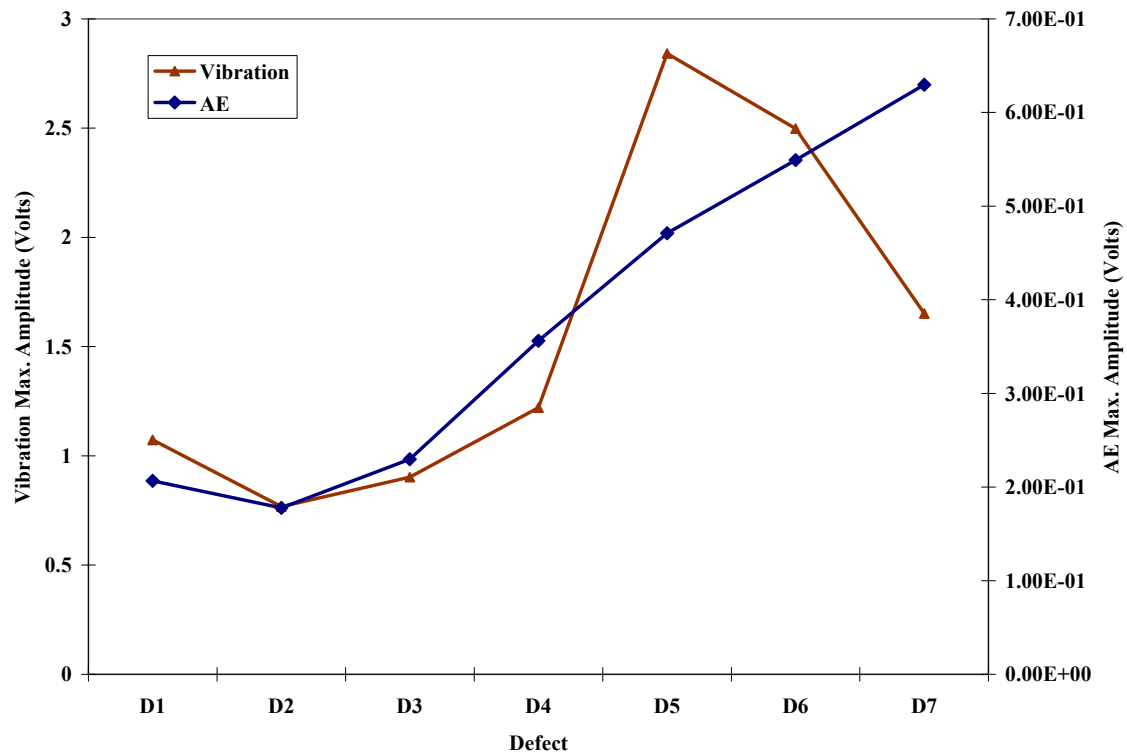


Figure 26 AE maximum amplitude values for experiment-2, defects D1 to D7

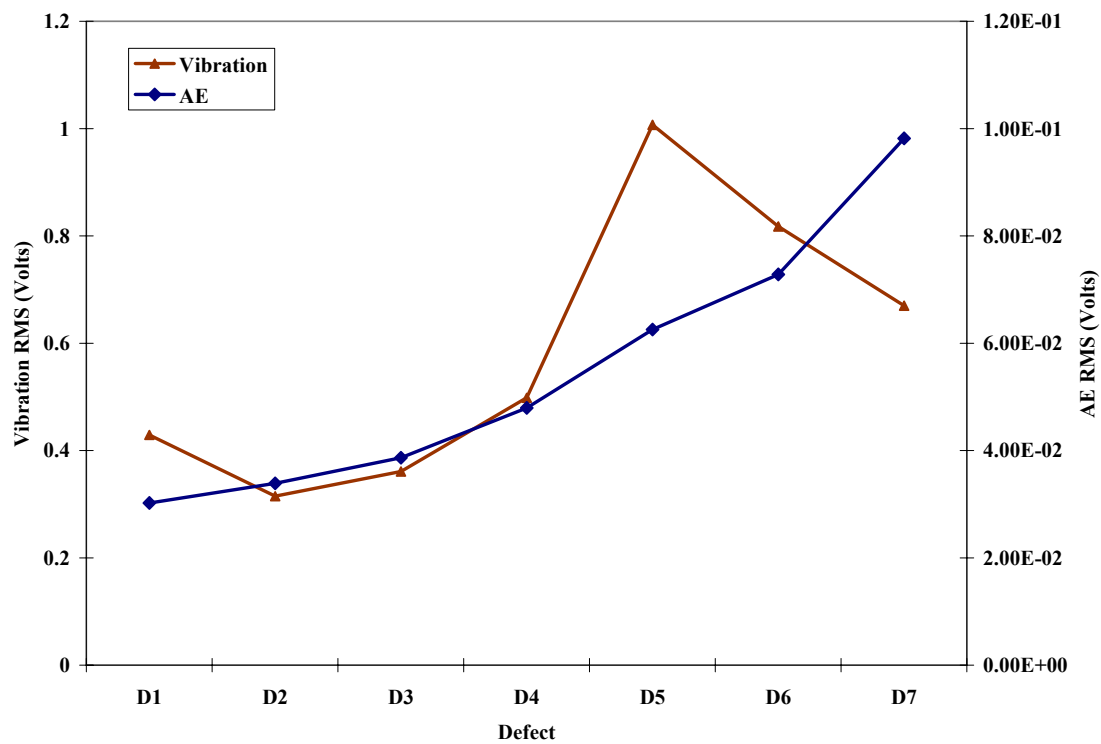


Figure 27 Vibration r.m.s values for experiment-2, defects D1 to D7

11. Discussions

The source of AE for seeded defects is attributed to material protrusions above the surface roughness of the outer race. This was established as the smooth defect could not be distinguished from the no-defect condition. However, for all other defects where the material protruded above the surface roughness, AE transients associated with the defect frequency were observed. As the defect size increased, AE r.m.s, maximum amplitude and kurtosis values increased, however, observations of corresponding parameters from vibration measurements were disappointing. Although the vibration r.m.s and maximum amplitude values did show changes with defect condition, the rate of such changes highlighted the greater sensitivity of the AE technique to early defect detection, see appendix A. Again, unlike vibration measurements, the AE transient bursts could be related to the defect source whilst the frequency spectrum of vibration readings failed in the majority of cases to identify the defect frequency or source. Also evident from this investigation is that AE levels increase with increasing speed and load. It should be noted that further signal processing could be applied to the vibration data in an attempt to enhance defect detection. Techniques such as demodulation, band pass filtering, etc, could be applied though these were not employed for this particular investigation. The main reason for not applying further signal processing to the vibration data was to allow a direct comparison between the acquired AE and vibration signature. From the results presented two important features were noted; firstly, AE was more sensitive than vibration to variation in defect size, and secondly, that no further analysis of the AE response was required in relating the defect source to the AE response, which was not the case for vibration signatures.

The relationship between defect size and AE burst duration is a significant finding. In the

longer term, and with further research, this offers opportunities for prognosis. AE burst duration was directly correlated to the seeded defect length (along the race in the direction of the rolling action) whilst the ratio of burst amplitude to the underlying operational noise levels was directly proportional to the seeded defect width.

The variation of all data presented for test programme's 1 and 2 are detailed in tables 1 to 3 in Appendix C and tables 1 to 4 in appendix D. The standard deviation and coefficient of variation (CV) for all parameters presented in the paper are detailed. The CV is a measure of the relative dispersion in a set of measurements. From appendix C it was noted that the average CV for r.m.s, maximum amplitude and kurtosis for AE was 17%, 43% and 73% respectively. Correspondingly the average CV for equivalent vibration parameters was 11%, 26% and 43%. This showed that the kurtosis measurements/calculations had a greater variability about the average value than r.m.s and maximum amplitude. For test programme-2 the CV was less than 20% for AE parameters and just over 30% for vibration parameters.

12 Conclusion

It has been shown that the fundamental source of AE in seeded defect tests was due to material protrusions above the mean surface roughness. Also, AE r.m.s, maximum amplitude and kurtosis have all been shown to be more sensitive to the onset and growth of defects than vibration measurements. A relationship between the AE burst duration and the defect length has been presented.

13. References

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APPENDIX A

Table 1 Percentage changes in vibration and AE r.m.s values

AE % Change		L0	L1	L2	VIB % Change		L0	L1	L2
N	S1	0%	0%	0%	N	S1	0%	0%	0%
	S2	0%	0%	0%		S2	0%	0%	0%
	S3	0%	0%	0%		S3	0%	0%	0%
	S4	0%	0%	0%		S4	0%	0%	0%
SD	S1	-6%	-22%	-13%	SD	S1	5%	1%	1%
	S2	20%	-15%	-22%		S2	-6%	14%	0%
	S3	141%	63%	12%		S3	-4%	12%	-5%
	S4	150%	12%	10%		S4	16%	12%	0%
PD	S1	371%	-24%	-27%	PD	S1	4%	4%	0%
	S2	54%	-7%	-30%		S2	27%	-3%	-10%
	S3	148%	89%	36%		S3	13%	34%	36%
	S4	194%	124%	54%		S4	72%	35%	44%
LD	S1	170%	135%	35%	LD	S1	-2%	23%	8%
	S2	383%	210%	49%		S2	17%	26%	3%
	S3	871%	590%	212%		S3	44%	52%	21%
	S4	1313%	479%	344%		S4	172%	34%	34%
RD	S1	284%	223%	237%	RD	S1	134%	251%	162%
	S2	371%	189%	147%		S2	161%	343%	286%
	S3	843%	446%	353%		S3	192%	376%	339%
	S4	1048%	504%	458%		S4	238%	172%	143%

Table 2 Percentage changes in AE and vibration maximum amplitude values

AE % Change		L0	L1	L2	VIB % Change		L0	L1	L2
N	S1	0%	0%	0%	N	S1	0%	0%	0%
	S2	0%	0%	0%		S2	0%	0%	0%
	S3	0%	0%	0%		S3	0%	0%	0%
	S4	0%	0%	0%		S4	0%	0%	0%
SD	S1	13%	-23%	-20%	SD	S1	-3%	-16%	-5%
	S2	11%	-17%	-9%		S2	-6%	3%	-6%
	S3	90%	61%	12%		S3	-10%	17%	-8%
	S4	75%	19%	10%		S4	9%	22%	5%
PD	S1	992%	23%	41%	PD	S1	-4%	-8%	-3%
	S2	242%	72%	41%		S2	16%	4%	-11%
	S3	347%	319%	199%		S3	9%	30%	27%
	S4	262%	205%	172%		S4	71%	37%	40%
LD	S1	918%	539%	262%	LD	S1	-21%	27%	7%
	S2	1726%	664%	275%		S2	39%	37%	10%
	S3	3250%	1839%	692%		S3	89%	67%	30%
	S4	3546%	1264%	1026%		S4	159%	44%	34%
RD	S1	1652%	732%	1250%	RD	S1	110%	302%	186%
	S2	1951%	376%	378%		S2	147%	330%	301%
	S3	3681%	883%	482%		S3	209%	288%	260%
	S4	2992%	754%	579%		S4	264%	155%	115%

Table 3 Percentage changes in vibration and AE kurtosis values

AE % Change		L0	L1	L2	VIB % Change		L0	L1	L2
N	S1	0%	0%	0%	N	S1	0%	0%	0%
	S2	0%	0%	0%		S2	0%	0%	0%
	S3	0%	0%	0%		S3	0%	0%	0%
	S4	0%	0%	0%		S4	0%	0%	0%
SD	S1	6%	-10%	7%	SD	S1	-16%	-29%	-18%
	S2	-8%	-14%	23%		S2	-3%	-17%	-7%
	S3	-16%	-1%	19%		S3	9%	-7%	-22%
	S4	-29%	27%	10%		S4	4%	-11%	-18%
PD	S1	750%	158%	174%	PD	S1	18%	-6%	-8%
	S2	328%	270%	479%		S2	3%	42%	12%
	S3	190%	575%	664%		S3	6%	-10%	-15%
	S4	37%	98%	336%		S4	-2%	-11%	-20%
LD	S1	1999%	1291%	965%	LD	S1	-8%	11%	20%
	S2	2303%	932%	916%		S2	142%	44%	57%
	S3	1839%	1418%	1201%		S3	175%	13%	10%
	S4	974%	861%	1073%		S4	95%	25%	6%
RD	S1	3112%	864%	2995%	RD	S1	24%	84%	78%
	S2	2637%	213%	328%		S2	39%	71%	43%
	S3	2136%	352%	129%		S3	31%	-25%	-30%
	S4	837%	178%	109%		S4	25%	262%	363%

APPENDIX B

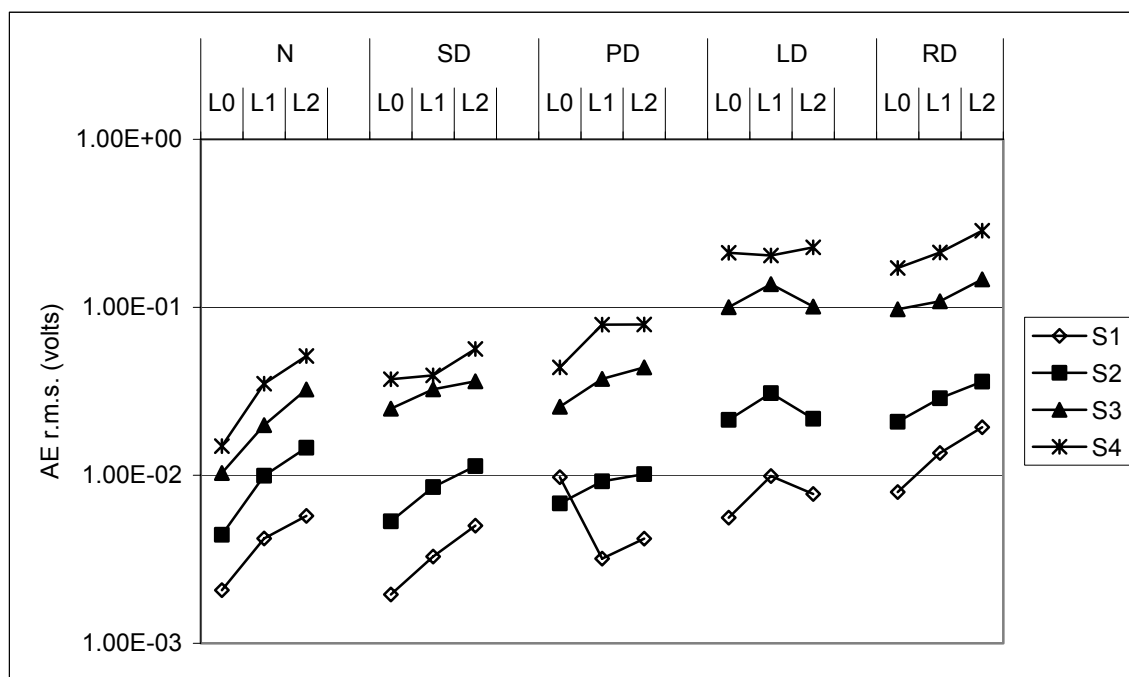


Figure 1 AE r.m.s. of different defects; increasing loads at a fixed Speed

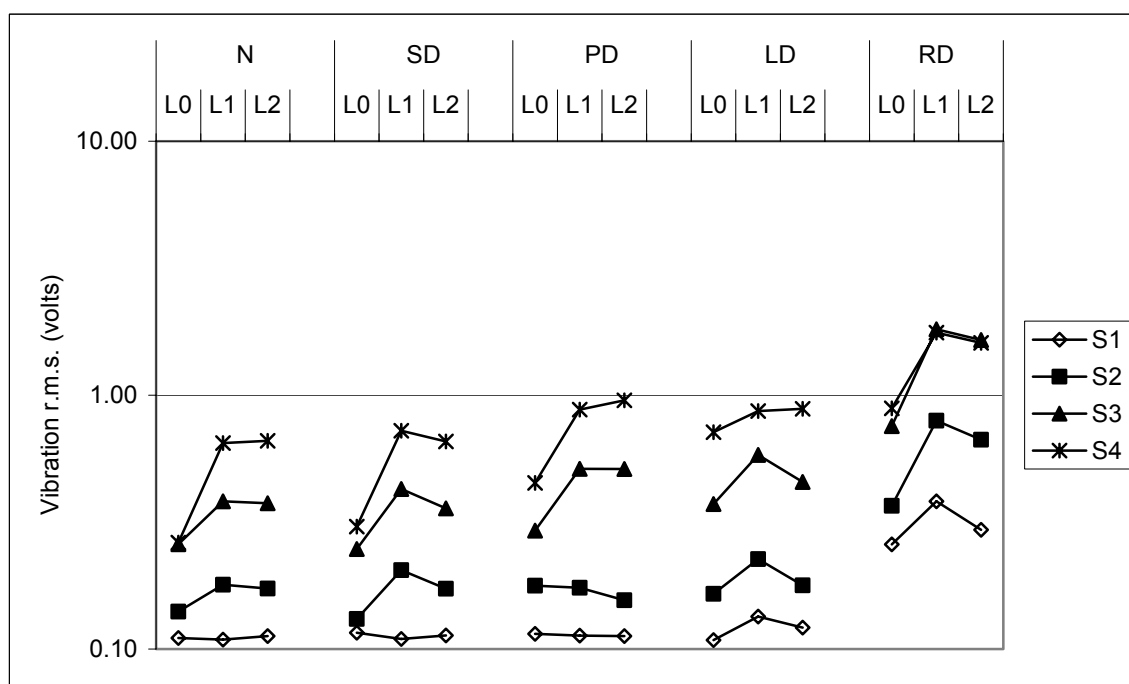


Figure 2 Vibration r.m.s. of different defects; increasing loads at a fixed Speed

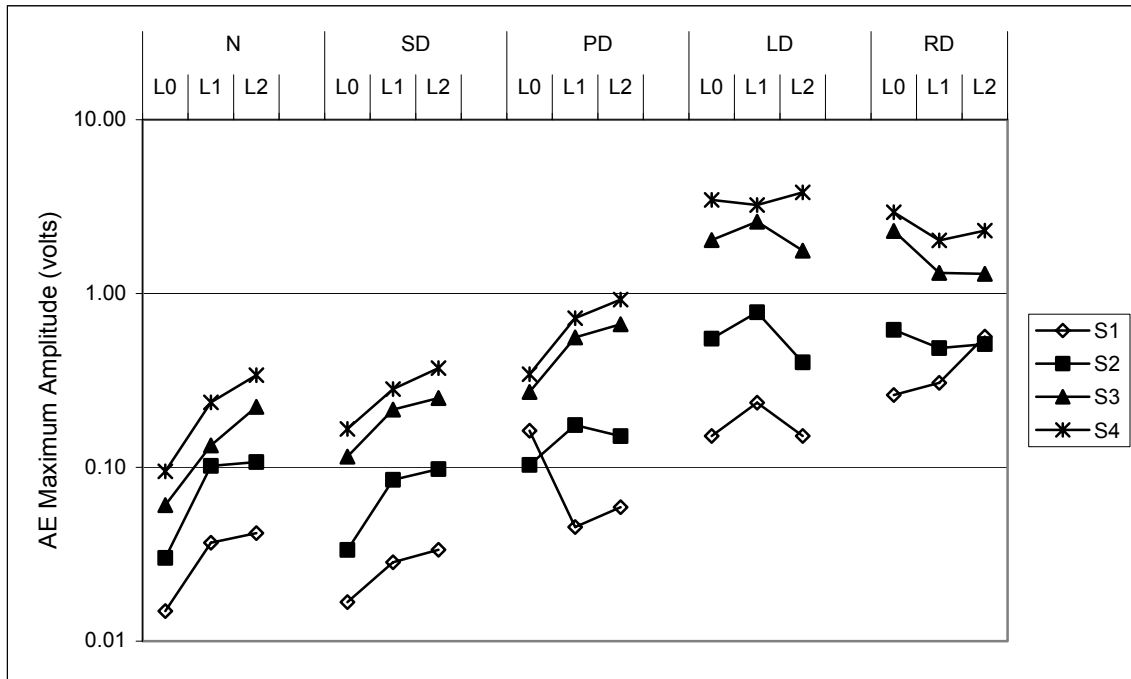


Figure 3 AE max amplitude of different defects at increasing loads and fixed speed

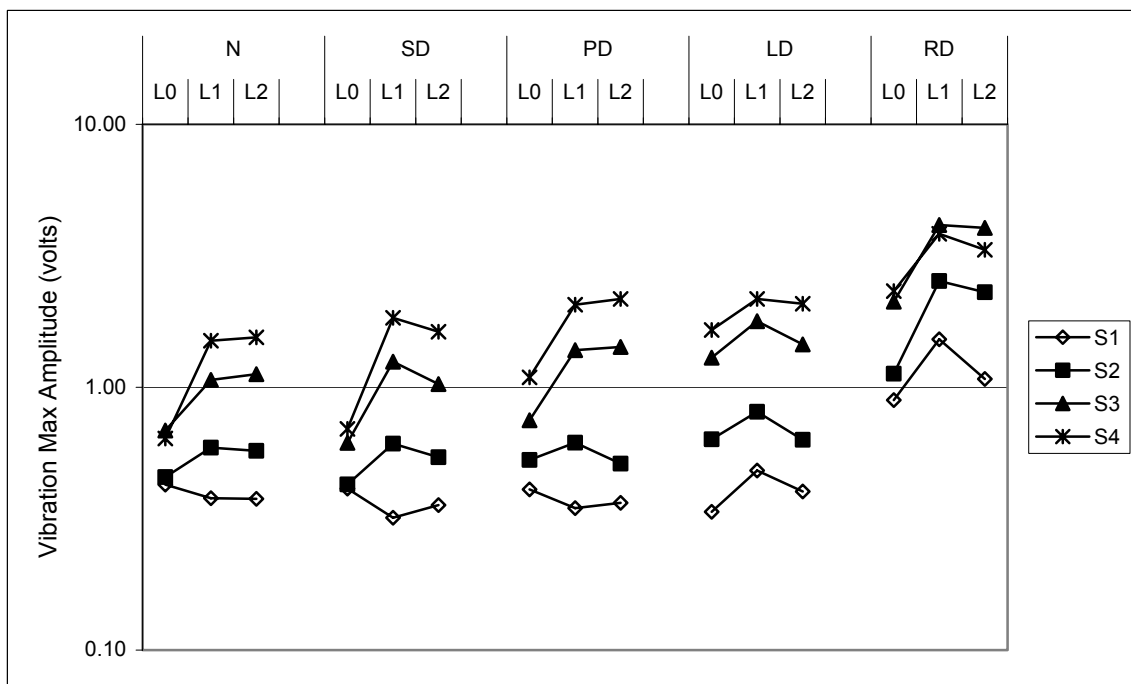


Figure 4 Vibration max amplitude of different defects at increasing loads and fixed speed

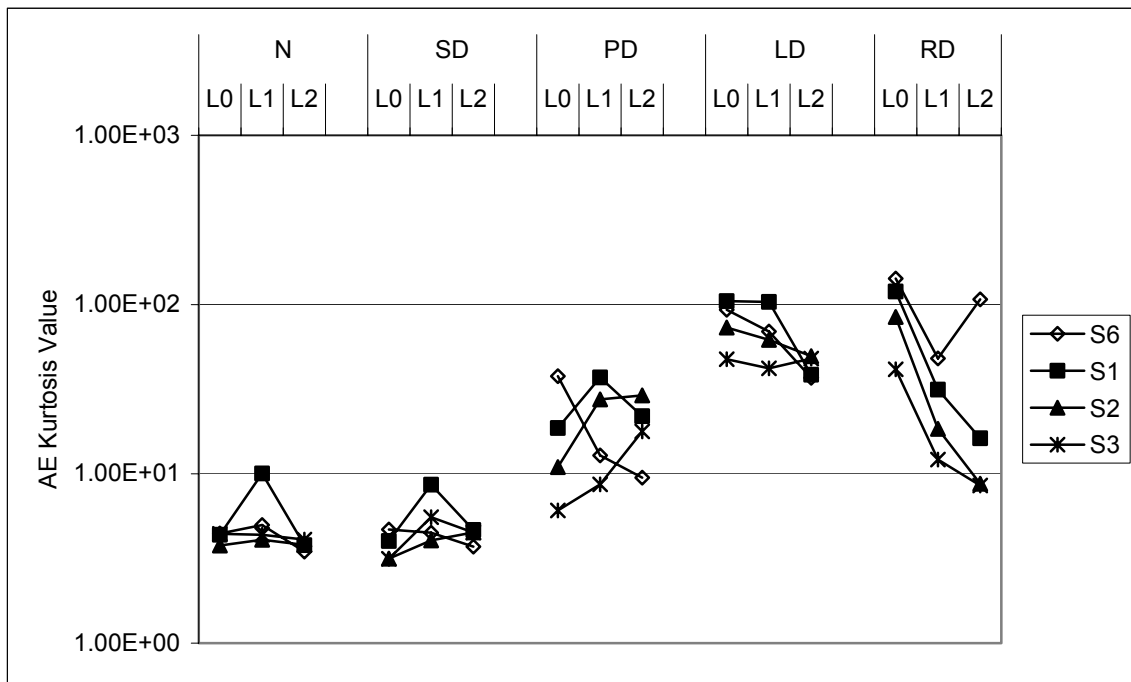


Figure 5 AE kurtosis of different defects at increasing loads and fixed speed

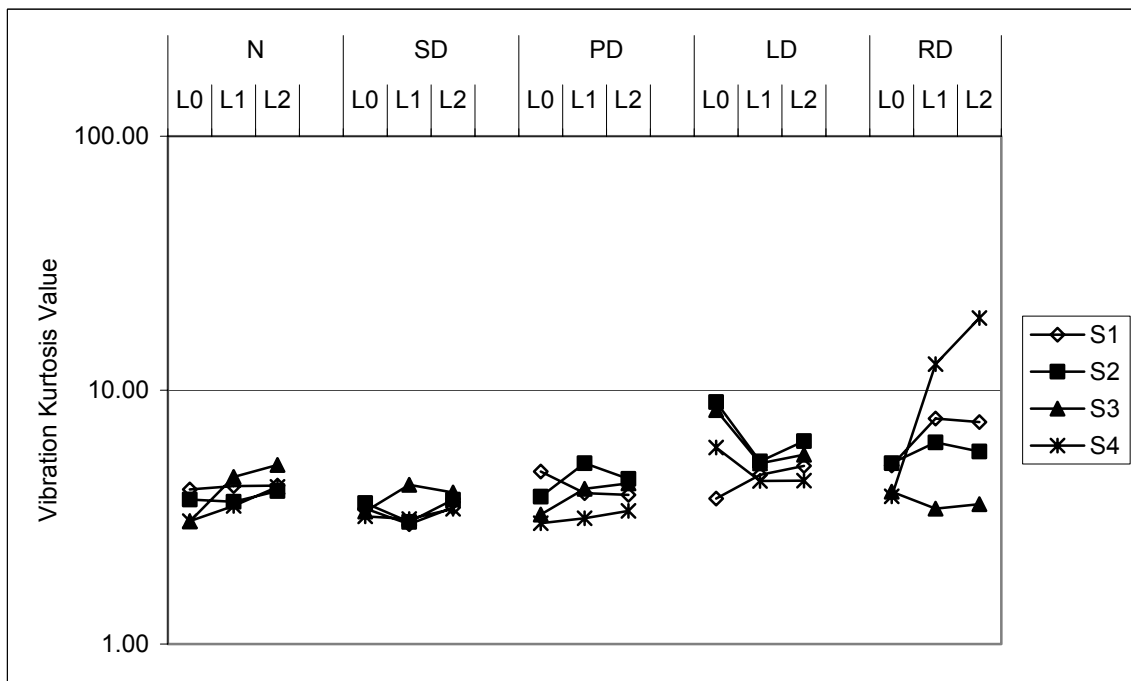


Figure 6 Vibration kurtosis of different defects at increasing loads and fixed speed

Appendix C

Table 1 Mean, standard deviation and coefficient of variation for all test conditions; r.m.s

Key:-

Mean	S. Deviation
Coefficient of Variation %	

AE RMS		L0		L1		L2		Vibration RMS		L0		L1		L2	
N	S1	0.00208	0.00007	0.00421	0.00015	0.00573	0.00016	N	S1	0.110534	0.004981	0.108938	0.005164	0.112476	0.00545
		3.57%		3.45%		2.76%				4.51%		4.74%		4.85%	
	S2	0.00442	0.00021	0.00995	0.00079	0.014597	0.000901		S2	0.140487	0.013768	0.17917	0.014676	0.173005	0.015096
		4.77%		7.91%		6.17%				9.80%		8.19%		8.73%	
	S3	0.01031	0.003509	0.019874	0.000973	0.032391	0.000954		S3	0.25882	0.049597	0.381994	0.045741	0.375416	0.042903
		34.03%		4.90%		2.94%				19.16%		11.97%		11.43%	
	S4	0.014935	0.002854	0.035125	0.001132	0.05129	0.001684		S4	0.262333	0.032162	0.647926	0.098311	0.660337	0.094787
		19.11%		3.22%		3.28%				12.26%		15.17%		14.35%	
SD	S1	0.001943	6.26E-05	0.00329	0.000161	0.005019	0.000193	SD	S1	0.116016	0.005796	0.109562	0.004174	0.113129	0.005431
		3.22%		4.91%		3.84%				5.00%		3.81%		4.80%	
	S2	0.005325	0.000298	0.008506	0.000512	0.011352	0.000407		S2	0.13138	0.008413	0.204407	0.017575	0.17294	0.01648
		5.59%		6.01%		3.59%				6.40%		8.60%		9.53%	
	S3	0.024921	0.001294	0.032501	0.001263	0.036285	0.001614		S3	0.247824	0.031248	0.42684	0.062943	0.358137	0.041745
		5.19%		3.89%		4.45%				12.61%		14.75%		11.66%	
	S4	0.037282	0.006864	0.039363	0.008259	0.056466	0.007488		S4	0.303562	0.048452	0.724074	0.101285	0.65741	0.087132
		18.41%		20.98%		13.26%				15.96%		13.99%		13.25%	
PD	S1	0.009798	0.009436	0.003197	0.000221	0.00421	0.000218	PD	S1	0.114764	0.011017	0.112968	0.006525	0.112439	0.005111
		96.30%		6.92%		5.19%				9.60%		5.78%		4.55%	
	S2	0.006792	0.008873	0.009208	0.000913	0.010153	0.001203		S2	0.177751	0.019647	0.174459	0.01839	0.155688	0.012463
		130.64%		9.92%		11.84%				11.05%		10.54%		8.01%	
	S3	0.025603	0.009668	0.037551	0.004384	0.043965	0.005116		S3	0.292589	0.02911	0.512618	0.059401	0.511783	0.067242
		37.76%		11.67%		11.64%				9.95%		11.59%		13.14%	
	S4	0.043898	0.004357	0.078959	0.006322	0.078806	0.012878		S4	0.451193	0.053642	0.877046	0.141166	0.953266	0.113108
		9.93%		8.01%		16.34%				11.89%		16.10%		11.87%	
LD	S1	0.005612	0.000734	0.009923	0.001416	0.007747	0.001341	LD	S1	0.108393	0.004147	0.134201	0.010703	0.121415	0.007239
		13.08%		14.27%		17.31%				3.83%		7.98%		5.96%	
	S2	0.021296	0.004553	0.030848	0.00833	0.02165	0.005113		S2	0.164899	0.020048	0.226054	0.024405	0.178172	0.01988
		21.38%		27.00%		23.62%				12.16%		10.80%		11.16%	
	S3	0.100221	0.03314	0.137379	0.036158	0.101017	0.027554		S3	0.372372	0.073207	0.581865	0.067104	0.455222	0.067104
		33.07%		26.32%		27.28%				19.66%		11.53%		14.74%	
	S4	0.210338	0.068644	0.203599	0.052927	0.227806	0.072744		S4	0.714118	0.192518	0.866022	0.15571	0.883662	0.168333
		32.63%		26.00%		31.93%				26.96%		17.98%		19.05%	
RD	S1	0.00795	0.001792	0.013571	0.001802	0.019334	0.001616	RD	S1	0.258267	0.023291	0.381882	0.046362	0.29481	0.043323
		22.54%		13.28%		8.36%				9.02%		12.14%		14.70%	
	S2	0.020854	0.006258	0.028761	0.003559	0.036157	0.001746		S2	0.366687	0.033127	0.793027	0.067234	0.667478	0.066637
		30.01%		12.37%		4.83%				9.03%		8.48%		9.98%	
	S3	0.096947	0.024285	0.10851	0.01382	0.146629	0.007698		S3	0.754606	0.090048	1.816725	0.178897	1.643293	0.190666
		25.05%		12.74%		5.25%				11.93%		9.85%		11.60%	
	S4	0.171096	0.0314	0.212082	0.017932	0.285769	0.012569		S4	0.887129	0.12968	1.763234	0.121782	1.607115	0.118789
		18.35%		8.46%		4.40%				14.62%		6.91%		7.39%	

Table 2 Mean, standard deviation and coefficient of variation for all test conditions; maximum amplitude

Key:-

Mean	S. Deviation
Coefficient of Variation %	

AE max. amplitud e								Vibration max. amplitud e							
		L0		L1		L2			L0		L1		L2		
N	S1	0.0149	0.006524	0.036803	0.020128	0.04131	0.011605	N	S1	0.426122	0.104572	0.37851	0.094475	0.376092	0.067449
		43.78%		54.69%		28.09%				24.54%		24.96%		17.93%	
	S2	0.029569	0.013988	0.102148	0.065422	0.108597	0.027766		S2	0.455451	0.114607	0.589201	0.141621	0.573061	0.156391
		47.31%		64.05%		25.57%				25.16%		24.04%		27.29%	
	S3	0.060725	0.028089	0.13416	0.032667	0.221715	0.049594		S3	0.684509	0.169395	1.065683	0.315576	1.121585	0.391334
		46.26%		24.35%		22.37%				24.75%		29.61%		34.89%	
	S4	0.095059	0.031538	0.236697	0.0657	0.33793	0.076411		S4	0.637855	0.123435	1.50238	0.400672	1.547755	0.49042
		33.18%		27.76%		22.61%				19.35%		26.67%		31.69%	
SD	S1	0.016767	0.00644	0.028275	0.00826	0.033363	0.006056	SD	S1	0.411469	0.075882	0.318643	0.066042	0.356	0.067684
		38.41%		29.21%		18.15%				18.44%		20.73%		19.01%	
	S2	0.033616	0.013939	0.084782	0.051091	0.097653	0.032219		S2	0.426683	0.086709	0.609701	0.124684	0.541524	0.108176
		41.47%		60.26%		32.99%				20.32%		20.45%		19.98%	
	S3	0.115335	0.017671	0.215026	0.05394	0.250093	0.077732		S3	0.614241	0.118372	1.25011	0.425267	1.027509	0.304789
		15.32%		25.09%		31.08%				19.27%		34.02%		29.66%	
	S4	0.166421	0.032748	0.281803	0.06331	0.37256	0.068917		S4	0.694292	0.149475	1.83638	0.487189	1.62518	0.456532
		19.68%		22.47%		18.50%				21.53%		26.53%		28.09%	
PD	S1	0.164954	0.158003	0.045307	0.018477	0.059005	0.023613	PD	S1	0.408531	0.120479	0.346724	0.071826	0.363265	0.071478
		95.79%		40.78%		40.02%				29.49%		20.72%		19.68%	
	S2	0.105695	0.175902	0.177965	0.068597	0.15174	0.074084		S2	0.528683	0.131054	0.615183	0.212818	0.511878	0.14524
		166.42%		38.55%		48.82%				24.79%		34.59%		28.37%	
	S3	0.272127	0.180325	0.563662	0.21607	0.676773	0.238314		S3	0.748415	0.126557	1.384229	0.411869	1.422985	0.472924
		66.27%		38.33%		35.21%				16.91%		29.75%		33.23%	
	S4	0.343804	0.107785	0.727329	0.259129	0.922697	0.432785		S4	1.089618	0.206767	2.060298	0.524359	2.166361	0.571468
		31.35%		35.63%		46.90%				18.98%		25.45%		26.38%	
LD	S1	0.15155	0.049152	0.23904	0.118443	0.150789	0.106757	LD	S1	0.335939	0.081127	0.482153	0.119156	0.40098	0.08549
		32.43%		49.55%		70.80%				24.15%		24.71%		21.32%	
	S2	0.549966	0.203333	0.793367	0.444417	0.399768	0.2828		S2	0.634	0.229519	0.806274	0.216681	0.631085	0.199209
		36.97%		56.02%		70.74%				36.20%		26.87%		31.57%	
	S3	2.032534	1.121462	2.601124	1.308942	1.769984	0.93768		S3	1.295439	0.578847	1.783113	0.575885	1.454256	0.551794
		55.18%		50.32%		52.98%				44.68%		32.30%		37.94%	
	S4	3.45586	1.841971	3.23032	1.671089	3.833406	2.09603		S4	1.650906	0.80296	2.166102	0.768099	2.077714	0.849431
		53.30%		51.73%		54.68%				48.64%		35.46%		40.88%	
RD	S1	0.262969	0.182349	0.306043	0.127173	0.564963	0.107298	RD	S1	0.893571	0.15583	1.522286	0.306173	1.075571	0.268539
		69.34%		41.55%		18.99%				17.44%		20.11%		24.97%	
	S2	0.617684	0.409719	0.491357	0.291556	0.518636	0.109704		S2	1.125646	0.211943	2.536524	0.415032	2.298293	0.471199
		66.33%		59.34%		21.15%				18.83%		16.36%		20.50%	
	S3	2.302343	0.971546	1.321508	0.7621	1.296574	0.328188		S3	2.114104	0.435389	4.138695	0.425519	4.035311	0.448041
		42.20%		57.67%		25.31%				20.59%		10.28%		11.10%	
	S4	2.934978	0.938397	2.018096	0.734277	2.307621	0.481824		S4	2.319563	0.585691	3.83158	0.688802	3.330045	1.508469
		31.97%		36.38%		20.88%				25.25%		17.98%		45.30%	

Table 3 Mean, standard deviation and coefficient of variation for all test conditions; kurtosis

Key:-

Mean	S. Deviation
Coefficient of Variation %	

AE kurtosis		L0		L1		L2		Vibration kurtosis		L0		L1		L2	
N	S1	4.436782	4.224488	5.000562	6.020565	3.46719	0.269321	N	S1	4.436782	4.224488	5.000562	6.020565	3.46719	0.269321
		95.22%		120.40%		7.77%				95.22%		120.40%		7.77%	
	S2	4.339619	3.836373	9.940779	18.61536	3.78912	0.596502		S2	4.339619	3.836373	9.940779	18.61536	3.78912	0.596502
		88.40%		187.26%		15.74%				88.40%		187.26%		15.74%	
	S3	3.781132	0.929848	4.113147	1.425231	3.806502	0.607442		S3	3.781132	0.929848	4.113147	1.425231	3.806502	0.607442
		24.59%		34.65%		15.96%				24.59%		34.65%		15.96%	
	S4	4.436208	1.815983	4.368583	1.391168	4.08898	0.903627		S4	4.436208	1.815983	4.368583	1.391168	4.08898	0.903627
		40.94%		31.84%		22.10%				40.94%		31.84%		22.10%	
SD	S1	4.665903	1.404395	4.505865	1.099453	3.713216	0.33158	SD	S1	3.418918	0.640817	2.965461	0.57377	3.451164	1.120604
		30.10%		24.40%		8.93%				18.74%		19.35%		32.47%	
	S2	4.005855	3.374727	8.603322	16.64647	4.663631	2.164177		S2	3.589427	0.922964	3.027202	0.696543	3.70372	1.41759
		84.24%		193.49%		46.41%				25.71%		23.01%		38.27%	
	S3	3.154107	0.154672	4.046815	1.061499	4.51331	3.257478		S3	3.32605	0.770929	4.241129	1.63703	3.952045	1.95179
		4.90%		26.23%		72.17%				23.18%		38.60%		49.39%	
	S4	3.147244	0.140312	5.552993	1.473932	4.506046	1.008311		S4	3.182082	0.840328	3.106119	0.81242	3.408502	1.090185
		4.46%		26.54%		22.38%				26.41%		26.16%		31.98%	
PD	S1	38.83491	33.28712	12.87823	16.92244	9.555857	7.467683	PD	S1	4.782516	3.497531	3.930797	1.367264	3.870064	1.147546
		85.71%		131.40%		78.15%				73.13%		34.78%		29.65%	
	S2	20.68345	28.22398	37.97499	37.64512	21.90824	34.64126		S2	3.806749	1.905564	5.158101	2.685232	4.469181	2.296074
		136.46%		99.13%		158.12%				50.06%		52.06%		51.38%	
	S3	11.00543	10.12472	27.76037	22.0749	29.87804	21.88277		S3	3.233571	0.819565	4.086293	1.724493	4.295411	1.919293
		92.00%		79.52%		73.24%				25.35%		42.20%		44.68%	
	S4	6.048639	2.731593	8.897458	5.541717	17.78524	16.71409		S4	2.993143	0.663417	3.129064	0.864127	3.343492	1.1013
		45.16%		62.28%		93.98%				22.16%		27.62%		32.94%	
LD	S1	92.16791	42.22209	69.02949	83.00089	37.11809	85.84416	LD	S1	3.740115	1.892375	4.63935	1.410001	5.031709	4.55721
		45.81%		120.24%		231.27%				50.60%		30.39%		90.57%	
	S2	105.2562	60.19319	105.3279	97.19804	38.20567	61.47599		S2	8.980184	5.905258	5.234576	1.707687	6.302449	4.265727
		57.19%		92.28%		160.91%				65.76%		32.62%		67.68%	
	S3	73.25391	51.09542	62.62468	44.02204	49.66386	42.60622		S3	8.351077	4.174584	5.146759	2.018436	5.565973	2.98152
		69.75%		70.30%		85.79%				49.99%		39.22%		53.57%	
	S4	47.4169	30.11592	42.26894	28.93362	48.3792	35.09275		S4	5.945212	3.375089	4.386871	1.583773	4.39866	2.813827
		63.51%		68.45%		72.54%				56.77%		36.10%		63.97%	
RD	S1	143.6338	154.7864	48.09199	48.03505	107.5937	37.13876	RD	S1	5.04944	2.16377	7.726035	2.621085	7.484124	5.198056
		107.76%		99.88%		34.52%				42.85%		33.93%		69.45%	
	S2	118.8805	94.60856	31.54254	44.56995	16.24523	5.002033		S2	5.157657	1.747392	6.227091	1.895961	5.732117	1.393952
		79.58%		141.30%		30.79%				33.88%		30.45%		24.32%	
	S3	84.78826	51.01301	18.52561	24.59273	8.73463	2.486449		S3	3.982678	0.953539	3.416066	0.629792	3.553674	0.529996
		60.17%		132.75%		28.47%				23.94%		18.44%		14.91%	
	S4	41.42224	18.42483	12.13047	8.991414	8.538072	2.609838		S4	3.815731	1.184192	12.65901	7.111769	19.23017	10.40532
		44.48%		74.12%		30.57%				31.03%		56.18%		54.11%	

Appendix D

Table 1 Mean, standard deviation and coefficient of variation for test programme-2; AE r.m.s

Average	0.03025	0.0339	0.03865	0.0479688	0.06255	0.0728235	0.0981857
Standard deviation	0.0005351	0.0008124	0.0012646	0.0028927	0.0030232	0.0038606	0.0036336
Coefficient of variation	1.77%	2.40%	3.27%	6.03%	4.83%	5.30%	3.70%
	Load 4.4kN						
	D1	D2	D3	D4	D5	D6	D7

Table 2 Mean, standard deviation and coefficient of variation for test programme-2; AE maximum amplitude

Average	0.2066417	0.1776417	0.2297167	0.3562063	0.4710313	0.549	0.6297857
Standard deviation	0.0398724	0.0306937	0.0412125	0.0253876	0.0503913	0.0670317	0.0736799
Coefficient of variation	19.30%	17.28%	17.94%	7.13%	10.70%	12.21%	11.70%
	Load 4.4kN						
	D1	D2	D3	D4	D5	D6	D7

Table 3 Mean, standard deviation and coefficient of variation for test programme-2; Vibration r.m.s

Average	0.429082	0.3148242	0.3610585	0.4984004	1.0070777	0.8177705	0.6699566
Standard deviation	0.0614877	0.0567484	0.0552029	0.0670442	0.137269	0.1381788	0.0760416
Coefficient of variation	14.33%	18.03%	15.29%	13.45%	13.63%	16.90%	11.35%
	Load 4.4kN						
	D1	D2	D3	D4	D5	D6	D7

Table 4 Mean, standard deviation and coefficient of variation for test programme-2; Vibration maximum amplitude

Average	1.0728039	0.7673333	0.9027242	1.2201647	2.8411781	2.4977007	1.6514511
Standard deviation	0.3867745	0.2769304	0.3311302	0.3188992	0.7856587	0.8620226	0.4262681
Coefficient of variation	36.05%	36.09%	36.68%	26.14%	27.65%	34.51%	25.81%
	Load 4.4kN						
	D1	D2	D3	D4	D5	D6	D7



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