Diagnostics and prognostics with Acoustic Emission, Vibration and Spectrometric Oil Analysis for spur gears; a comparative study

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ABSTRACT

Whilst vibration and spectrometric oil analysis for gear fault diagnosis are well established, the application of AE to this field is still in its infancy. This paper describes an experimental investigation on spur gears in which natural pitting was allowed to occur. Throughout the test period, AE, vibration and spectrometric oil samples were monitored continuously in order to correlate and compare these techniques to natural life degradation of the gears. It was observed that the AE technique was the most sensitive in detecting and monitoring pitting.

KEYWORDS

Acoustic Emission, condition monitoring, gear pitting, machine diagnosis, prognosis, spectrometric oil analysis, vibration analysis

1. INTRODUCTION

Acoustic emission (AE) was originally developed for non-destructive testing of static structures [1], however, over recent years its application has been extended to health monitoring of rotating machines and bearings. The use of vibration analysis for gear fault diagnosis and monitoring has been widely investigated and its application in industry is well established [2, 3, 4]. Similarly, Spectrometric Oil Analysis (SOA) has been routinely used for elemental analysis of wear particles, contaminants and additives in lubricants for more than 50 years [5]. The basic idea of spectrometry is to identify and quantify wear particles from an oil sample. Typical spectrometers are capable of detecting wear particles of between 5 and 10µm. In this paper, the authors present results from an experimental programme that observed the relationship between AE, vibration and SOA with natural progressive pitting in a pair of spur gears.

2. ACOUSTIC EMISSION

AE is defined as transient elastic waves generated due to a rapid release of strain energy caused by structural alteration in/on a solid material under mechanical or thermal stresses. Primary sources of AE are crack initiation, crack propagation, plastic deformation and friction. AE was originally developed as a method of Non-Destructive Testing (NDT) and attempts to apply this technique to condition monitoring of rotating machinery started in the late 1960's [6]. However, the main concern on application of the AE technique is the attenuation of the signal during propagation and as such the AE

sensor has to be as close to its source as possible. This limitation may pose a practical constraint when applying this technique to certain rotating machinery.

3. EXPERIMENTAL SET-UP

The test-rig employed for this experimental work consisted of two identical oil-bath lubricated gearboxes, connected in a back-to-back arrangement. The gear set employed was made of 045M15 steel (without any heat treatment) which had a measured hardness of 137 Hv30. The gears (49 and 65 teeth) had a module of 3 mm, a pressure angle of 20°, and a surface roughness (Ra) of between 2-3 μm. A simple mechanism that permitted a pair of coupling flanges to be rotated relative to each other, and locked in position, was employed to apply torque to the gears.

The AE sensors employed for this experiment were of a broadband type with relatively flat response in the region between 100 kHz to 1MHz. The sensor was placed on the pinion with 49 teeth and on the pinion bearing casing. Data were acquired from the sensor fixed on the pinion via a slip ring. An accelerometer was fitted onto the bearing casing of the pinion gear to record vibration data. The accelerometer used for vibration measurement in this experiment was a resonant type sensor with a frequency response between 10 Hz and 8000 Hz. The lubricant oil employed for these test was SAE 20W-50. Also, to accelerate the pitting process the face width of the pinion employed was half that of the wheel.

4.   EXPERIMENTAL PROCEDURES

The two gear fatigue tests were performed at a rotational speed of 745 rpm and applied torque of 220Nm. At regular intervals visual inspection of gear surface damage was undertaken, oil sump temperatures were measured and oil samples were drawn for SOA (see table 1).

Table 1   Inspection, SOA collection intervals and oil temperatures at respective inspection intervals for all the test conditions

Test 1		Test 2	
CIT* (hr)	Temp (^{0}C)	CIT* (hr)	Temp (^{0}C)
0	23.1	0	23.8
9	60.9	17	60.5
20	64.1	28	61.9
31	63.8	40	62.9
41	65.3	52	63.8
54	65.2	70	63.1
70	66	86	63.9
91	63		
116	64		

Cumulative inspection time (hr)

Continuous values of AE r.m.s were calculated in real time by the analogue-to-digital converter (ADC) controlling software. This software employed a hardware accelerator to perform calculations in real time for a programmable time interval set by the user, 10ms in this instance and a sampling interval of 90ms was employed. Anti-aliasing filters were also employed prior to the ADC. Raw vibration waveforms, sampled at 8192 Hz, were

recorded for a period of 1 second at intervals of 30 minutes. Vibration r.m.s values were calculated over the recorded duration (1-second).

During the inspection interval, gear teeth surfaces on both the pinion and gear were visually inspected for pitting or other abnormalities such as scoring and scuffing. The largest pitted area on any single tooth was recorded. The authors set the failure, or test termination, criterion at 50% pitted area of the gear tooth surface area. The visual inspections were performed by two separate inspectors independently and repeated for consistency. This inspection error was determined to be $\pm 5\%$ of pitted area. The spectrometer used for SOA was an Atomic Emission type, namely Inductively Coupled plasma (ICP). The ICP used for determining levels of Fe elements in the lubricating fluid had an accuracy of $\pm 3\%$ at an average precision of 95% confidence level.

5   RESULTS

Figure 1 shows percentage of the gear surface pitted area plotted against the test operating time. A linear model was fitted to the acquired data with a correlation coefficient value (R^2) of 0.9724. Figure 2 shows results of AE r.m.s levels from the sensor on the pinion gear plotted against percentage of pinion gear pitted area. The relationship between AE levels and level of pitting was linear. It can also be seen that despite the application of the same torque, both tests had different AE r.m.s values at 10% pitting though the gradient of progression from 10% pitting was nearly identical. The authors attribute the difference in AE r.m.s levels to the assembly of the rig during

installation of the second test gear. The authors cannot guarantee that the exact positioning of the gear wheels and clearances within the gearbox were identical for each test condition; best practice was followed. Figure 3 shows a plot of pinion bearing AE r.m.s levels versus the percent pinion gear pitted area illustrating an exponential relationship between AE levels and percentage of gear pitted area. It should be stated that the average attenuation from the gear face to the bearing casing was measured at approximately 35dB. However, as observed by Toutountzakis et al [7] the attenuation value does vary significantly. Figure 4 was taken from Toutountzakis' report [7] which shows the AE response acquired simultaneously from the sensors mounted on the pinion gear and bearing casing; the variation in attenuation values is evident. The reason for this was attributed to the position of the bearing ball/roller elements during rotation. Toutountzakis employed the same test-rig as the authors.
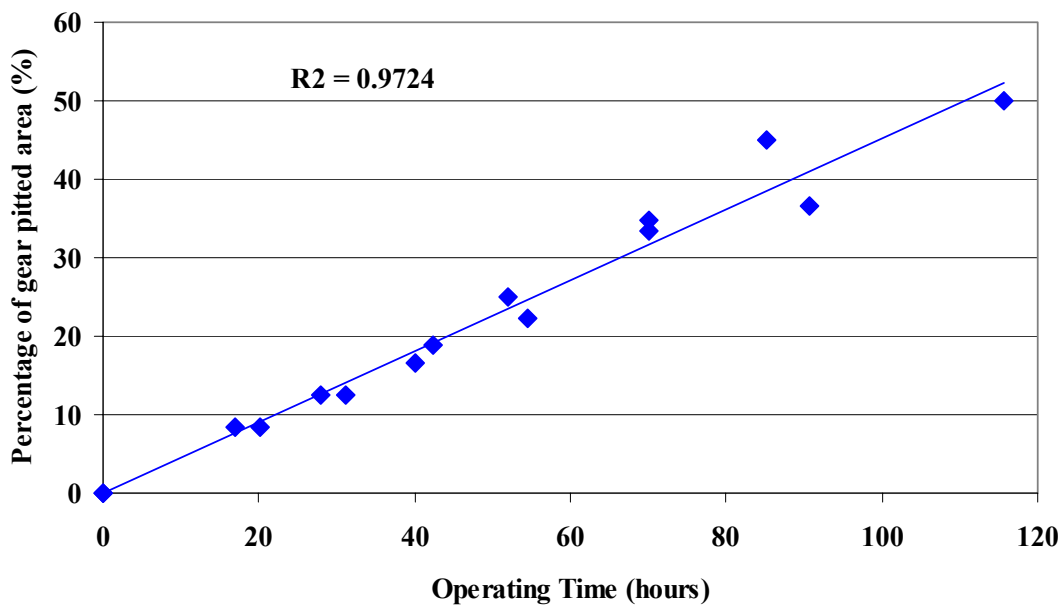

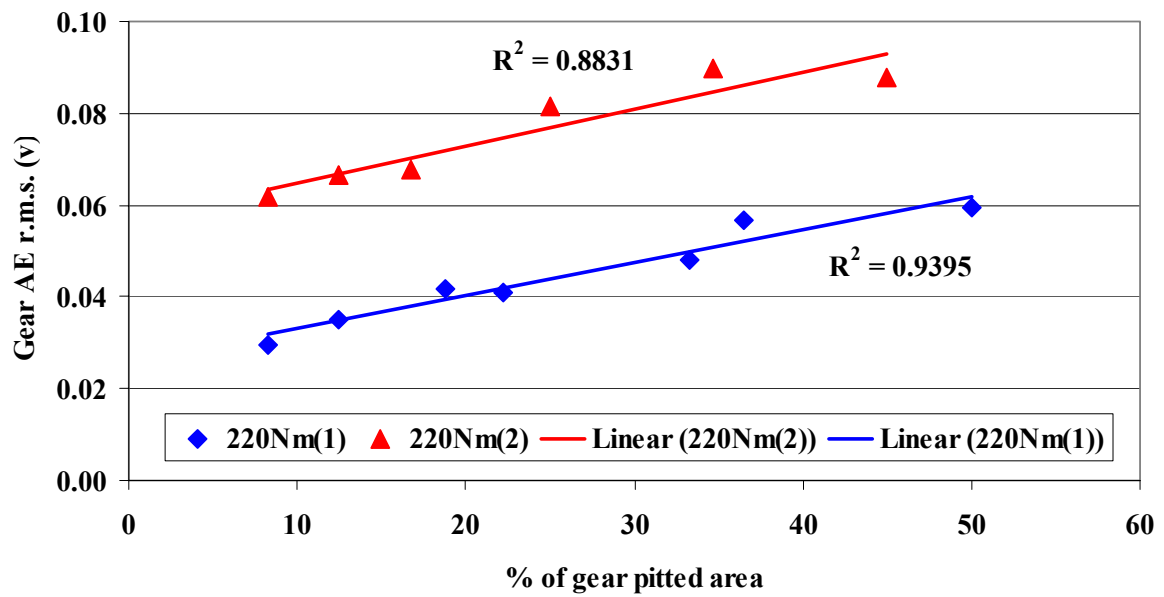**Figure 1   Pitting rates of the test gears under 220Nm at 745 rpm**

Figure 2   **AE r.m.s plotted against % gear surface area pitted; 220 Nm, 745 rpm**
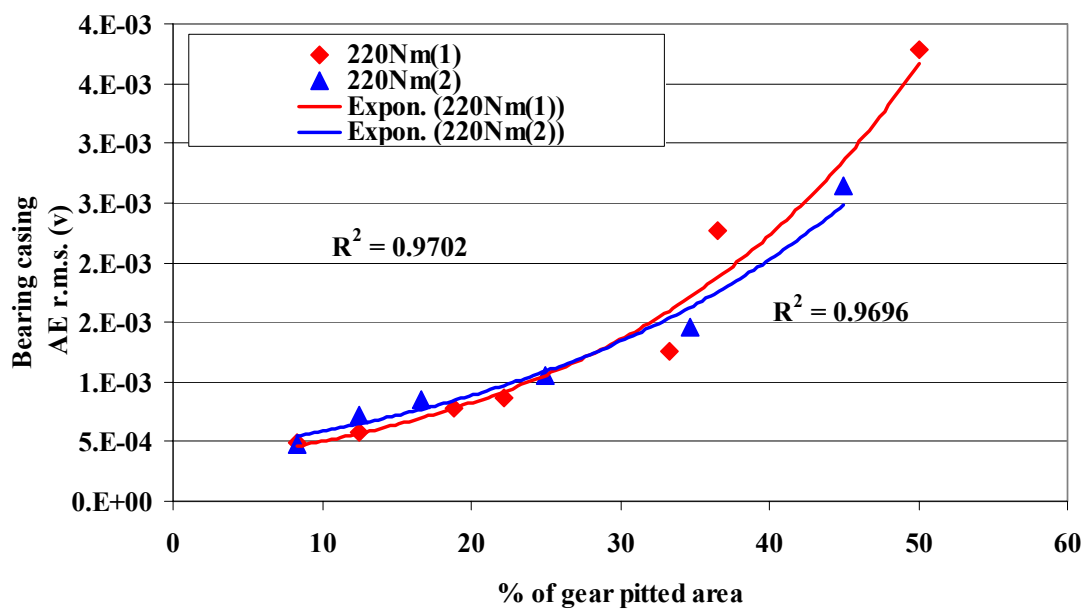

Figure 3   **Bearing casing AE r.m.s against % gear surface area pitted; 220 Nm, 745 rpm**
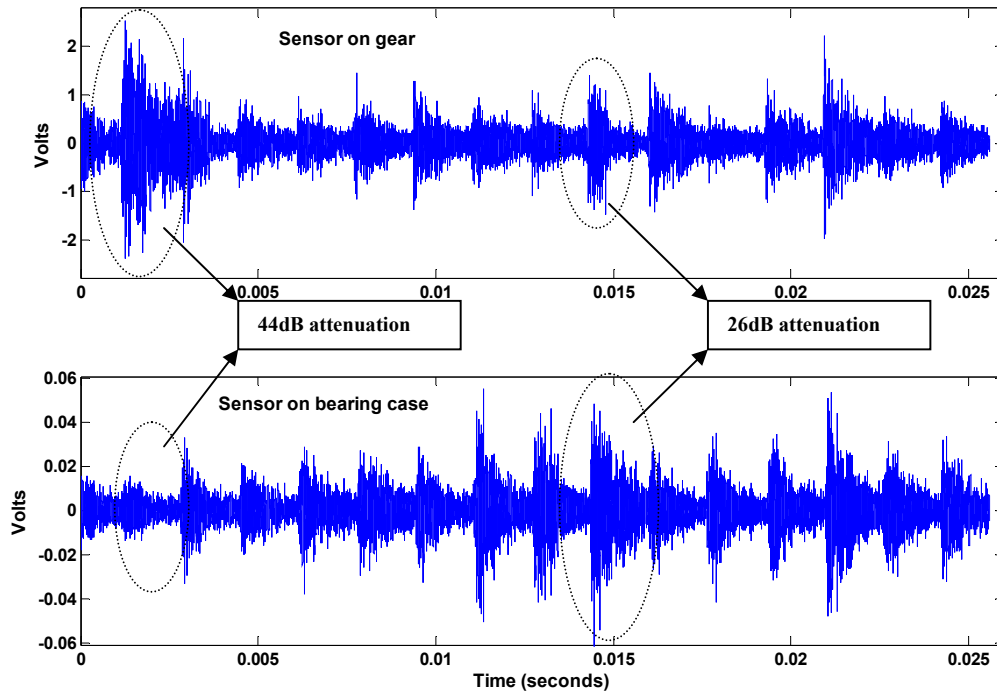
Figure 4   Variation in AE attenuation levels between pinion gear and bearing casing [7]

Figure 5 shows vibration r.m.s values plotted against percentage of pitted area. Vibration levels remained relatively constant until 30% pitted area, after which levels rose steadily. Results from the SOA analysis, figure 6, were inconclusive; whilst 'test 1' indicated a possible linear relationship between Fe concentration and percentage pitted area 'test 2' showed a similar pattern to vibration results; relatively constant Fe concentration until just after 30% pitted area when levels steadily increase. Interestingly, the experiments revealed pitting occurred from the dedendum and moved towards the pitch-line, figure 7 show a heavily pitted (42% surface area) gear.
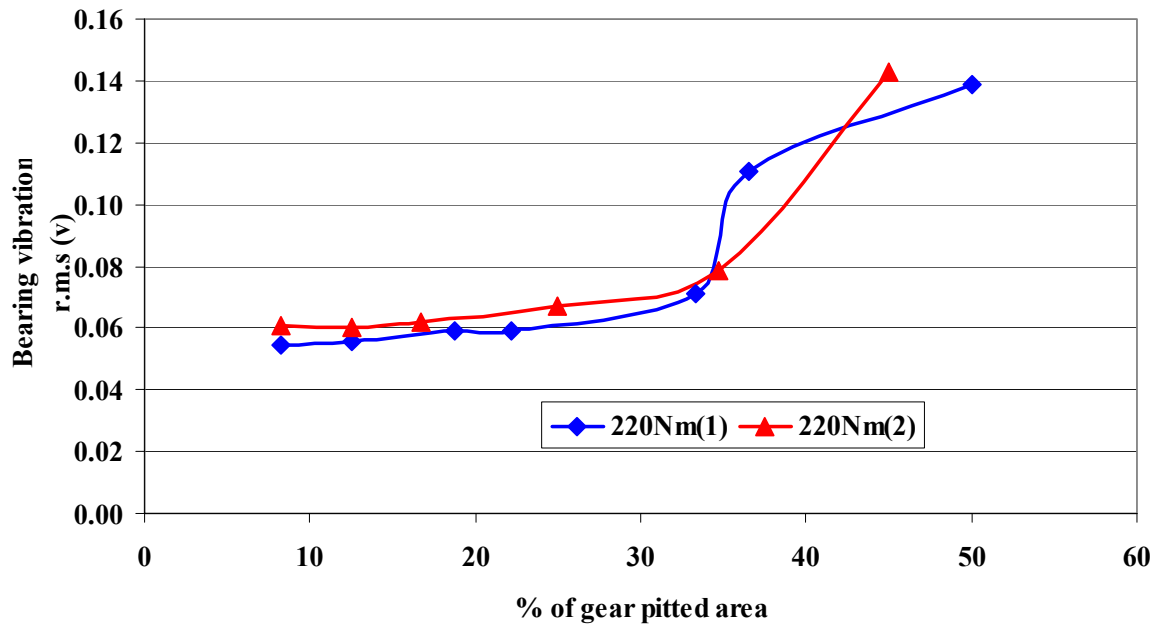
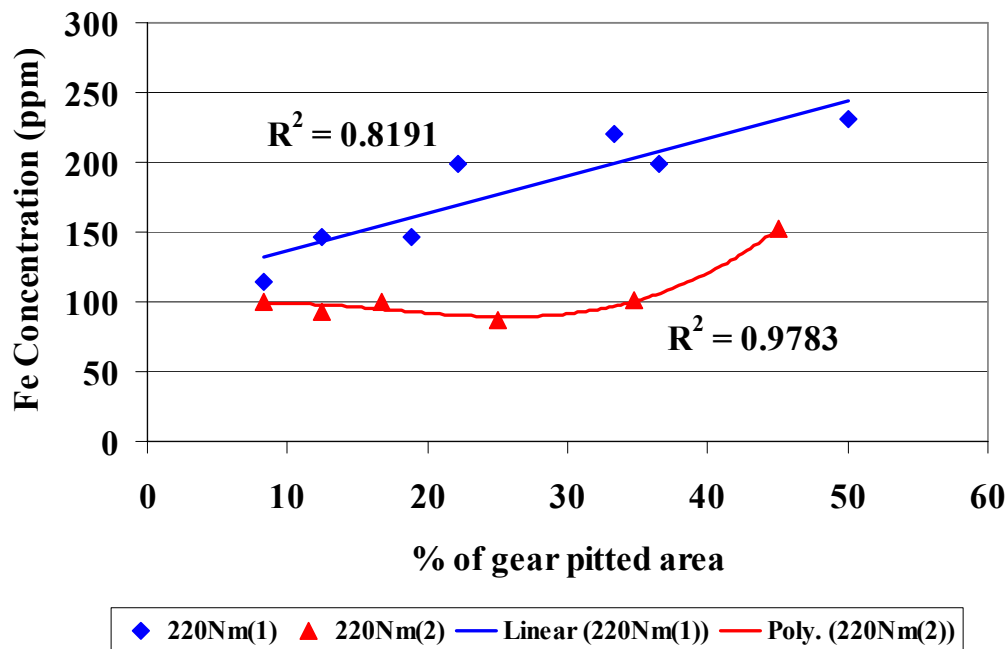**Figure 5**   **Vibration r.m.s against % pitted area; 220 Nm, 745 rpm**

Figure 6   **Fe concentration against % pitted area; 220 Nm, 745 rpm**

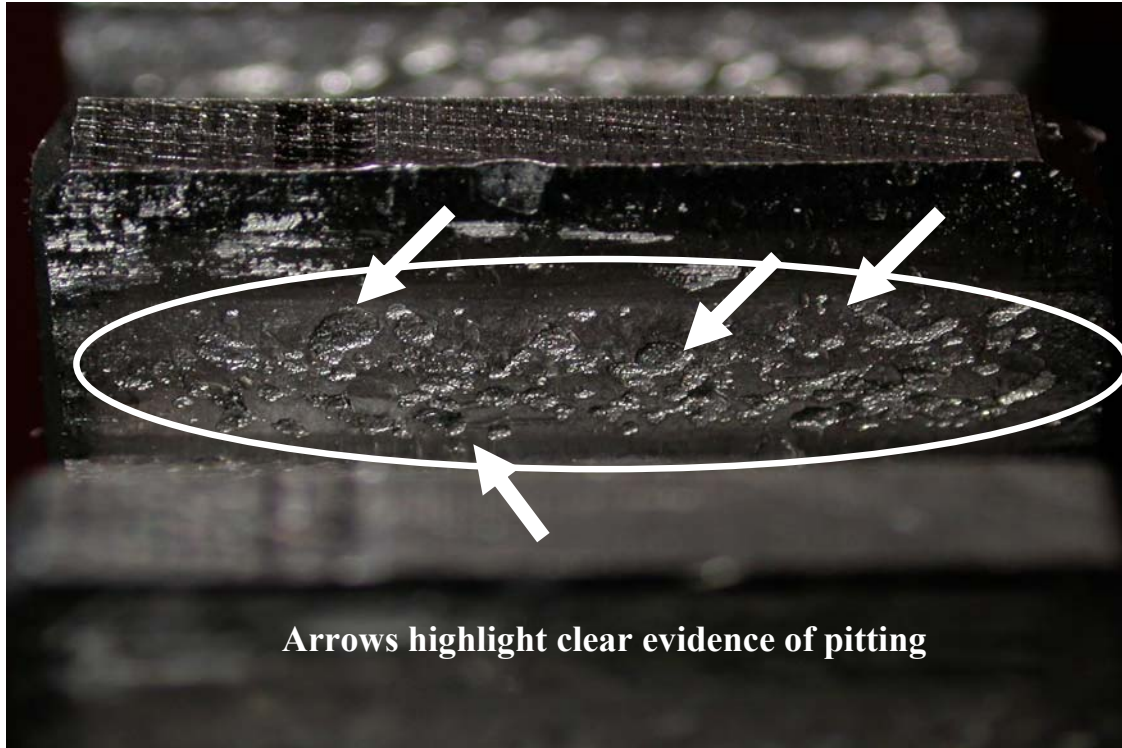Arrows highlight clear evidence of pitting

Figure 7   42% pitted area of gear face

6.   DISCUSSION

In relating AE activity to pitting rates cognisance of the effects of surface roughness, lubrication regime, friction and the slide-to-rolling ratio of the meshing gears must be considered. Xiao et al [8], Diei [9], Dornfeld et al [10] and Price et al [11] observed a correlation between AE r.m.s and the rate of frictional energy dissipation from sliding contact. It was noted that the basic mechanism for AE generation during sliding was the elastic deformation of the material at asperity contacts. This deformation was augmented by increased rates (sliding speed), contact forces and lubrication. Based on the observations of AE activity and pitting progression during this investigation the authors postulate that AE levels will increase with increasing gear pitted area. A consequence of

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the increase in pitted area is an increase of surface roughness and friction, leading to an increase in AE levels.

It was observed that AE r.m.s levels measured from the pinion and bearing casing showed increasing levels with increased pitting area which was not necessarily the case for vibration and SOA observations. This emphasised the sensitivity of the AE technique. From vibration results a plateau was observed for the vibration r.m.s until the gear surface pitted area increased to approximately 30%, see figure 4. This showed that vibration technique was unable to monitor the pit growth process until the pit development was advanced. Hence at this point, it can be concluded that the AE technique has an advantage over the vibration technique in terms of pit growth monitoring. The reason for the delayed increase in vibration also confirms that the changes in stiffness only occur at high levels of surface damage [12]. For SOA monitoring the levels of Fe concentration in the two tests differed by as much as 100% for a pitted area of 35%. Moreover, the relationship between the FE concentration levels and pitted area differed significantly for the two tests. This was rather disappointing and suggests that SOA may be able only to provide approximate indications of current gear level damage and unable to form the basis of a prognostic monitoring system.

7   CONCLUSIONS

From the results presented it was clearly evident that the AE r.m.s monitoring indicator could be directly correlated to the gearbox pitting rates. It offered much earlier indication

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of damage than vibration analysis which could only detect damage after 30% of pitted area was achieved. The near linear relationship between AE and pit progression offers great potential, and opportunities, for prognostics in rotating machinery. In contrast, the performance of SOA and vibration diagnostic techniques was disappointing. Neither technique appears suitable for use in prognostic systems.

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