Identifying seeded defects in gearboxes with Acoustic Emission; Limitations

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Abstract

Opportunities exist for developing the Acoustic Emission (AE) technique on various forms of rotating machinery, such as gearboxes. This paper provides a short summary on recent developments in the application of AE to gear defect diagnosis, and, experimental results are presented that examine and explore the effectiveness of AE for seeded gear defect diagnosis. It is concluded that the application of AE to seeded gear defect detection is fraught with difficulties. The viability of the AE technique for seeded gear defect detection is also called into question, particularly if observations are made from the non-rotating components of a machine such as the bearing casing.

Keywords: Acoustic Emission, condition monitoring, gear fault diagnosis, gear defect identification, machine health monitoring.

Introduction

Application of the high frequency the Acoustic Emission (AE) technique in condition monitoring of rotating machinery has been growing over recent years [1-5]. The main drawback in the application of the AE technique is the attenuation of the signal and as such the AE sensor has to be close to its source. However, it is often practical to place the AE sensor on the non-rotating member of the machine, such as the bearing or gearbox housing. Therefore, the AE signal originating from the defective component will suffer severe attenuation before reaching the sensor.

In general, researchers assess the applicability of AE technique on rotating machinery by undertaking seeded and natural defect simulations. For seeded defects Siores et al [6] explored several AE analysis techniques in an attempt to correlate gearbox failures such as tooth breakage, scuffing and worn tooth during seeded defect tests. Singh et al [7] introduced a simulated pit of equal diameter and depth into the testing gearbox and commented that AE could provide earlier detection over vibration analysis technique for pitting of gears, but noted it could not be applicable at extremely high speeds or for unloaded gear conditions. Tandon et al. [8] attempted to correlate AE parameters with gear defect size using simulated pits on the pitch-line with constant depth and varying diameters. Tandon observed that the monitored AE parameters increased with defect size (pit diameter) and load. The publications sited above have concluded that observations of AE energy, r.ms and amplitude were able to offer earlier defect detection than vibration analysis. It was the intension of the authors to validate the AE technique for seeded gear defect detection. It is worth stating that a few investigators [9,10,11] have shown AE activity to increase with increased natural pitting.

Experimental set-up and procedures

The test-rig employed for this investigation was a back-to-back oil-bath lubricated gearbox. The gears (49 and 65 teeth) had a module of 3 mm, a pressure angle of 20°, and a surface roughness of between 2-3 µm. The experiment is performed under combination of applied torque; 0, 55 and 110 Nm and running speeds of 745 and 1460 rpm. The lubricant employed was an EP SAE 80W-90, GL-4 API mulit-grades gearbox oil so as to keep natural pitting and wear to minimum level during the seeded defect tests.

The AE sensors used for this experiment were broadband type sensors with operating range between 100 KHz to 1MHz (Model: WD, PAC). One sensor was placed on pinion (49 teeth) and the other on the bearing casing (figure 1) of the pinion shaft. The cable connecting the sensor placed on the pinion with the pre-amplifier was fed into the shaft and connected to a slip ring. The output signal from the AE sensors was pre-amplified at 40dB. The signal output from the pre-amplifier was connected (i.e. via BNC/coaxial cable) directly to a commercial data acquisition card where a sampling rate of 10MHz was used during the tests. Prior to the analogue-to-digital converter (ADC), the card employed anti-aliasing filters that can be controlled directly in software.

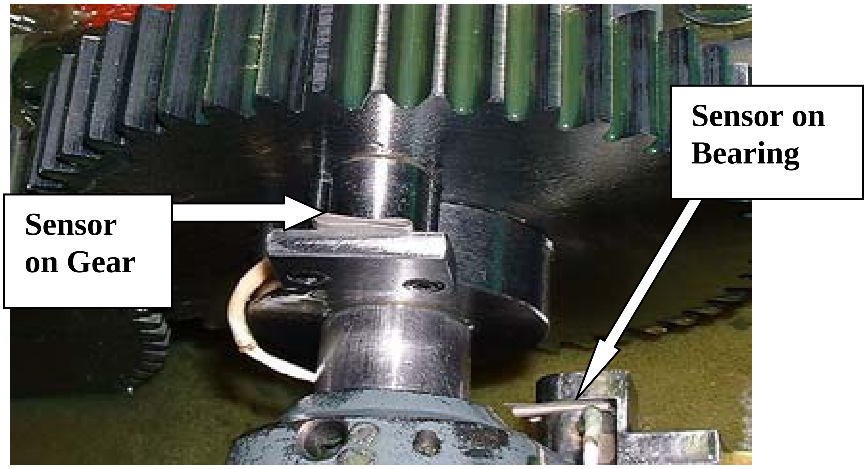

Figure 1 AE sensors located on the pinion and bearing casing.

The gearbox was run-in in excess of 15 hours before the actual experiment was carried out. The tests, at a rotational speed of 745 rpm, were undertaken with a seeded defect (extended from the pitch-line) measuring 12 mm along the face width by 3 mm from pitch-line to tooth tip (see figure 2). The seeded defect was introduced on the tooth flank of a tooth using an engraving machine. The gearbox was run for 30 minutes prior to acquiring AE data for the no load condition. The gearbox was then shut down to adjust to the next torque level (55 Nm). After another 30 minutes of continuous running, the AE data for this load condition was acquired. This procedure was repeated for the load condition of 110 Nm. Based on the sampling rate of 10 MHz, the acquisition time available for recording was 0.0256 seconds which represented 0.32 (16 teeth) revolutions of the pinion at 745. By employing a trigger mechanism, only AE data from the portion of the pinion gear wheel where the defect was located was acquired. The trigger system was set such that the defective gear tooth was at the mid point of the acquisition window (0.0256 seconds), see figure 3.

Results

The results presented, unless otherwise stated, were acquired from the AE sensor located on the pinion. The recorded AE time waveform was divided into five regions, with each region representing 3-teeth, see figure 4. The r.m.s. value of each region was computed and plotted against the three loading conditions. It was thought that this method of grouping the data would enhance the possibilities of detecting the seeded defect particularly as the defect has been seeded in the centre of the acquisition window. A total of 50 data-sets, each equivalent to a time frame encompassing 16 teeth (for 745 rpm), were acquired and averaged in each region. The averaging could be accomplished due to the optical triggering system employed ensuring that the acquisition system always started at the same rotational position of the gears.

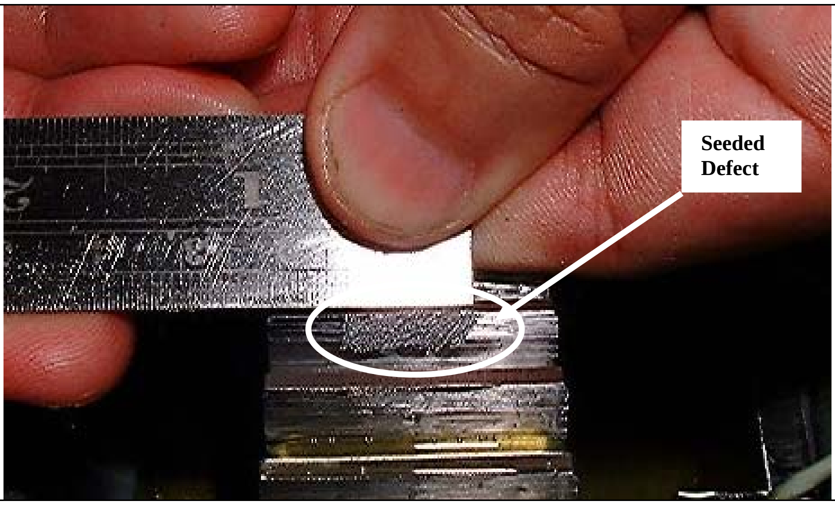

Figure 2 **Seeded large addendum defect**

Taking the 3-teeth analysis as an illustration, the r.m.s. values remained random for all loading conditions (see figure 5), as no definite trend was observed. The centre region ‘3’, where the seeded defect was introduced, did not exhibit the highest r.m.s. value as expected. In order to confirm the authenticity of these results, the recorded AE data was split further into regions representing 2-teeth and 1-tooth for all test conditions. Similar results were obtained, see figure 5. The inconsistency between the 1-tooth, 2-teeth and 3-teeth analysis revealed that this technique was not capable of defect identification. The results would have been conclusive had the r.m.s. levels for the defective tooth being higher than other regions within the acquisition window. This contradicts the work of a few researchers [6, 7, 8, 10] that claimed AE indicators such as r.m.s/energy could clearly identify a simulated pit defect.

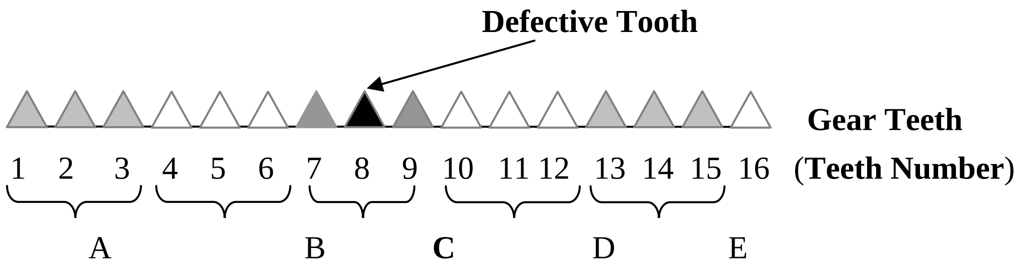

Figure 3 **Sectioning of gear teeth for analysis.**

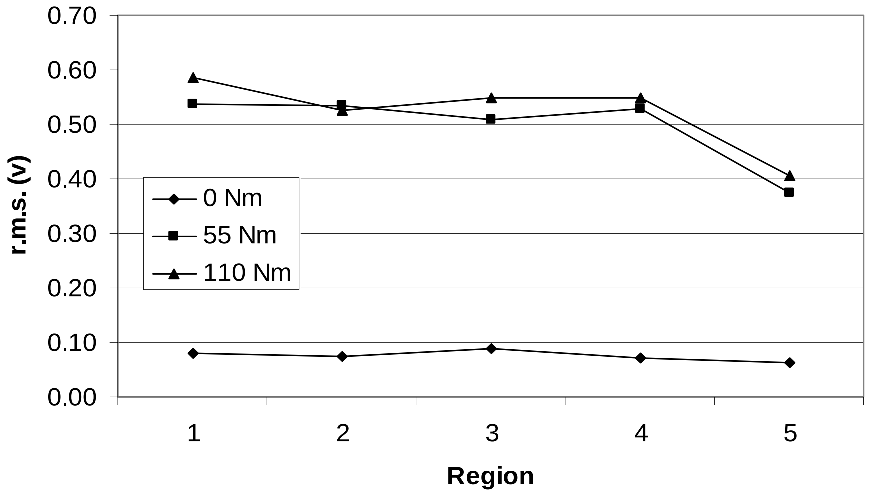

Figure 4 **AE r.m.s under various loads for 3-teeth analysis at 745 rpm. (5 regions)**

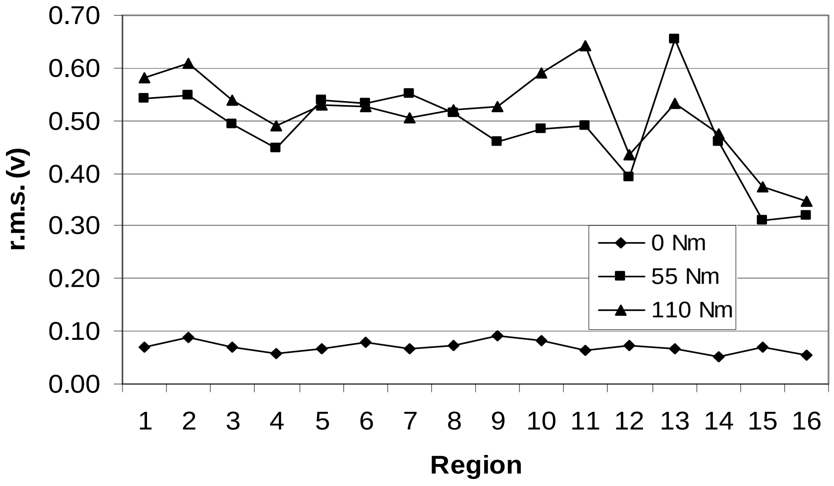

Figure 5 **AE r.m.s against loads for 1-tooth analysis at 745 rpm. (16 regions)**

AE Observations from the bearing housing

Whilst AE signatures recorded on the pinion was triggered when the defect was in the 'gear mesh window', the AE sensor on the bearing casing was synchronised with the AE sensor on the pinion. As such, when the data acquisition system was triggered, both AE sensors captured data simultaneously. During the test, it was noted that the AE bursts relating to the gear mesh, as detected on the sensor fixed onto the pinion, were also observed from the sensor on the bearing casing, see figure 6. However, continuous observations of the AE sensor on the bearing casing showed intermediate loss of the AE bursts associated with the gear mesh (figure 7). The reason for this is attributed to the bearing cage being directly under the AE transmission path. Transmission of AE burst to the bearing casing sensor will only be achievable when the bearing ball/roller elements are directly under the AE transmission path in the load zone. As the relative attenuation ranged from 44dB to 26dB depending on the particular gear mesh AE burst, see figure 6, in addition to the high probability of loss of transmission path through the bearing, see figure 7, the authors see identifying gear defects and monitoring gear deterioration from the bearing casing as fraught with difficulties, again contrary to other investigators [6, 7, 8, 10]. This must raise issues of repeatability and robustness.

Discussions

The results of AE r.m.s presented thus far were considered unsatisfactory in identifying the defect location. This resulted in additional test to explain the discrepancies, particularly as other authors had supported the applicability of these parameters to seeded gear defect detection. These new tests were carried out using the same test set-up, but in this instance the AE r.m.s. data was monitored and recorded continuously while oil temperature in the gearbox was also measured at fifteen minute intervals.

These additional tests were run at three load conditions until the AE r.m.s. and oil temperatures stabilised. The tests were terminated when the AE parameters and oil temperatures remain stable for one hour. Stabilisation at the oil temperatures was achieved when the temperature remained within 0.2^0C for the duration of one hour. Figure 8 illustrates that the gearbox system only reached a stabilised temperature in excess of 6 hours of continuous running. The starting point for all three test conditions investigated was dependent on the ambient temperature prior to testing. A smoothening technique was applied to the continuous AE data using moving average of 255 periods. From figure 8, it was noted that the AE r.m.s. varied with time as the gear box reached a stabilised temperature. This implied that depending on what time the AE data was collected for a given speed and load condition, the variation in AE activity r.ms could be as much as 33%. For these particular tests the point at which the data was captured is highlighted in figure 9. Thus, the AE signal captured during seeded defect tests were 'snapshots' that are largely influenced by load and oil temperature. As 'snapshots' only provide information at an instance in time, the repeatability of the derived AE parameters will be subjected to considerable variation.

The complications of the effect of oil temperature on AE activity have far reaching consequences, particularly as most of the published work to date have not take cognisance of this effect. The authors of this paper believe it is fundamentally flawed to compare AE activity from defect free and/or simulated defect conditions under varying loads without accounting for the influence of oil temperature. Taking cognisance that AE activity is generated during the meshing of the gears, principally due to asperity contacts [13], the introduction of a seeded defect, which removes surface material, digresses from the basic source of AE generation. Therefore the authors argue that defect identification of seeded defects of this nature cannot be accomplished with the AE technique, particularly under repeated testing. This statement will hold true if seeded defect involved the removal of material from the surface. However, other authors [6, 9, 10] have claimed success and it is argued that the more likely reason for this is as follows: It is highly possible that in the process of material removal from the gear face 'mounds' or 'protrusions' will be formed at the boundaries of the seeded defect, see figure 10. These are created due to the displacement of material from the region of material removal. The authors postulate that it is these 'protrusions' that was responsible for AE activity. However, this activity will only last until the 'protrusions' are flattened during the operation of the gear, see figure 11. In the later instance, AE will be generated by asperity contacts.

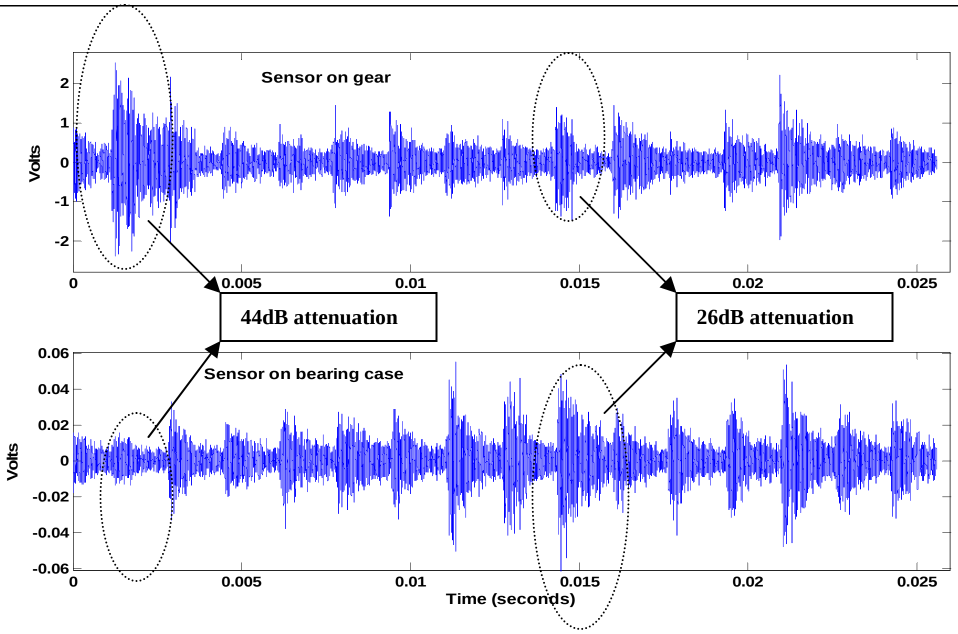

Figure 6 **AE bursts detected on pinion sensor were observed on bearing casing sensor, speed 745 rpm and load 55 Nm.**

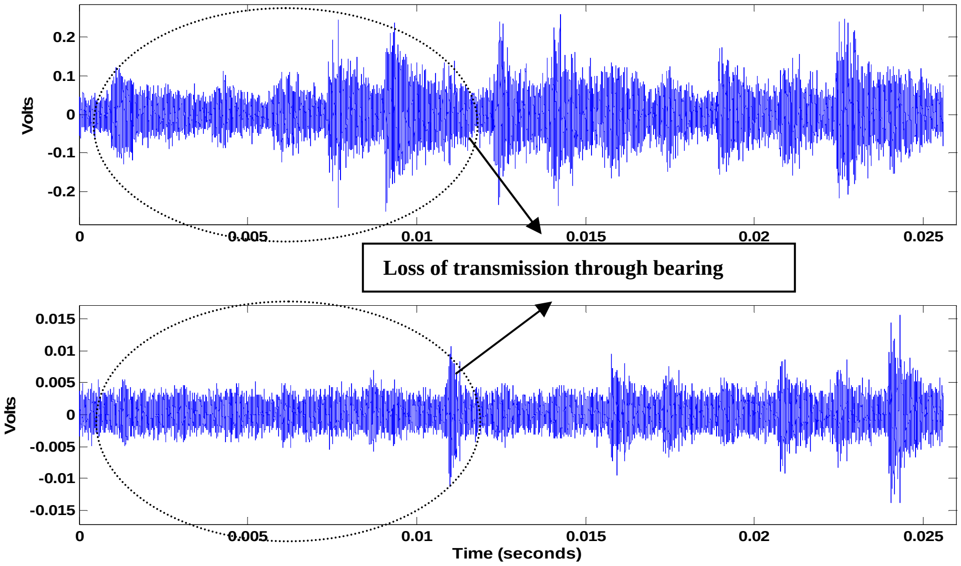

Figure 7 Loss of transmission path at particular gear mesh positions observed on bearing casing sensor, at speed 745 rpm and load 55 Nm.

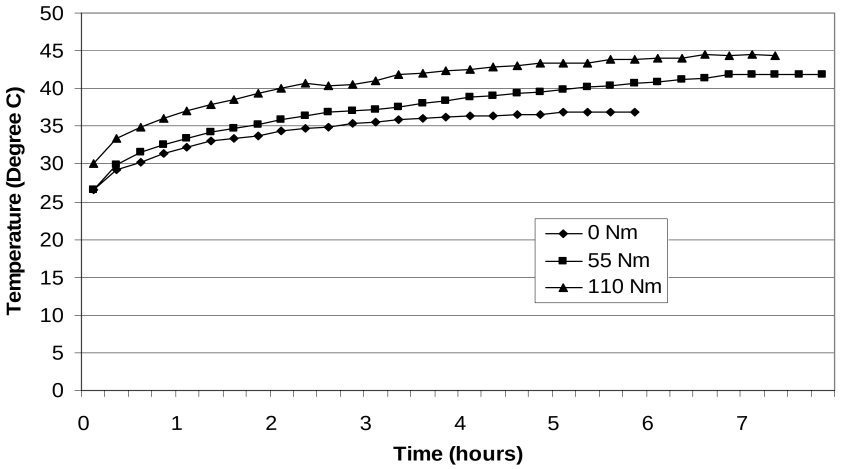

Figure 8 Oil temperatures monitoring with no-load, 55 Nm-load and 110 Nm-load conditions at 745 rpm.

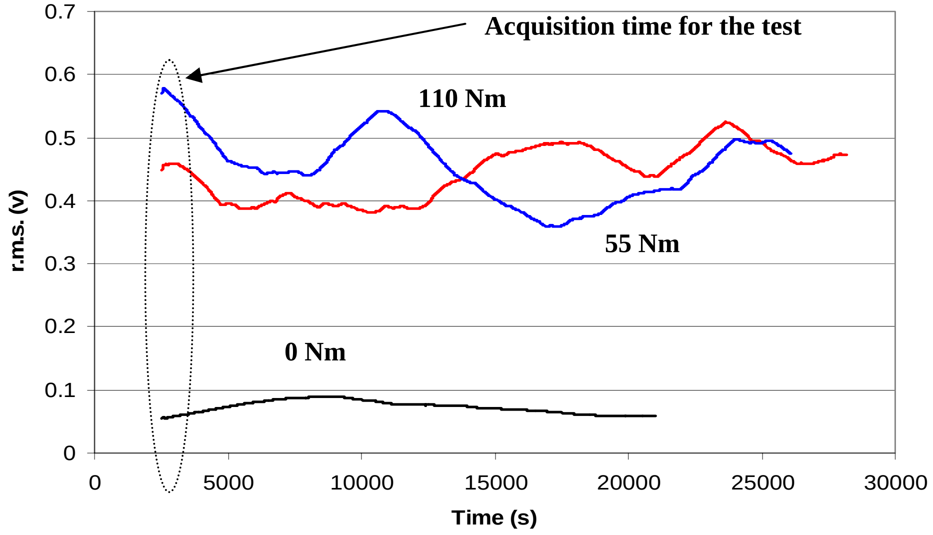

Figure 9 Continuous AE r.m.s values 1460 rpm.

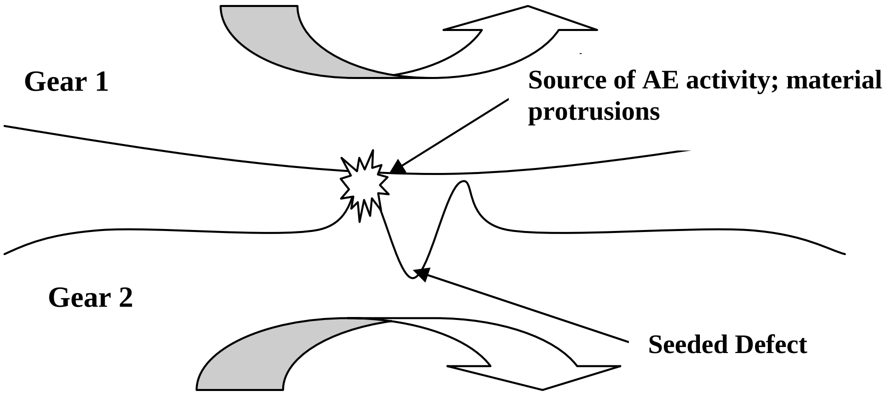

Figure 10 Mounds or Protrusions of the gear surfaces in contact during rotation.

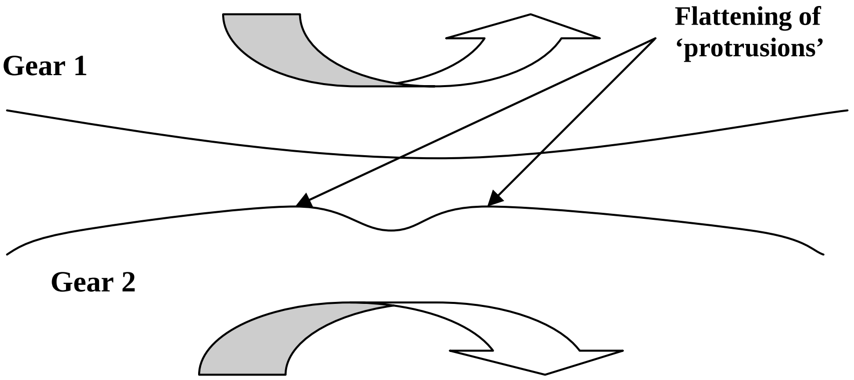

Figure 11 Flattened protrusions of gear surfaces

Conclusion

This paper has demonstrated that artificially seeded gear defect detection with AE is fraught with difficulties. Experiments to identify a seeded defect with AE r.m.s. was not satisfactory. The influence of oil temperature on AE activity has been presented. This work is part of an ongoing program which aims to further investigate some of the drawbacks detailed.

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