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Identification of the Onset of Cracking in Gear Teeth Using Acoustic Emission

R Pullin[1], A Clarke, M J Eaton, M R Pearson and K M Holford
Cardiff School of Engineering, Cardiff University, The Parade, Newport Road, Cardiff, Wales, UK, CF24 3AA

Abstract. The development of diagnostic methods for gear tooth faults in aerospace power transmission systems is an active research area being driven largely by the interests of military organisations or large aerospace organisations. In aerospace applications, the potential results of gear failure are serious, ranging from increased asset downtime to, at worst, catastrophic failure with life-threatening consequences. New monitoring techniques which can identify the onset of failure at earlier stages are in demand. Acoustic Emission (AE) is the most sensitive condition monitoring tool and is a passive technique that detects the stress wave emitted by a structure as cracks propagate. In this study a gear test rig that allows the fatigue loading of an individual gear tooth was utilised. The rig allows a full AE analysis of damage signatures in gear teeth without the presence of constant background noise due to rotational and frictional sources. Furthermore this approach allows validation of AE results using crack gauges or strain gauges. Utilising a new approach to AE monitoring a sensor was mounted on the gear and used to continuously capture AE data for a complete fatigue load cycle of data, rather than the traditional approach where discrete signals are captured on a threshold basis. Data was captured every 10th load cycle for the duration of the test. A developed fast fourier transform analysis technique was compared with traditional analytical methods. In this investigation the developed techniques were validated against visual inspection and were shown to be far superior to the traditional approach.

1. Introduction

Detection and diagnostic methods for gear tooth faults is a fundamental research activity for military and aerospace organisations such as NASA [1-3]. In addition Health and Usage Monitoring Systems (HUMS) are mandatory for helicopter operators servicing, for example, the North Sea oil industry. Currently methods for detecting damage in transmission systems are predominantly based on vibration [4,5].

Any gear failure results in increased asset downtime and maintenance expenditure and at worst can cause catastrophic life threatening failure. It is essential therefore that any new techniques that can identify damage at earlier stages than vibration methods should be investigated and employed as part of a global Structural Health Monitoring (SHM) system.

Acoustic Emission (AE) monitoring is a possible alternate technique to vibration analysis. It is one of the most sensitive damage detection methods and is used widely in other applications such as bridge structures and pressure vessels. Furthermore it offers significant advantages in terms of early fault detection and diagnosis compared to other techniques [6]. AE is the detection of stress waves, released as a result of damage advancement, that propagate through a solid material as it undergoes stress.

[1] pullinr@cardiff.ac.uk

Compared with the reasonably mature applications of AE to structural monitoring, use of AE to monitor rotating machinery in general, and high speed, heavily loaded aerospace transmission gears in particular, is at the developmental stage. Researchers have investigated AE from spur gears [7-10] predominantly using measures of RMS AE levels, with some success in detecting gross changes. However a much clearer understanding of AE sources in gear contacts and radically improved signal analysis and interrogation methods are necessary to detect the onset of damage and to provide viable automated techniques for identifying damage onset in these applications.

The aim of this paper therefore is to build on previous investigations [11] and to further assess novel methods for identification in gear structures using AE.

2. Experimental Procedure

A bespoke test rig as described in [11] was manufactured to allow the static loading of an individual gear tooth pairing (Figure 1). A PANCOM acoustic sensor (50-450 kHz) was attached and coupled to the gear using cyanoacrylate. The response of the system to a Hsu-Nielsen source [12, 13] was used to ensure the correct sensitivity of the installed monitoring equipment. AE data was captured using a MISTRAS group PCI 2 data acquisition system. The system was used to record both AE transients and wave-streams for the life of a tooth subjected to fatigue loading (0.35-3.5 kN at 1Hz).

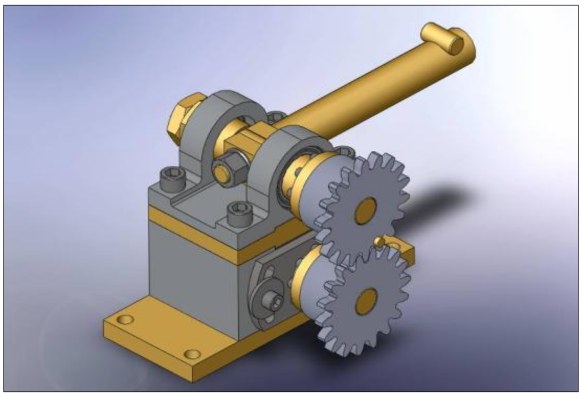

Figure 1. CAD Model of developed test rig.

Traditional AE data was captured throughout the test whilst a wave-stream was captured every 10th cycle using a micro-switch positioned under the loading arm and a decade counter connected to the external trigger of the acquisition system. Wave-streams, unlike traditional waveforms are independent of threshold and AE data is sampled over a user defined period, in this example one complete cycle. In contrast the traditional approach uses timing strategies to determine when a signal has surpassed and dropped below a threshold and a waveform is then recorded. Figure 2 presents an example wave-stream covering two cycles with the corresponding sinusoidally varying load superimposed. Visual observation of the onset of cracking was used to validate any findings.

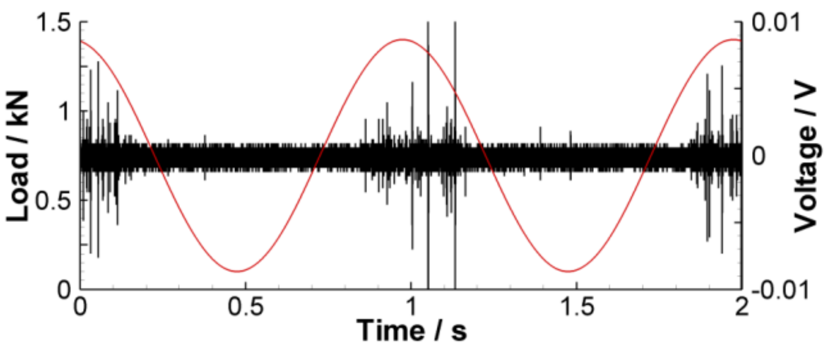

Figure 2. Example AE Wave-stream and discrete signal

3. Results and Discussion

The completed analysis has been separated into two distinct sections – *viz.* a traditional analysis that examines the amount of acoustic energy and the frequency of the detected acoustic signals and a novel approach that utilises wave-streams. Periodic visual observation showed that the crack started shortly after 22’000 cycles.

3.1 Traditional Analysis

Conventional analysis of AE data relies on the assessment of parameters that describe detected acoustic waves that exceed and drop below a user defined threshold as previously described. These parameters include measures of energy, amplitude, timing features such as rise to peak and duration and counts (number of threshold crossings). In theory, during a fatigue investigation, the amount of detected energy should remain linear when there is no crack present. Energy will be detected from load machine and test rig noise but this should remain constant on a cycle per cycle basis. However as a fatigue crack starts to initiate a new energy source will be observed, changing the rate of energy detected and hence an indication of the onset of cracking is noted. A similar pattern should be seen for the number of detected signals that pass the threshold, more commonly known as hits. Figure 3 shows the energy and hits detected above 900 N for the entire test.

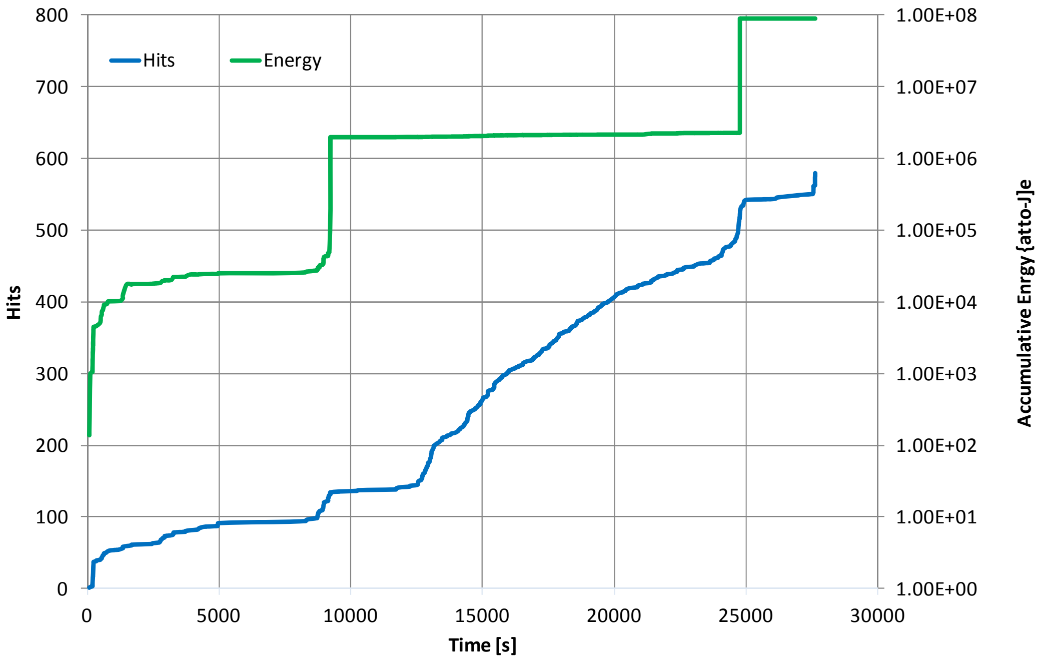

Figure 3. Traditional AE analysis based on energy and detected signals for above 900 N

It can be seen from the traditional approach that there is no clear change in detected signals after visual observation until just prior to 25’000 cycles. An initial assessment of all the detected signals showed no clear identification and therefore the signals detected above 900 N were considered. However there are also rises at approximately 0, and 9’000 and 13,000 cycles making automatic identification difficult.

3.2 Novel Approach

The captured wave-streams were used to perform further analysis. Initially, the RMS approach favoured by other researchers [7-9] was adopted. The RMS level of each wave-stream was calculated and can be seen in Figure 4.

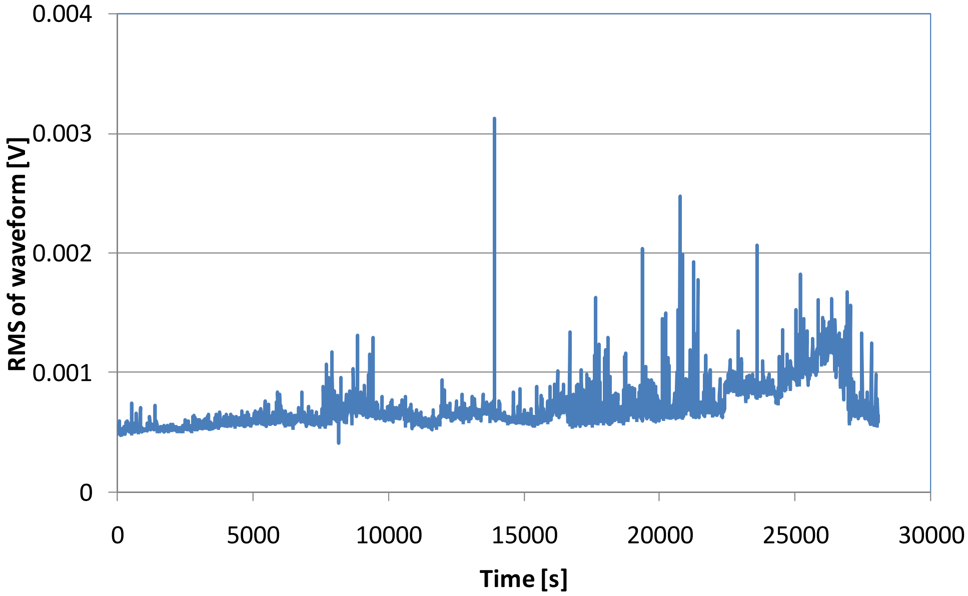

Figure 4: RMS level of wave-stream

It may be seen that whilst the RMS approach does demonstrate an overall increase in Acoustic Emission towards the later stages of the test, it does not clearly discern the onset of cracking in the gear tooth. Subsequently, a fast fourier transform (FFT) of an entire wave-stream was completed for every cycle. This FFT was then sub-banded into distinct frequency ranges/sub-bands. In theory noise due to rotating signals will occur at a distinct frequency band (in this example load machine noise) whilst damage will occur at higher frequencies, typically 100-150 kHz in metallic materials. The sub-banding process was designed to visually show how different noises dominate frequency bands throughout the test. Figure 5 shows the peak amplitude of the FFT of every wave-stream, captured through the duration of the test, separated into eleven sub bands. Each band was 20kHz wide, equally spaced between 80 and 300 kHz.

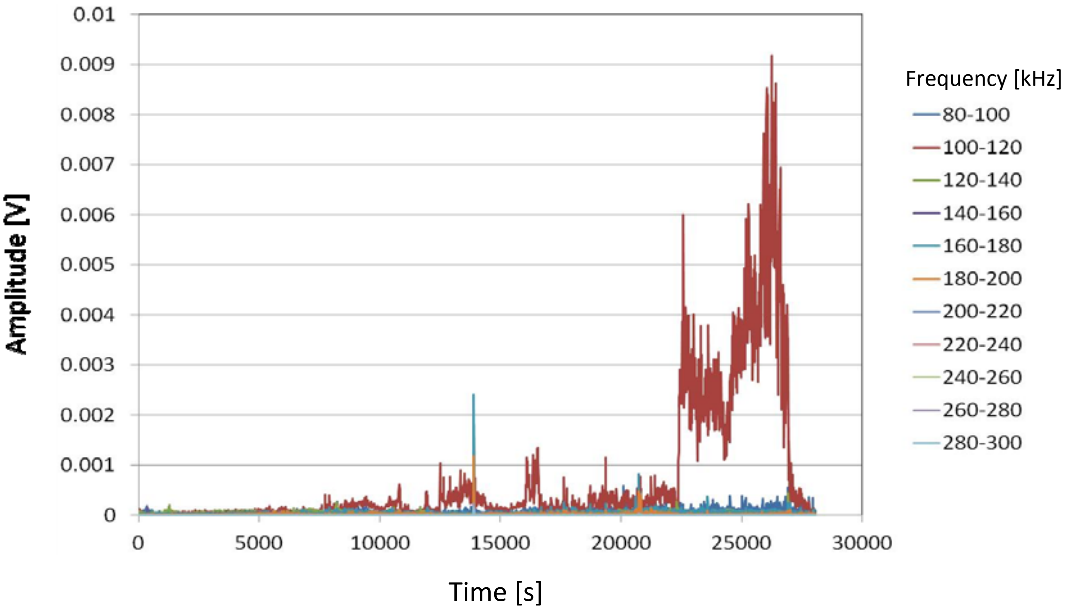

Figure 5. Peak value of FFT in distinct frequency bands

Figure 5 clearly shows a distinct rise in the peak amplitude of the FFT of the wave-stream in the 100-120 kHz sub-band. The plot shows that in this frequency range several peaks occur but particularly after the visual observation at 22,000 cycles there is a clear rise that continues to the end of the test, clearly crack growth. A further demonstration of the technique is presented in Figure 6.

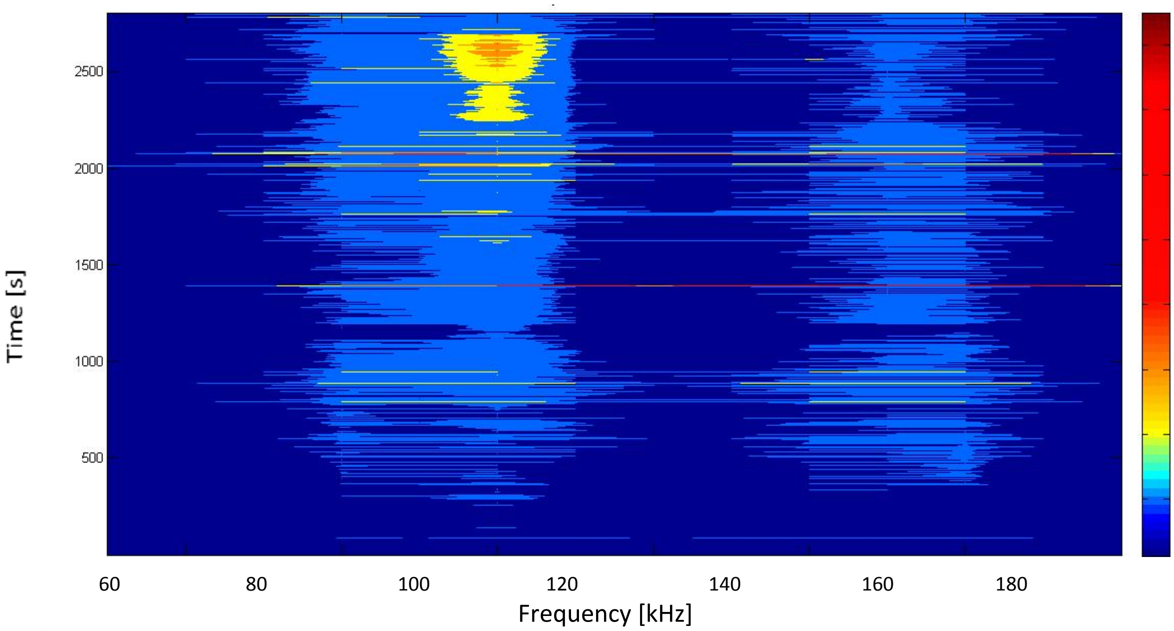

Figure 6. Intensity of FFTs in 100-120 kHz frequency bands

Figure 6 shows the intensity of each individual FFT in the 60-190 kHz frequency band plotted against test cycles. In this analysis, intensity is the sum of the amplitudes of the FFT at each frequency within the band. It is proposed that this banded approach is more suitable for complex shapes such as gear teeth where signal paths to the sensor may be subject to attenuations, that merely tracking a single frequency. An alternate approach using mean levels within each band identified similar trends.

The plot clearly demonstrates that something novel occurs shortly after 22’000 cycles and is therefore identifying the crack in the tooth. This demonstrates the sensitivity of the technique but importantly is visual, therefore a non-AE expert could easily identify a new mechanism happening in the gear system. In addition the sub-banding process allows background noise to be filtered, in this static gear rig, leaving only crack signatures. The same approach should function as effectively in rotating machinery, subject to further development. Figure 6 also demonstrates higher levels of intensity in the 100-120 kHz band from about 200 seconds onwards.

The novel technique presented has clearly demonstrated damage detection where a traditional approach failed. In addition the method outlined could offer further damage assessment opportunities including the ability to assess gear run in and possibly the detection of the breakdown in lubricant in gear boxes which will cause asperity contacts in the gears to develop. The techniques developed need to be assessed in rotating structures to validate these findings.

Although the process has focussed on gear structures it is evidently applicable to damage detection in any fatigue test where the identification of a novel source such as fatigue crack is important. The process will be trialled on other aerospace materials such as composites and will be the focus of future applications.

4. Conclusions

A novel test rig, designed to fatigue load an individual gear tooth, has been utilised to assess the performance of traditional AE analysis compared with a wave-stream approach. A traditional analysis could not easily identify the onset of cracking. Wave-streams captured very 10^{th} cycle were used to identify fatigue cracking of the gear tooth. An assessment of the peak FFT value for distinct sub-bands of the captured data allowed a very visual approach to crack detection to be realised. Furthermore an intensity analysis of the one sub-band further demonstrated the technique developed. All results were validated against visual observation.

5. Acknowledgements

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6. References

[1] Wong AK, "Vibration-based helicopter health monitoring – an overview of the research programme in DSTO", DSTO-HUMS2001, 2001.
[2] Decker HJ, "Gear crack detection using tooth analysis", NASA-TM2002-211491, 2002
[3] Decker HJ, "Crack detection of aerospace quality gears", NASA-TM2001-211492, 2002
[4] Larder BD, "Helicopter HUM/FDR: Benefits and Developments", *American Helicopter Society 55th Annual Forum*, Montreal, Canada, 25-27th May 1999.
[5] McColl J, "Overview of transmissions HUM performance in UK, North Sea Helicopter Operations", *in proceedings of the IMechE Seminar on Rotor Transmission System Health Monitoring* – experience update, November, 1997
[6] Loutas TH *et al.*, "Condition monitoring of a single-stage gearbox with artificially induced gear cracks utilizing on-line vibration and acoustic emission measurements", *Applied Acoustics*, 2009, **70**, 1148-1159.
[7] Toutountzakis T, Tan CK, Mba D, "Application of acoustic emission to seeded gear fault detection", *NDT E Int*, 2005, **38(1),** 27-36
[8] Tan CK and Mba D, "Investigation of the acoustic emission source during a comparative study on diagnosis of a spur gearbox", *Tribol. Int*., 2005, **38(5)**, 469-480
[9] Tan CK and Mba D, "Experimentally established correlation between acoustic emission activity, load, speed, and asperity contact of spur gears under partial elastohydrodynamic lubrication", *Proc Inst Mech Eng Part J, J*. Eng Tribol, 2005, **219**, 401-409
[10] Loutas TH *et al.*, "A novel approach for continuous acoustic emission monitoring on rotating machinery without the use of slip ring", *Trans ASME J Vibration and Acoustics*, 2008, **130**, 064502-2
[11] Pullin R, Clarke A, Eaton M, Holford K M, Evans S L, and McCory J P," Detection of Cracking in Gear Teeth Using Acoustic Emission", *Applied Mechanics and Materials*, 2010, **24-25**, 45-50
[12] Hsu NN, Breckenridge FR. Characterization and Calibration of Acoustic Emission Sensors. *Mater Eval*. 1981, **39(1**):60-8.
[13] ASTM. A standard guide for determining the reproducibility of acoustic emission sensor response. *American Society for Testing and Materials*, 2010;E976.