Condition Monitoring of Rotating Machinery with Acoustic Emission: A British–Australian Collaboration

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Abstract Industries such as transport and energy generation are aiming to create cleaner, lighter, more reliable and safer technology. Condition monitoring of rotating machinery is an established way of reducing maintenance costs and associated downtime. Whereas vibration based condition monitoring has been validated in literature and in industrial applications, acoustic emission (AE) technologies are a relatively new and unexplored solution for machine diagnostics. Being based on the passive recording of ultrasonic stress waves, their frequency range gives direct access to phenomena such as friction in gear teeth sliding, bearing rolling contacts and crack formation and propagation. However, the complexity of AE signals generated in multiple machine components requires a better understanding of their link with tribological phenomena. To further knowledge in this area, a team of researchers from Cardiff University, Queensland University of Technology and University of New South Wales are conducting a joint research activity which includes: (i) the use of a twin-disk test-rig to reproduce controlled rolling-sliding contact conditions typical of gear contacts, (ii) the analysis of AE data using advanced cyclostationary signal processing and (iii) the establishment

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of a relationship between tribological conditions and AE signal characteristics. This paper outlines this project, discusses its preliminary results and introduces future extensions of this research to key industrial applications.

1 Introduction

The development of detection and diagnostic methods for gear or bearing faults or surface distress in power transmission systems is an active research area [8, 9, 20], with wide applicability ranging from wind turbine gearboxes to aerospace power transmissions. The potential results of gear or bearing failure are serious, from increased asset downtime and maintenance expenditure to catastrophic failure with life-threatening consequences. For example, there are currently widespread problems with gearbox failures in wind turbines, where a typical gearbox life is around 5 years with replacement costing hundreds of thousands of pounds [15, 17]. Thus, new monitoring techniques which can identify incipient failures are in great demand. AE monitoring is such a technique which is used widely in other applications and which offers significant advantages in terms of early fault detection and diagnosis when compared to other techniques [11]. It is arguably the most sensitive NDT technique available, and relies upon the detection of stress waves which propagate through the solid material as it undergoes strain. When compared with the reasonably mature application of AE to structural monitoring, the use of AE to monitor rotating machinery in general, and gears and bearings in particular, is still at the developmental stage, particularly when applications such as high speed, heavily loaded aerospace or wind turbine transmissions are considered. Researchers have investigated the AE from spur gears [12, 16, 18] and from rolling element bearings [2, 6, 19] but there remains much confusion surrounding the sources of acoustic emission in concentrated elastohydrodynamic (EHL) contacts within gears and bearings. Further work is required not only to understand the source mechanisms and propagation but also to provide an automated technique for identifying damage in these types of applications. It is well known that surface failure (micropitting) usually originates at prominent asperity features, and investigations have shown that it may be possible for AE to provide a measure of the level of asperity contact for meshing gears under a range of operating conditions [16] and for rolling element bearings [6]. However, these AE investigations often operate under conditions which are not wholly representative of typical aerospace or wind turbine design practice or do not link closely with corresponding tribological research into contact conditions (particularly under mixed lubrication conditions where asperity contact is likely).

This paper presents two case studies detailing initial work as part of a British-Australian collaboration aimed at improving understanding of the fundamental link between tribological conditions and the generation of AE for lubricated contacts, and also to apply novel analysis techniques to improve the ability of AE-based technologies to detect faults within mechanical systems.

2 Analysis Techniques

The AE wavestream data recorded during the tests outlined in this paper have been analysed using a number of techniques, outlined below:

2.1 Frequency Content/Binned Analysis

The wavestreams were analysed in terms of their frequency content using amplitude FFT algorithms within the Matlab environment. The analysis of successive wavestreams allowed the evolution of frequency content with time to be examined. Furthermore, to allow for slight fluctuations in operating speed, the frequency content was analysed in frequency "bins" or ranges, summing content within each range, to evaluate the particular frequency ranges of interest. A full description of these techniques may be found in Cockerill et al. [5].

2.2 Chebyshev Moments

A reconstruction of the wavelet decomposition of a signal, in particular, can be used as a form of time-frequency transform, where each wavelet level is more sensitive to certain frequencies within a signal.

The Chebyshev moments calculation procedure from Crivelli et al. [7] is as follows:

1. sample a discrete waveform with N points;
2. compute a discrete wavelet transform using M detail levels (Daubechies 10);
3. reconstruct and rectify the wavelet details into a $N \times M$ matrix;
4. compute the Chebyshev moments of the $N \times M$ matrix up to the desired degree.

Steps 2–3 produce a virtual image (matrix) of the time domain signal, where each row represents a wavelet detail level (approximately a frequency band). As the degree of the Chebyshev moment increases, more detail about the representation of the signal will be carried in the representation. These moments can be used as signal descriptors and further used for comparing datasets, as shown by Sebastian et al. [13]. From previous tests, a polynomial degree of 5 (25 moments) is sufficient to carry enough information while maintaining the computational effort low enough to be usable in real time applications.

3 Case Studies

3.1 QUT Bearing Rig

The data analysed in this section was collected on a bearing prognostic test-rig located in the laboratories of the Queensland University of Technology (QUT), Brisbane (Australia). The test rig comprises a variable-speed electric motor, driving the main shaft where a test bearing (type 6806) is installed and loaded radially by a screw mechanism and a spring. The bearing is installed in healthy conditions and loaded at approximately 1.5 times its dynamic load rating in order to accelerate the degradation process. Degradation is obtained by repeating a duty cycle which includes a series of constant speed intervals with different rotating speeds (in the range 210–1300 rpm), with one full duty cycle repeating every 960 s. The run-to-failure test is considered complete when RMS vibration levels reach 24.5 g.

Chebyshev descriptors were extracted from the AE data for each revolution of the bearing test rig and different speeds. Figure 1 shows the individual moment values at 500 rpm on an exponentially weighed moving average (EWMA) control chart. The EWMA control chart is used for monitoring when the process goes "out of bounds". It assigns an exponentially weighted average to all prior data so that it becomes less sensitive to small drifts in the process (running in, periodic variations …). This results in violations when the drift is quick, i.e. when damage is present. As such, when analysed, the values indicate that signals are consistent in the first part of the test but as expected tend to deviate towards the end.

Figure 2 shows the number of EWMA control chart violations (number of parameters out of control) at different speeds, with control boundaries set at 2σ. The variations become apparent with Chebyshev moments much earlier in the test and at slower speeds when compared with traditional statistical moments (mean, standard deviation, skewness and kurtosis). It is also clear that, especially at runs closer to the failure of the bearing, the Chebyshev moments-based analysis can pick up variations in the signals at speeds where statistical moments are not showing any violation. It is also apparent that some Chebyshev moments appear to be highly correlated. This is likely due to the fact that two nearby moments can be sensitive to similar effects in relatively long signals, due to the polynomial order they represent. However, further investigation is required to confirm this assumption.

3.2 Cardiff Variable Lambda Rig

In order to investigate in a fundamental way the relationship between the generation of AE and conditions within elastohydrodynamic (EHL) rolling/sliding contacts, such as those between the teeth of heavily loaded gears or in the roller/raceway contact in a rolling element bearing, a power-recirculating twin disc test rig was developed. This rig can be seen in Fig. 3 and is described more fully by Clarke

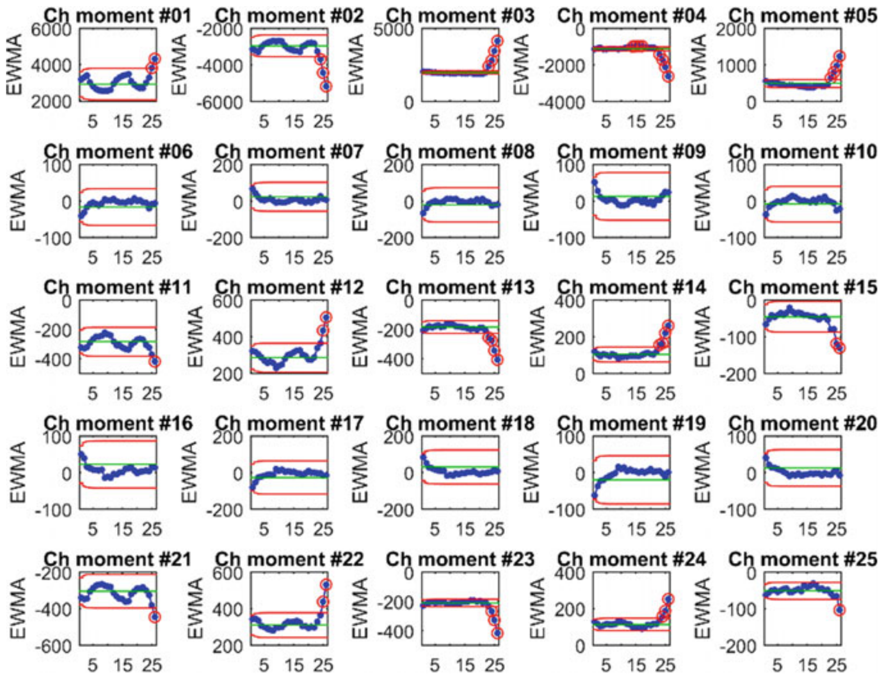

Fig. 1 Individual Chebyshev moment values @500 rpm plotted against test run: EWMA control charts. Violations (red circles) when values fall out of bounds (red lines). Some moments are more sensitive than others to changes in signal time/frequency content

et al. [3, 4]. It is capable of operating well into the mixed lubrication regime where load is carried by both direct asperity contact and by a partial hydrodynamic film.

In this rig, power is recirculated between the EHL contact between the test disks, and a gear pair, meaning that the drive motor only has to overcome frictional and other losses in the system. The test disks (made to typical gear material and hardness specifications) are 76.2 mm in diameter and have a 304.8 mm crown radius, which results in an elliptical EHL point contact with a nominal 4:1 aspect ratio, with the major axis parallel to the shaft. They are finished using an axial grinding technique which generates the crown, and gives a surface with similar roughness directionality to that of ground gear teeth in relation to the motion of the surfaces.

The shafts on which the disks are mounted are gear connected, giving a slide/roll ratio in this work of 0.5. The fast shaft speed is adjustable between 200 and 3000 rpm, and the hydraulically applied load can be varied to generate Hertzian contact pressures of up to 2.1 GPa. The contact is lubricated using a naval gear oil, supplied at a controlled temperature. The rig is fitted with an acoustic emission sensor mounted on the slower disc, connected to the AE system via slip rings. Raw AE wavestreams were recorded at 5 MHz sampling frequency using a Mistras AE system with a configuration similar to that of Cockerill et al. [5].

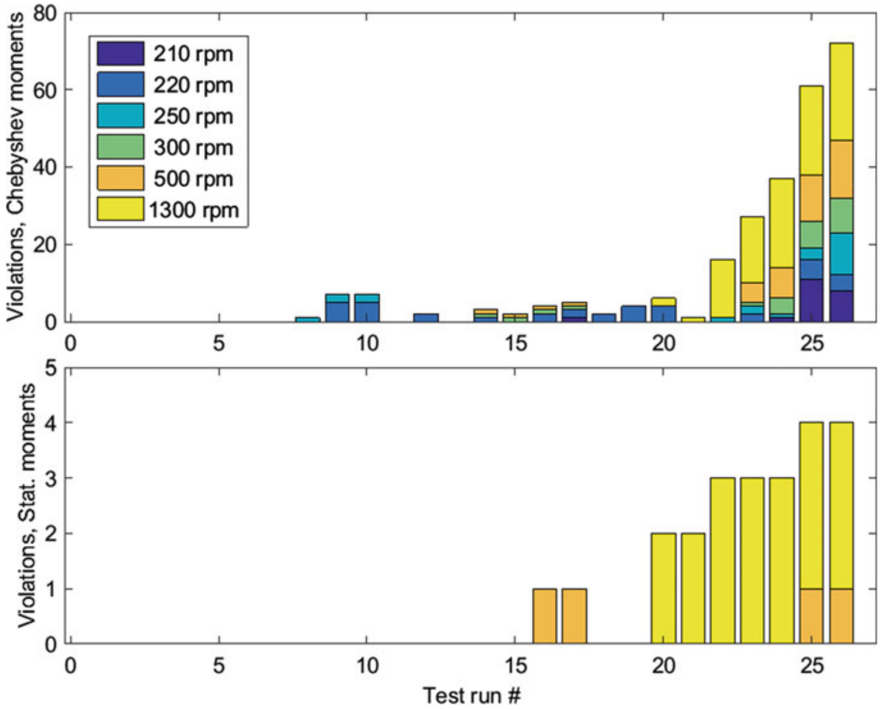

Fig. 2 Number of violations at different RPM during the bearing run to failure: Chebyshev moment violations (above) are more sensitive at low speed and provide an earlier and more gradual warning when compared to statistical moment violations (below)

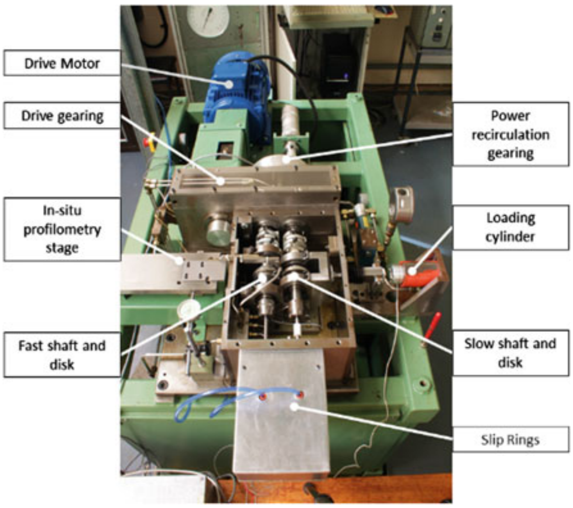

Fig. 3 Twin disc test rig for investigation of mixed lubrication conditions

In order to quantify the contact conditions, the concept of the lambda ratio (Λ) is used. This quantifies the combined effects of load, speed and temperature on mean metallic contact levels, and is defined as:

$$\Lambda = \frac{h}{\sqrt{R_{q1}^2 + R_{q2}^2}} \tag{1}$$

where h is the calculated smooth-surface film thickness, and R_{q1} and R_{q2} are the root mean square surface roughnesses for the two disk surfaces. The smooth-surface film thickness is calculated using the well-known formula given by Chittenden et al. [1] and the effects of temperature on lubricant viscosity (and therefore on film thickness) are taken into account by using the disk temperatures (measured using embedded thermocouples) to calculate lubricant viscosity. It is widely accepted [3, 4, 10, 14] that mixed lubrication occurs over a range of Λ between 0.1 and 2, with direct asperity contact carrying an increasing proportion of the total contact load as Λ decreases.

Initially, the test disks were run-in using the procedure described in Clarke et al. [3, 4], and for the tests reported here the surface roughness of the disks was stable. In order to measure the AE generated by the contact at a range of Λ ratios, the disks were initially run at a fast disk speed of 300 rpm, with load applied to generate a maximum contact pressure of 1.2 MPa. Shear heating of the lubricant within the contact caused the temperature of the test disks to rise (leading to a reduction in Λ), with AE wavestreams being frequently recorded during this temperature rise. Subsequently, the oil supply temperature was increased in order to extend the range of Λ ratios experienced further into the mixed lubrication regime, and the process repeated at fast disk speeds of 500, 1000, 1500 and 2000 rpm. Following the tests, wavestreams were examined for their frequency content by using a binned FFT. Frequencies between 150 and 300 kHz were found to be particularly sensitive to contact conditions. Figure 4 clearly demonstrates that there is a link between AE and the level of mixed lubrication. For any of the five speeds, as Λ falls, the level of AE increases, clearly demonstrating the interaction of asperities on the contacting surfaces to be a source of AE.

As these interactions occur more frequently (and are more heavily loaded) as Λ falls, so the AE activity increases. The effect is more pronounced at the higher speeds, which may be explained when one considers that at higher speeds, the overall levels of energy within the system increase, so it is reasonable to expect that any AE signal will be higher as the test speed and overall energy levels are increased. The results of these tests clearly demonstrate the potential of AE to be used as a tool to monitor contact conditions within realistic, heavily loaded elastohydrodynamic contacts operating within the mixed lubrication regime.

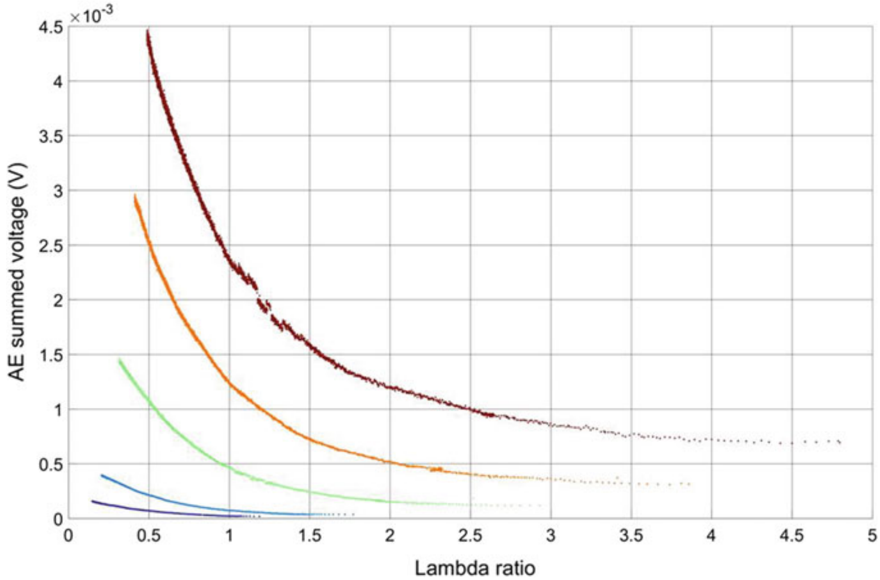

Fig. 4 Total AE voltage between 150 and 300 kHz versus Lambda Ratio (Λ). Each line represents data collected at a particular fast disk rotational speed—from bottom to top these are 300, 500, 1000, 1500 and 2000 rpm

4 Discussion and Planned Work

The results clearly demonstrate the sensitivity of AE to tribological conditions both at a component level (in the bearing tests) and at a contact level (in the disk machine mixed lubrication tests). There is clearly scope for using AE to develop sensitive monitoring techniques which can not only detect component-level failure but can provide insight into the status or health of the lubrication mechanism between surfaces. Many failure mechanisms (such as micropitting) which are prevalent in highly loaded power transmission systems are initiated at the surface roughness level, and the results shown here give confidence that AE may be able to provide early insight into incipient failures of this nature. In order to develop this research programme, further tests are planned at the bearing level (on two rigs at different universities in order to provide some "blind" test data for analysis techniques), at the surface level (tribometer tests with dry and lubricated surfaces of various roughness), on simulated gear tooth contacts (disc machine tests to investigate further the AE response under mixed lubrication conditions and during micropitting initiation) and on gear/bearing systems under various operating conditions. These activities should provide useful data and insight and allow the evaluation of the effectiveness and viability of AE as a sensitive condition monitoring technique for rotating machinery. Further research will involve developing models for the mechanism of AE generation within these tests.

5 Conclusions

At this initial stage of the collaborative project, it can be concluded that:

- AE is a sensitive tool capable of detecting the failure of components such as rolling element bearings.
- Advanced techniques such as Chebyshev moments may be used to enhance the sensitivity of AE monitoring.
- AE is sensitive to conditions within lubricated rolling/sliding contacts operating under mixed lubrication conditions.
- In particular, AE between 150 and 300 kHz rises as the levels of asperity interaction/direct metallic contact rise as indicated by a reduction in lambda ratio.
- Overall levels of AE within the contact rise as the speeds of the surfaces are increased, due to an overall increase in energy within the system.
- Further work is planned to investigate these phenomena in more detail.

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