THE USE OF ACOUSTIC EMISSION FOR BEARING CONDITION MONITORING

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Abstract
This paper reports research currently in progress at Swansea University in collaboration with SKF Engineering & Research Centre as part of a continuing investigation into high frequency Acoustic Emission. The primary concerns are experimentally producing subsurface cracks, the type of which would occur in a service failure of a ball bearing, within a steel ball and to closely monitor the properties of this AE from crack initiation to the formation of a ball on the ball surface. It is worth noting that there is evidence that the frequency content of the AE changes during this period, although this has yet to be proved consistent or even fully explained. Conclusive evidence could lead to a system which detects such cracks in a bearing operating in real life conditions, advantageous for many reasons including safety, downtime and maintenance and associated costs.

The results from two experimental procedures are presented, one of which loads a single ball held stationary in a test rig to induce subsurface cracks, which are in turn detected by a pair of broadband AE sensors and recorded via a Labview based software system. This approach not only allows detailed analysis of the AE waveforms but also approximate AE source location from the time difference between two sensors.

The second experimental procedure details an adaptation of a four-ball lubricant tester in an attempt to produce naturally occurring subsurface cracks from rolling contact whilst minimising the AE arising from surface wear. This thought behind this experiment is reinforced with 3D computational modelling of the rotating system.

Nomenclature
\begin{align*}
p_0 & \quad \text{Yield-inducing contact pressure} \\
p_0 & \quad \text{Maximum contact pressure} \\
\sigma_Y & \quad \text{Yield stress} \\
P & \quad \text{Normal load} \\
E^* & \quad \text{Effective Young’s modulus between two objects in contact} \\
R & \quad \text{Effective radius between two objects in contact} \\
a & \quad \text{Radius of (assumed circular) area formed by two objects in contact}
\end{align*}
Introduction
Detecting a defect within a bearing component before it is causes significant damage to the component, bearing or secondary damage to the associated equipment would be a significant goal for many of those involved in condition monitoring. To achieve this it is necessary to identify the subsurface cracking which occurs before a spall has formed on the surface of a component, and Acoustic Emission (AE) provides evidence that this could become a reality once a greater understanding of the associated phenomena is gained [1]. Several research programs find relationships between statistical analysis of the AE and, for example, defect sizes, but this often involves ‘seeding’ defects onto a bearing component, producing AE which would only occur once a component was in unacceptable condition [2, 3].

The current research programme centres around experimental and computational analysis of the high frequency AE arising from rolling contact test performed with a standard four-ball lubricant tester. This piece of equipment has been used in similar research programs and is justified for the application due to its ability to simulate rolling contact between standard bearing balls and an outer raceway [4]. Many previous examples of such research involve seeding defects onto surfaces of rotating elements to directly affect rolling contact, which arguably does not sufficiently simulate AE corresponding to a service failure within a bearing. Hence this research aims to produce a more ‘realistic’ failure by subjecting the elements to cyclic stresses under exaggerated loading conditions. The added advantages of the four ball machine are that sensors can be placed much closer to the source of any defect than in a fully assembled bearing, the transmission path of the arising AE is more straightforward and there are many less elements to distinguish between when trying to trace a fault.

Previous tests have highlighted the need to overcome two main drawbacks with the experimental procedure, and it is solutions to these drawbacks and the further results obtained which are reported in this paper. The first problem is the duration of a rolling contact four-ball test and the data recorded, most of which is unwanted when a test lasts several hours. The second problem is distinguishing between AE generated from continuous surface wear (which should not occur in a healthy bearing and is therefore unwanted in these experiments) and AE generated from subsurface cracking which is the focus of the research.

A possible solution to the first problem is presented whereby a slot is machined out of the ‘race cup’, finishing at the depth of maximum stress below the raceway in order to weaken the element. Two theories behind different failure mechanisms are noted, and evidence for both is presented. The second problem is addressed through compression of a single ball; in an attempt to produce stresses which theory predicts should induce subsurface cracks, similar to methods which are used to produce c-cracking in silicon-nitride balls [5]. The frequency content of the AE produced can be compared to that recorded during four-ball rolling contact tests.

In addition to the experimental analysis, some computational modelling is used to attempt to describe the natural frequencies associated with elements of the four-ball system, which it is hoped may also assist in the identification of fault-related AE.
Equipment and Test Components

The first experiment utilised a DARETC compression rig, capable of 30 kN of compressive force applied either over a defined period of time or a defined distance. A small steel clamp was manufactured in order to securely clamp a single ball in place and allow a reasonable transmission path for the AE sound waves (fig. 1). The ball was compressed between two blocks of tool steel which have a hardness similar the ball.

Hertz theory of elastic contact [6] is used to calculate the loading condition at which plastic deformation should initiate. It is written that a good approximation of the Yield-inducing contact pressure can be given by:

\[ p_{Y} = 1.6 \sigma_y \]  

(1)

The following equation can then be rearranged to find the load which results in this pressure.

\[ p_0 = \left( \frac{6PEr^2}{\pi^3R^2} \right)^{\frac{1}{3}} \]  

(2)

As the equation describes contact between only two surfaces the result is doubled, as in the experiment the ball contacts at two points and thus the pressure is distributed over twice the surface area described by equation (2). Calculations result in a theoretical load of 0.63 kN required to deform the ball plastically, so we make the assumption that subsurface cracking initiates at this point and that we should expect to see the beginnings of AE activity when this load is reached in the compression experiment.

The four-ball machine is employed for the second experimental procedure. In an attempt to speed up the onset of cracking the race cup has been weakened by grinding a 1mm wide slot on opposite sides of the raceway (fig 2), finishing at the depth beneath the curved raceway at which the stress is maximum. The depth at which the stress is maximum can be calculated from Johnson [6]: “Principal shear stress has a value of approximately 0.31p_0 at a depth of 0.48a (for v=0.3)”

Having calculated the contact radius ‘a’ in this particular case as 0.624 mm, our maximum stress should occur at a depth of 0.3 mm and race-cups were machined accordingly.

Figure 1: Steel clamp and diagram

Figure 2: Race-cup with slots ground on either side (sectional view)
Slots are angled so that the appropriate depth occurs at the position above which the lower balls rotate. In addition, the race cups used have been specifically machined from standard steel grades rather than hardened steel. Each test continues until a failure occurs, a failure being defined as a visible spall forming on the surface of either a ball of the raceway, detectable by a sudden increase in system vibration. An automatic cut-out switch is connected to the power supply to shut down the four-ball machine when the vibration rises beyond a predetermined threshold.

The purpose of weakening the race cups in this way is to reduce the time (i.e. number of stress cycles) until a failure occurs, and there are two theories behind this method. The most obvious is that introducing a weakness at the point of maximum stress beneath the raceway should allow a crack to develop and propagate within the race cup element. Traditionally the four ball experiment is designed to produce cracks within one of the ball elements, but the research is interested in identifying subsurface cracking regardless of the element in which it occurs. The second theory accounts for the small deflection of the raceway due to the slot beneath, which in turn creates an increased stress acting upon the balls each time the deflection is encountered. It would then be expected that a failure occurs within the top ball. Evidence that both these mechanisms take place is presented in the results.

**Data Acquisition and Handling**

For the single ball compression experiment two PAC WD broadband AE sensors, with a response range of 0.1-1 MHz, were located at either end of the clamp, the output signals from which were given a gain of 60 dB, band pass filtered between 20 kHz and 1 MHz, and in turn recorded by a National Instruments “LabVIEW” based software system. Recording was triggered as the compression began and was continuous until the target load was reached, between 2 and 3 minutes per test. A data sampling rate of 5 MHz is used throughout.

The same system is used for the four-ball experiment, with the two sensors located on opposite sides of the race-cup where they are non-intrusive but close as possible to the source of AE. The length of the tests reported here are such that continuous data acquisition is impossible; there is simply not enough storage space to record so much data or time to analyse it afterwards, so a LabVIEW Virtual Instrument (VI) was tailored to record periodically. Tests performed with a compressive load of 5 kN collected data samples for one complete revolution of the top ball at either 5 or 10 second intervals, increasing to either 1 or 2 minute intervals at 3 kN. These intervals were controlled by the VI in use, and the trigger signal to begin recording was provided by the tachometer mounted on the rotor of the four-ball machine. Data samples are automatically numbered sequentially as they are saved to disc by the VI.

**Finite Element Analysis**

Having gathered a large amount of AE data from previous rolling contact tests with the four ball machine it was possible to compare the frequency content of the detected AE against the natural frequencies obtained through computational analysis. This was carried out utilising the software packages CATIA and Autodesk Inventor for a single ball element constrained at two opposite points on its surface, in common with a lower ball in the four-ball arrangement. Element sizes in a tetrahedral mesh were automatically optimised for machine performance
with approximately 60,000 elements used in both analyses. Slight differences in the exact number and meshing algorithm should account for small differences, but in general the results are a good match. All modal frequencies up to 350 kHz are then selected (table 1) for comparison against data recorded from a typical four-ball machine rolling contact test (fig 3).

| Mode | Frequency (Hz) | Mode | Frequency (Hz) | Mode | Frequency (Hz) |
|------|---------------|------|---------------|------|---------------|
| 1    | 6445          | 12   | 213470        | 23   | 314360        |
| 2    | 36321         | 13   | 213600        | 24   | 315130        |
| 3    | 36402         | 14   | 216570        | 25   | 319250        |
| 4    | 45052         | 15   | 216720        | 26   | 319390        |
| 5    | 59827         | 16   | 227380        | 27   | 319450        |
| 6    | 59977         | 17   | 279190        | 28   | 319630        |
| 7    | 201400        | 18   | 284100        | 29   | 320240        |
| 8    | 201940        | 19   | 284190        | 30   | 320400        |
| 9    | 202330        | 20   | 313410        | 31   | 328750        |
| 10   | 211710        | 21   | 313530        | 32   | 329400        |
| 11   | 212070        | 22   | 314210        | 33   | 339420        |

Table 1: Modal frequencies (0-350 kHz) of a single ball as calculated by CATIA software

Figure 3: Comparison of natural frequencies calculated by CATIA and Autodesk Inventor (far left) and frequency content detected during a typical four-ball rolling contact test
Note that frequency content from 0 to 100 kHz is outside of the linear operating region of the AE sensor used.

It is not possible thus far to distinguish between AE generated through surface wear (present across the entire test) and AE generated through subsurface cracking. By applying the same technique to model the modified race cup, and comparing against AE generated during a test in which that race cup develops a fault, it is hoped that cracking will generate amplified AE signals which may be detectable visually or through correlation or cyclostationary analysis.

**Results  a) Single Ball Compression Tests**

In the first experiment a number of balls were compressed under increasing forces up to a maximum of 30 kN. Some balls were used in a single test, others were compressed and then re-compressed under an increased load, a list of the loading conditions is given in table 2.

The AE was captured continuously throughout each test (typical duration of 2.5 minutes) and afterwards the waveform was analysed in its entirety. AE appeared as occasional bursts in the time domain (fig 4), the frequency content was simultaneously analysed to ensure the burst was within the expected range. AE is produced each time energy is released as a crack forms and develops, so documenting the time at which each AE burst occurred provided a reference of subsurface damage with increasing load. AE was observed with a range of amplitudes and hence was subcategorised into low amplitude (20 mV or below), mid amplitude (between 20 mV and 40 mV) and high amplitude (greater than 40 mV) AE.

| Test ID | Compressive Load (kN) | Ball | Test ID | Compressive Load (kN) | Ball |
|---------|------------------------|------|---------|------------------------|------|
| CT01    | 0.7                    | A    | CT08    | 5.0                    | F    |
| CT02    | 0.7                    | B    | CT09    | 8.0                    | F    |
| CT03    | 1.0                    | B    | CT10    | 8.0                    | G    |
| CT04    | 1.0                    | C    | CT11    | 10.0                   | G    |
| CT05    | 2.0                    | D    | CT12    | 12.0                   | H    |
| CT06    | 3.0                    | D    | CT13    | 20.0                   | I    |
| CT07    | 3.0                    | E    | CT14    | 30.0                   | I    |

Table 2: Single Ball Compression Tests
In general the assumption made in section 2 was supported by the first appearance of any AE at a load of approximately 0.6 - 0.7 kN (fig 5). Balls which were recompressed gave slight inconsistencies but in general showed less AE activity in the second repetition of the initial loading region (fig 6). The frequency content was as expected, peaking at the same frequencies observed in four-ball rolling contact tests.
a) Four-Ball Rolling Contact Tests

A limited number of tests were performed with the modified race cup elements. A rotor speed of 1500 rpm was used, and a 300 kg load was applied to the four ball machine resulting in a maximum contact pressure between top and lower balls of approximately 6.7 GPa. As shown in table 3 initially it was the top ball which spalled, and only when the raceway eventually failed was a new race cup installed for the next tests.

| Test ID     | Race-Cup ID | Duration (hh:mm) | Spalled Element |
|-------------|-------------|------------------|-----------------|
| RSC300-2    | 1           | 05:00            | Top Ball        |
| RSC300-3    | 1           | 15:58            | Top Ball        |
| RSC300-5    | 1           | 116:04           | Raceway         |
| RSC300-6    | 2           | 14:30            | Top Ball        |

Table 3

The fact that two distinct failure modes are observed supports both theories presented previously, and suggests that the raceway can withstand a greater number of stress cycles than a top ball in this current configuration. Figure 7 shows typical results from a four ball rolling contact test.

Discussion

As mentioned previously, the purpose of these tests is try find a method of distinguishing between AE generated from surface wear in the four ball tests, and AE generated when a crack initiates and develops. The single ball compression tests partly solve the problem as no surface wear is present, however the assumption has to be made that deformation of the
material gives rise to subsurface cracking. Upon close inspection post-testing there was visible evidence of deformation of the surface of balls H and I, subjected to 20 kN and 30 kN respectively, so it can be assumed that the subsurface has undergone physical changes in these cases, and to a lesser degree under reduced loading conditions. One drawback is the material between which a ball is compressed, which ideally should be equal to or of greater hardness than the ball. The balls used in these tests register a hardness of 804 HV whereas the tool steel blocks register just 706 HV, resulting in a greater deformation of the blocks than the ball, also visible post-testing. The nature of AE arising from crack initiation and growth can still be analysed using these results, but this is perhaps not satisfactory when trying to compare the size and nature of cracks within a ball as they might occur during rolling contact.

Preliminary four-ball rolling contact tests performed using the modified race-cup suggest that the average time-to-failure in comparison to a normal race-cup and consistent shaft speed may have been reduced, at least in terms of the number of stress cycles the raceway can withstand. It appears that results may also support theory that the top ball is subjected to increased stresses due to a deflection in the weakened raceway, however more tests need to be performed before this can be concluded.

Computational analysis has allowed us to quickly identify the expected natural frequencies of a particular steel ball, and AE obtained from both experiments does appear to be amplified at these corresponding frequencies. The aim now is to use the same analysis for the weakened race-cup and obtain reasonable data for rolling contact tests in which a spall occurs in the raceway. If large amounts of data can be recorded during the latter stages of the test leading towards failure it is hoped further analysis, potentially involving cross-correlation and cyclostationary techniques, can begin to distinguish between the two sources of AE.

Conclusions
By analysing the frequency domain of AE signals there is evidence to suggest that useful information regarding the specific source of AE can be traced, which can then be applied to the stage between a subsurface crack forming to the eventual spalling, resulting in the detection of a failure before it has occurred and caused secondary damage. Clearly the key to developing any ‘early warning’ system, in this particular method of experimentation, requires the separation of AE resulting from constant surface wear and that originating from cracks. This paper presents a method of producing cracks in a static compression test and a method of weakening a component of the four-ball experiment in order to produce failures in a shorter period of time. This, it is hoped, can enable a significant reduction of the contact pressure between components in this experiment in accordance with more realistic loading conditions. Computational modelling may also help with the problem of relating the discrete frequencies of AE to the source, the size of a fault and crack propagation.

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