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Observations on Acoustic Emissions from a Line Contact Compressed into the Plastic Region

Technical Note

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Abstract

Some observations from Acoustic Emissions (AE) recorded during a yield test of a bearing raceway, compressed into plasticity using a rolling element are presented. The general objective of the study is to establish whether there is enough evidence of the onset of sub-surface plasticity in the AE signature. It is discussed here how AE monitoring during compression could indicate the onset of subsurface plasticity as a precursor to damage propagation to the surface. Some comparisons are drawn between the acoustic emission activity, levels and time-frequency response during elastic deformation and at yield loads.

Keywords
Acoustic Emissions, Condition Monitoring

1. Introduction

It has been shown that damage in wind turbine bearings under normal operating conditions can start with subsurface damage. In the case of planetary bearing raceways, radial loads are high and transient, generating high stress concentrations underneath the surface, leading to the formation of White Etching Cracks (WEC) around small non metallic inclusions Evans (2012). WEC tends to be accompanied by butterfly-shaped cracks, which through the application of cyclic loading will propagate and eventually reach the surface. Once that occurs, spalling will occur and progress relatively quickly, generating debris and further surface damage. At this point, failure of the entire gearbox is imminent.

The objective of this work is two-fold. Firstly, we wish to better understand the AE response from the initiation of a subsurface crack in a bearing, with the aim of designing good condition monitoring strategies based on AE. Secondly, in order to validate condition monitoring strategies, artificial defects need to be seeded into bearings. To this end, subsurface

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damage is a relatively realistic defect compared with surface damage, which has been investigated in the past for condition monitoring applications Fuentes et al. (2015); James Li & Li (1995).

2. Acoustic Emissions from Deformation

When a solid undergoes a change to its micro-structure, the disturbances at the molecular level generate stress waves through the material. These can typically be observed in the frequency range of approximately 100kHz to 10MHz. Many mechanical processes in materials will generate AE such as crack initiation and propagation, friction, corrosion, phase changes, and stress. The first systematic study of the AE response to applied mechanical stresses was done by Kaiser (1950). It is from this work that the Kaiser effect was coined, which described the absence of emissions from a material at a stress level which it is has observed before. A significant amount of work has been carried out since Kaiser's thesis, and AE are now used widely in the field of Non Destructive Testing (NDT).

Rather than being a continuous source, AE is typically released from cracks and stress concentrations as discrete bursts. If one were to playback the sound using a simple heterodyne to bring the sound to the audible frequency range, the sound would be analogous to a gun firing in a canyon. AE waves propagate in different modes, depending on how the material is excited, but it will typically involve a combination of longitudinal, transversal and surface waves, each travelling at different speeds and carrying different percentage of the total energy. If the material is thin enough, Lamb waves will also be generated, although this is generally not the case for large bearings since the material thickness is orders of magnitude greater than the wavelengths produced. The objective of this study is to characterise AE waveforms produced when a roller is pressed onto the raceway of a Cylindrical Roller Bearing (CRB), to establish whether differences in waveforms can be used as an indicator of the onset of plastic deformation to identify bearing damage.

The key focus of this work is to measure characteristic differences from elastic and plastic deformation mechanisms as well as other sources. A significant amount of work has been carried out on this matter on the numerical front. The key question being why does elasticity and plasticity generate AE, and can this be modelled? It is at dislocations that the source of AE lies, so answering this requires a deep understanding of dislocation dynamics. Several models for sources have been proposed to explain the observed AE response. Some good reviews of these can be found in Heiple & Adams (1987a,b) and more recently in Mathis & Chmeliik (2012). Interesting links have been made, such as the finding that AE activity can predict stress intensity factors in notches Dunegan et al. (1968) as well as crack propagation and fatigue life Roberts & Talebzadeh (2003). The response of AE has also been shown to depend greatly on the microstrucutre of the material, with coarse grain sizes resulting in higher AE activity and magnitude at yield, whereas materials with finer grain structures exhibit less energetic yields as observed by AE Kocich et al. (2012). Fracture mechanics have also been used to explain the formation of different wave modes as a result of stress concentrations around a crack, and the influence of crack shape and orientation Lysak (1996).

3. Test Set-up

The general idea of this test was to develop an understanding of the AE signature generated from sub-surface yield on a bearing raceway. To this end, a jig was designed and built to provide loading conditions representative of a rolling contact in planetary bearing. The jig supported the bearing raceway while pressure is applied on a roller directly above, as shown in Figure 1. The roller was held in an enclosure, providing alignment during compression. It was approximated using Hertzian line contact theory that material sub-surface yield would occur with a normal load of 1000kN applied. A hydraulic press with a maximum load rating of 2000kN was used to compress the raceway on the jig.

The bearings used for this study was an NU2244 CRB. An initial bearing (for which results are not shown here) was loaded progressively up to 1700kN. During this, peak AE amplitude was recorded at 1000kN, and surface damage became

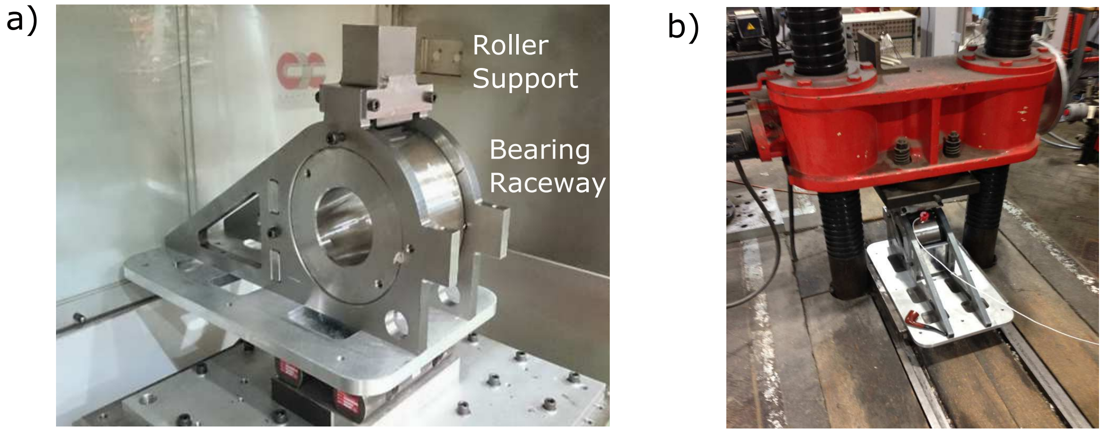

Fig. 1. Photos of a) jig for bearing and roller support and b) test setup under hydraulic press

visible after 1250 kN. Using this as a guide, three different sites were compressed on a new raceway, 144 degrees apart. Sites 1:3 were loaded to 1000kN, 800kN and 1200kN respectively. The results for these are presented in this technical note.

The AE response was gathered using Physical Acoustic Corporation (PAC) Micro-30D differential transducers and a National Instruments (NI) cDAQ system was used for data acquisition. Pre amplifiers were used for the AE signals, with a bandpass filter between 10kHz and 2MHz. All waveforms were acquired at 1 MHz. For the purpose of this test, only a single transducer was used, since source location was not required. Additionally, a force reading was taken from the hydraulic press during the test. An illustration of the raw data gathered for a test is shown in Figure 2

4. Analysis Procedure

Because of the high frequencies and thus sample rates involved in AE data acquisition, large amounts of data need to be stored and processed. The traditional processing of AE data usually takes advantage of the burst-like nature of emissions, which in fact makes the data very sparse; useful information is typically condensed in about 1% of the total number of data points. This has motivated the practice of extracting "hits" or "events". Typically, a hit is defined as an exceedance of a threshold that is high enough above the noise level to trigger most genuine AE bursts and little false ones. The AE community has tended to focus on simple features extracted from these bursts, such as energy, rising time, decay time, duration, counts-above-threshold, and maximum amplitude. While these features are often useful in applications such as condition monitoring where they are used to highlight abnormal behaviour, the objective here is to highlight more detailed aspects of AE response during yield. For this reason a time-scale analysis has been used to examine the AE hits generated during compression. The time-scale representation of a waveform conveys similar information to time-frequency, but without the need to trade time resolution with frequency resolution, as a Short Time Fourier Transform (STFT) would. The time-scale analysis is done here using a complex continuous wavelet transform. For clarity, Figures 4 and 5 have been plotted with the approximate frequencies that correspond to the scales used for analysis, so they are herein referred to as spectrograms.

The general disadvantage of this approach is that it is difficult to summarise the large amounts of data. On the other hand, it allows for a closer examination of the spectral content of the AE and allows a detailed qualitative view of the output. To put this in context, a compression test from 0 to 1000 kN will generate between 1000 and 3000 hits (see Figure 2 for example), and this largely depends on the threshold used when defining a hit. A relatively low, noise-adaptive threshold has been used in this case to capture every possible AE event.

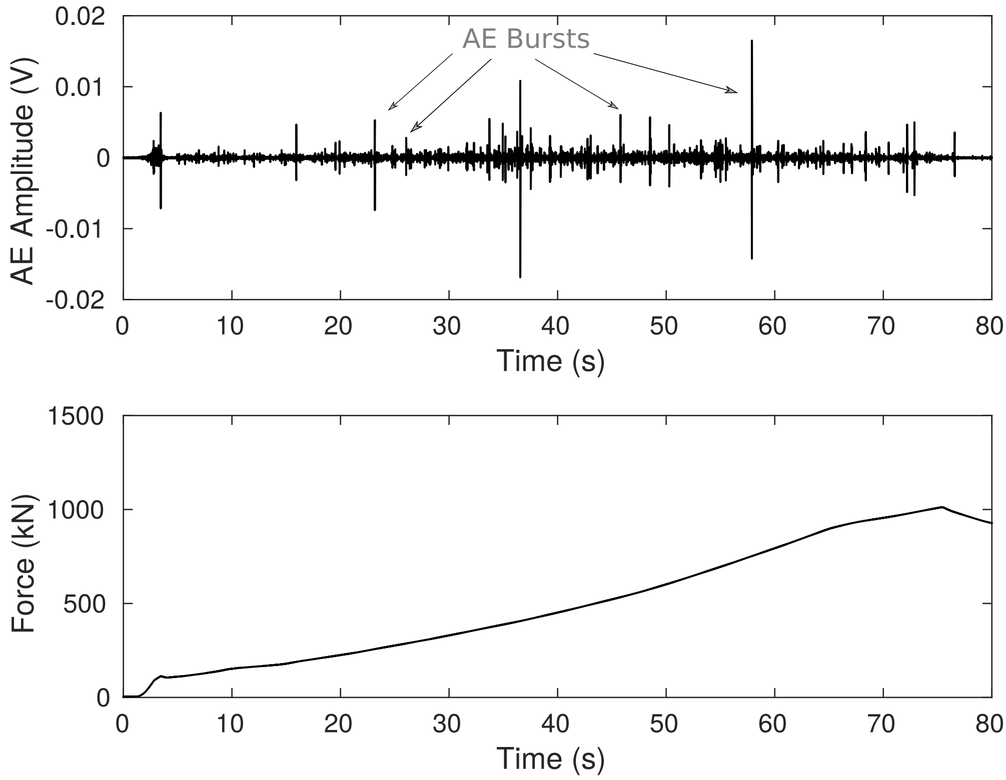

Fig. 2. a) Raw AE data for a compression test and b) load applied during test. Note that the nature of the response is burst-like, although there are so many bursts that it is impossible to distinguish them in such a long stream

5. Discussion of Results

A summary of the hit count, and cumulative energy is shown in Figure 3. Note that one of the tests (site 1) is believed to have sustained most damage as it generated an order of magnitude higher cumulative AE energy levels than the other two sites. This is attributed to the random nature of non metallic inclusions; a site with a higher count, larger inclusions, or where these are better aligned with the shear plane would tend to release more energy throughout the compression. The highest energy release for all sites was observed close to 800 kN.

Although thousands of spectrograms have been generated for the individual hits, only a total of 8 are presented here for conciseness. Four spectrograms for sites 1 and 3 are shown in Figures 4 and 5. They have been selected to represent the average burst that occurs at low, medium and high loads within a test. Also, note that in these results only the first 2000 micro seconds are shown, which highlights the initial response and leaves out all the reflections. It can be seen in Figure 4 that there is a significant low frequency component throughout the response of the tests at the lower loads. Note that on these spectrograms the amplitudes are normalised against the maximum amplitude of each burst. The amplitude of the low frequency component part of the 760kN burst on site 1 becomes small compared with the highest amplitude. That particular burst is the one with the highest energy observed throughout the tests, and it is close to the theoretical yield of 1000 kN. The distribution of energy seems to shift towards higher frequencies as the load gets close to yield point. For site 3, which released much less cumulative energy (see fig 3), there is a clear difference in the patterns of the spectrograms from low to high loads, although the reduction in relative amplitude of the low frequency components at the higher loads is not evident. This is an interesting distinction between two tests at similar loads. The fact that the spectral distribution of the AE events with the highest energy is generally different from those at a similarly high load, but with less energy release seems to indicate that there are characteristics in the spectral domain and in the arrival times and frequencies of different wave modes that could potentially characterise AE at the onset of plasticity.

6. Conclusions

A set of results from Acoustic Emission data gathered during compression tests on a bearing from a wind turbine gearbox has been presented. The focus of this note has been to highlight that apart from large AE energy releases during yield, there are some clear differences in the spectral distribution of the AE bursts. There are enough characteristics in the time-scale (or frequency) representation of the response during compression in the elastic and plastic regions, to be able to use them as features that could be exploited for condition monitoring of bearings.

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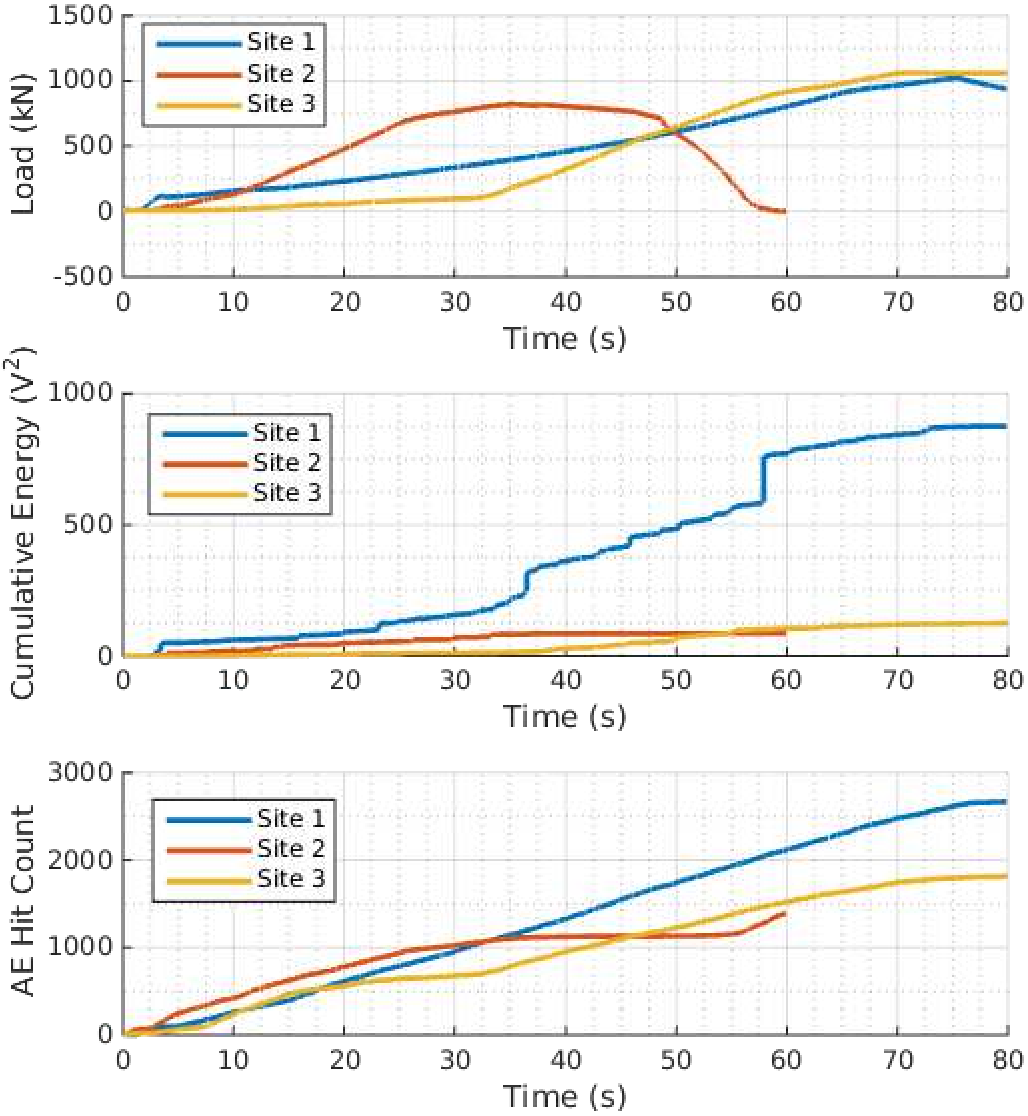

Fig. 3. Summary of results indicating load (top) for AE on the three loaded sites using traditional metrics such as cumulative energy (middle) and hit count (bottom). Yield is most evident on the cummulative energy in site 1 close to 800kN.

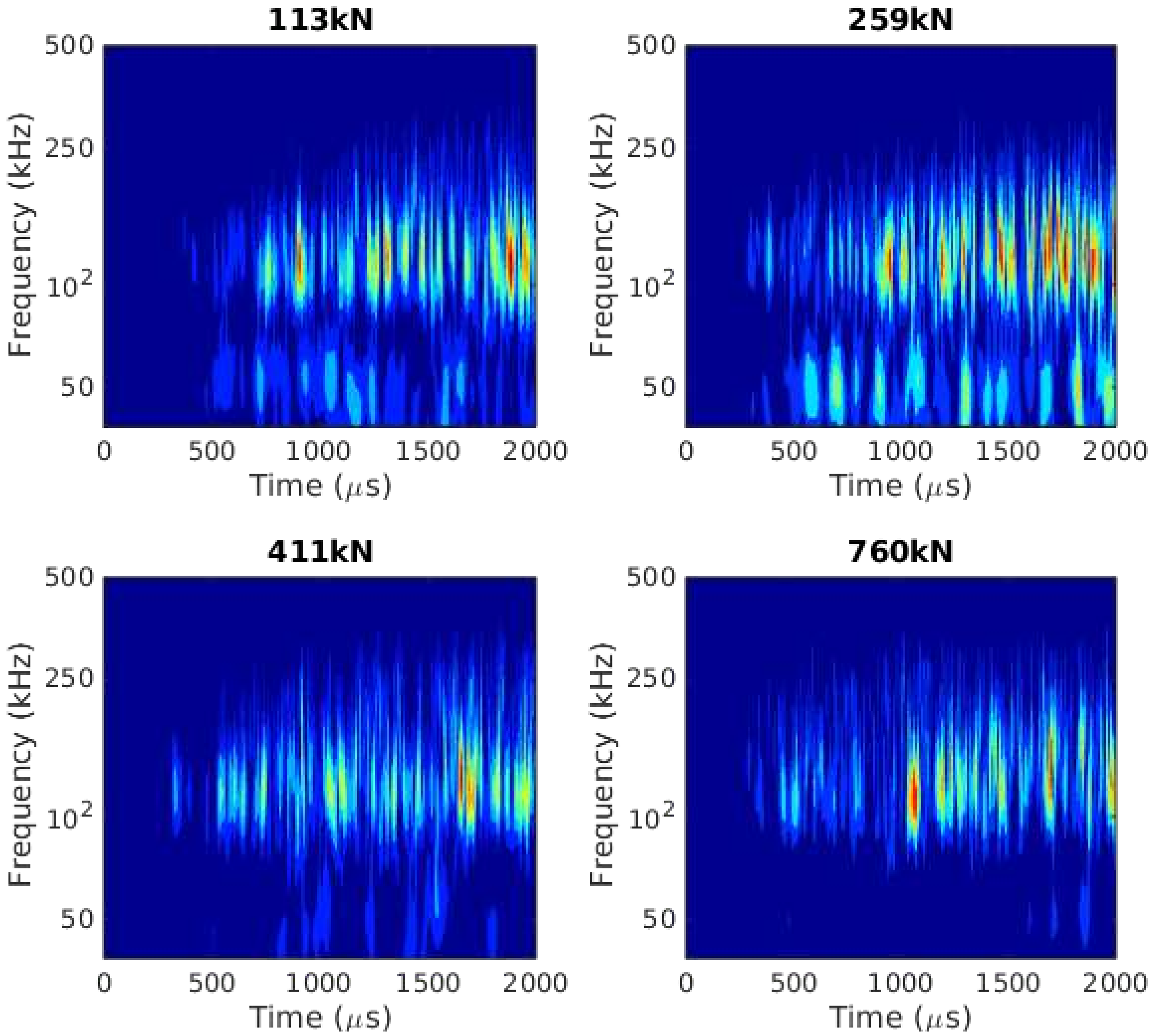

Fig. 4. spectrograms for selected AE hits for Site 1. Note that large scales correspond to low frequencies. The highest burst, occurring at 760kN has a distinct pattern, with response shifted towards slightly higher frequencies, and without much energy in the lower frequencies. The timing of arrivals is also different. Note that the amplitudes are normalised against the maximum amplitude of each burst

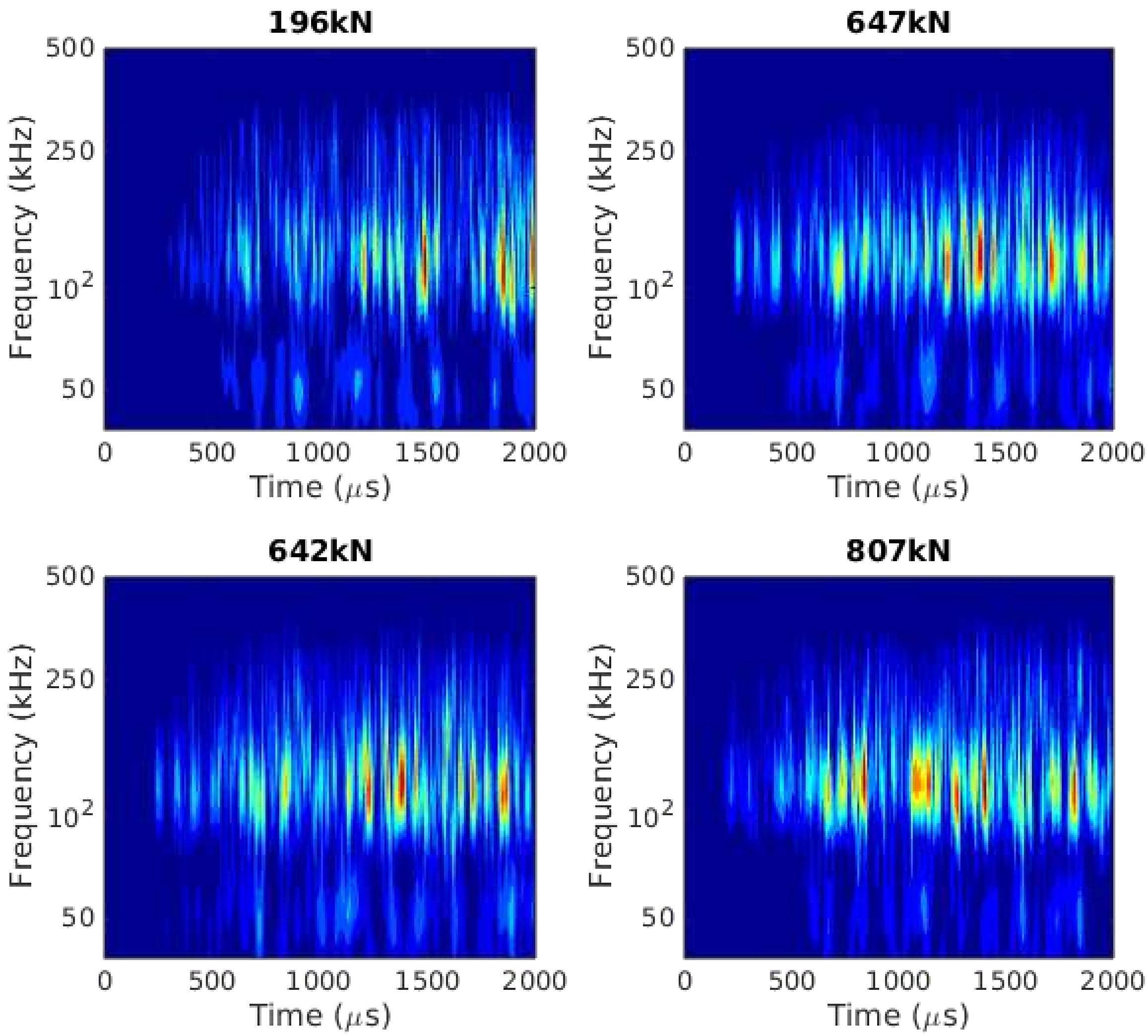

Fig. 5. spectrograms for selected AE hits for Site 3. Note that large scales correspond to low frequencies. Note here that in comparison with the hits from Site 1, the higher loads are not as distinct in terms of frequency distribution. The timing of arrivals of the burst at 807kN is noticeably different from the rest. Note the repeatability of the bursts close to 640kN. Note that the amplitudes are normalised against the maximum amplitude of each burst