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# Changes in Acoustic Emissions When Cutting Difference Rock Types

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# CHANGES IN ACOUSTIC EMISSIONS WHEN CUTTING DIFFERENT ROCK TYPES

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*ABSTRACT:* machine cutting of rock is widely used in the coal mining industry. Developing an acoustic emission monitoring system that is capable of detecting changes in rock cutting conditions has the potential to enable the development of a real-time control system which can optimise the operation of rock cutting machines such as longwall shearers and roadheaders. A laboratory-based study was undertaken to record acoustic emissions during rock cutting using a linear rock cutting machine. The study considered a range of variables that might impact design of a control system including rock type, cutting depth, cutting speed and location of an acoustic emission sensor. The study found significant differences in the frequency domain of acoustic emissions with changes in cutting configuration including rock type.

## INTRODUCTION

Mechanical cutting is extensively utilised in the mining and tunnelling industries as the primary means of rock excavation. In most instances, control of cutting machines is dependent on auditory and visual observations of a skilled operator. There is an increasing amount of excavation required in harsh and extreme underground environments. When combined with the desire to ensure high levels of machine utilisation and productivity, the development of systems that will enable semi-autonomous machine operation is attractive to OEM and operators alike.

Mechanical rock excavation is a costly process that can require large amounts of capital and consumes large amounts of energy. The efficiency of the rock cutting process which can be degraded with wear of the cutting tools, has a direct impact on a machine's productivity. Quite often monitoring of the state of wear is based on visual inspection of the cutting tools which is not only hazardous but also results in downtime of the machine. An on-line monitoring system would improve a number of operational aspects including reducing the frequency of unnecessary machine downtime for inspections; eliminating unnecessary cutter tool change-out and consequently decreasing overall cutting tool costs; reducing energy consumption; and, increased safety by eliminating the need for physical inspections of the working face.

Research to develop sensors has been undertaken sporadically since the early 1960s particularly in the area of horizon control of longwall shearers in the coal industry but it has been meet with limited success (NASA, 1982). It was found that the effectiveness of many of these investigations was constrained by the local geology. The most successful system was based on natural gamma radiation and deployed on longwall shearers in the United Kingdom (Marshall, 1989). In the 1990s, efforts continued with a focus on more recently developed technologies that might allow more universal application in a greater range of rock conditions and machine types including x-ray fluorescence, synthetic Doppler radar, infrared thermography and vibration (Pazuchanics and Mowrey, 1991).

It is known that solids emit low-level acoustic emissions or seismic signals when subjected to changes in induced stress or deformation (Kaiser cited in Hardy, 1981). Acoustic emissions (AE) are mechanical vibrations that propagate through solid, liquid or gaseous materials (Hardy, 2003). While much of the focus of measuring acoustic emissions during cutting has been limited to the metal machining industry, there is scope for application to rock cutting.

## PROJECT OBJECTIVES

Williams and Hagan (2006) reported variations in the nature of the acoustic signal with changes in rock cutting conditions. Improvements were subsequently made to the instrumentation and test procedure that principally provided a capability to measure AE signals at high sampling rates.

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A follow-on project was undertaken to assess whether differences in rock cutting configuration would be manifested in the higher frequency spectrum of the AE signal. In particular, to determine whether a unique characteristic or AE "signature" could be ascribed to a cutting configuration and that any changes to the cutting configuration would result in a different signature. Monitoring the AE signal could then form the basis of a real-time monitoring system.

The test program involved changes in cutting depth, cutting speed, positioning of the sensor and material being cut. Fast Fourier Transforms were used to determine the frequency content in the AE signal.

## TEST APPARATUS

The linear rock cutting machine used in the experiments was a modified Invicta 6M Shaping machine as shown in Figure 1 located in the *Machine Cuttability Research Facility* at UNSW.

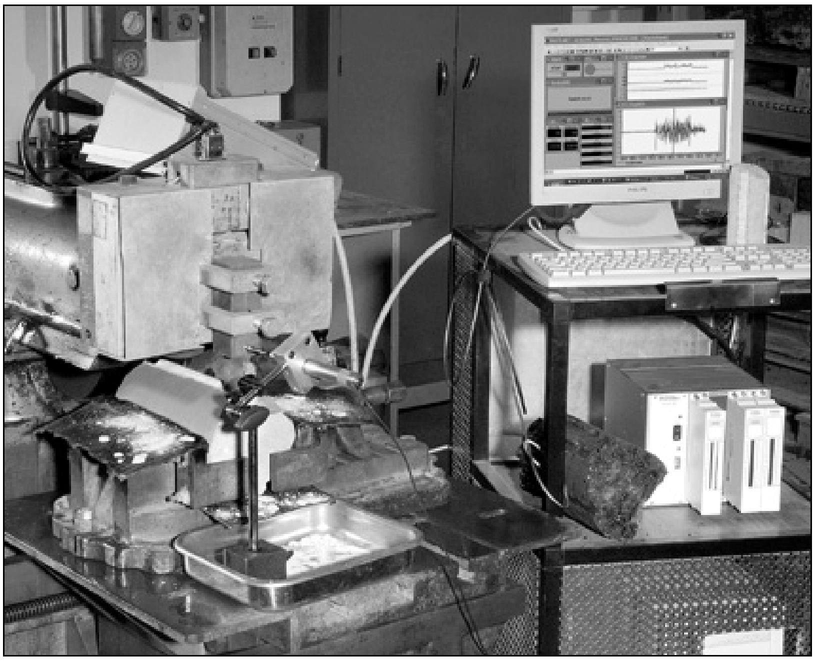

**Figure 1 - Linear rock cutting machine used in cutting tests**

The data acquisition system incorporated a Physical Acoustics Corporation A
E transducer model number R15α as shown in Figure 2. The transducer has an operating frequency range of 50 – 200 kHz.

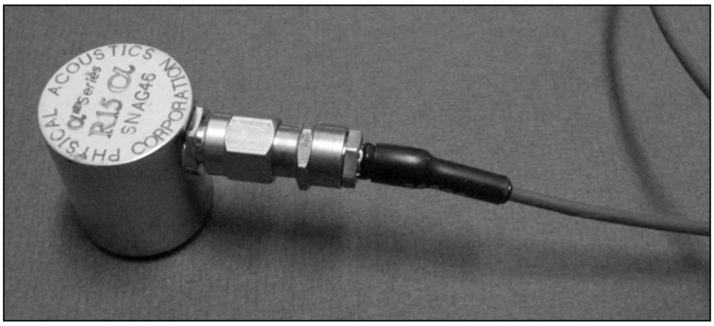


**Figure 2 - The AE transducer sensor, model R15α**

The sensor was connected to a PAC 2/4/6-C preamplifier. The values 2/4/6 represent the three selectable gain settings of 20 dB, 40 dB and 60 dB respectively and bandwidth of 10 kHz – 900 kHz. The gain was adjusted to maximise the acoustic signal.

The signal conditioning unit was a National Instruments (NI) SCXI – 1100 analogue input module. This unit is suited to high performance signal conditioning. The analogue signal was then fed to a NI 6229M analogue to digital card having a 16 bit analogue input resolution and a maximum sampling rate of 250,000 samples per second (250 kS/s).

DASYLab was used as the data acquisition software to control the hardware and store the data from each test. The arrangement of the data acquisition system is shown in Figure 3.

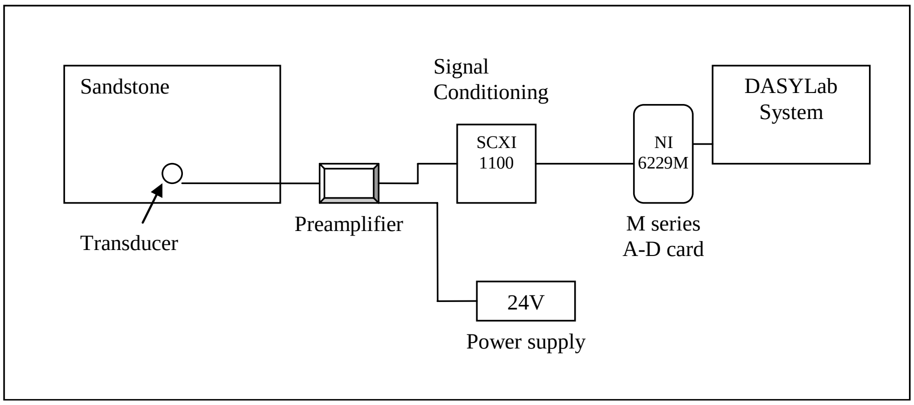


**Figure 3 - A schematic of the data acquisition system used in the study**

## TEST PROCEDURE

Three material types were used in the study – sandstone, coal and a gypsum-based casting plaster. The sandstone block had dimensions of 395 mm long and 265 mm wide with a UCS of approx 40 MPa. The coal sample was encased with a protective plaster casing that provided confinement during cutting. During a cutting test, the sample was fixed to the table of the shaping machine.

Preliminary cutting tests were undertaken to:

- ensure compatibility of the various elements in the data acquisition system,
- confirm the transducer had sufficient sensitivity to detect an AE signal during rock cutting,
- adjust the gain on the preamplifier for maximum sensitivity,
- determine an appropriate data sampling rate,
- configure the software and hardware settings, and
- determine the level of background noise.

## RESULTS

### Initial recorded data

The magnitude of the acoustic signal against time was plotted for the first series of tests. These graphs indicated the level of energy release was not consistent during rock cutting and mirrored the changes in force on the cutting tool with time. An example of an acoustic/time graph when cutting in sandstone is shown in Figure 4.

The acoustic/time graph was useful to identify changes in cutting conditions as these were reflected in the nature of the acoustic signal. Figure 5, for example, illustrates an arrangement where in one test the cutting tool was made to pass through coal and plaster. In between cutting the coal and plaster, there was a small air gap where the cutting

tool was temporarily disengaged from cutting material albeit for a small nick of coal. The corresponding acoustic/time graph shown in Figure 6 shows changes in the pattern of the acoustic signal at the different stages of cutting.

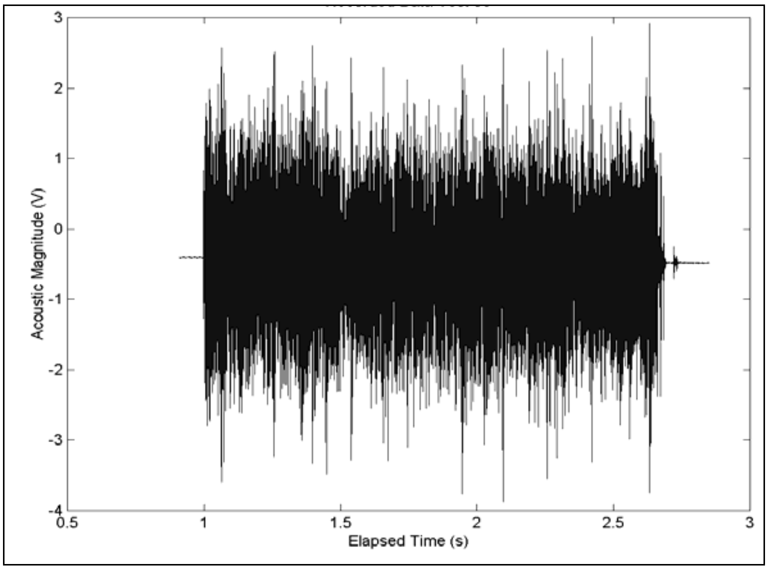


**Figure 4 - A typical plot of the acoustic signal during cutting in sandstone**

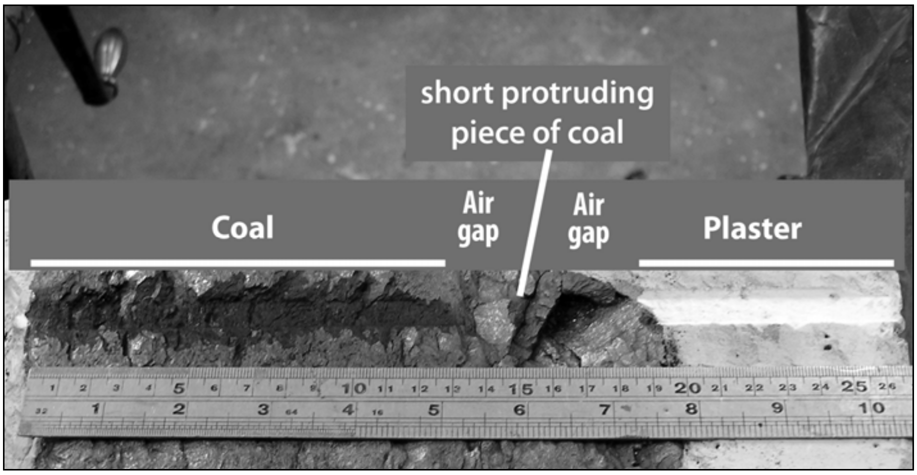


**Figure 5 - The test arrangement involving cutting in coal and plaster**

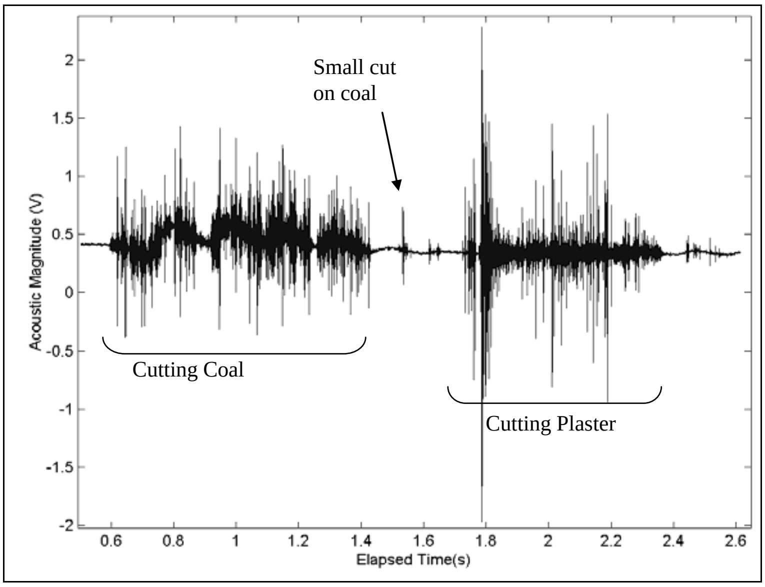


**Figure 6 - Changes in the measured acoustic signal when cutting in coal and plaster**

## SIGNAL ANALYSIS

While the acoustic/time graph can provide a visual contrast with changes in rock cutting condition, a better method was needed that could quantify the changes in acoustic signal.

To this end the frequency domain within the acoustic signal was examined along the lines of Shen and Hardy (1996). They reported on the presence of peak frequencies, or *Major Dominant Frequencies* (MDFs) in an acoustic signal. The objective in this project was to determine whether a unique set of frequencies, the AE signature, could be defined which would characterise a given cutting configuration.

Analysis of the frequency content in the acoustic signal was based on Fast Fourier Transforms (FFT). MATLAB, a commercially available software package, was used for the FFT analysis.

### Sampling rate

One important factor that can constrain the usefulness of frequency analysis is the range of frequencies in the signal that can be considered. The Nyquist criterion states that the maximum useful frequency that can be discerned within an analogue signal, termed the folding frequency, is equal to half the sampling frequency.

Various research undertaken in the 1980s and 1990s such as that by Pazuchanics and Mowrey (1991) at the USBM reported acoustic signals were recorded at sampling rates of up to 1000 samples/second (S/s) in real-time and up to 10 kS/s when recorded to tape and played back later at slow speed. This levels equate to a folding frequency of between 500 Hz and 5 000 Hz. This was a limit imposed by the technology available at the time but given current data acquisition systems are capable of achieving real-time sampling rates at least ten times this level then frequencies of 100 kHz or more can now be considered.

A series of tests were conducted at sampling rates ranging between 100 S/s and 200 kS/s. Graphs of the frequency spectrum at sampling rates of 10 kS/s, 100 kS/s, 150 kS/s and 200 kS/s are shown in Figures 7 to 10 respectively. These sampling rates correspond to folding frequencies of 5 kHz, 50 kHz, 75 kHz and 100 kHz respectively.

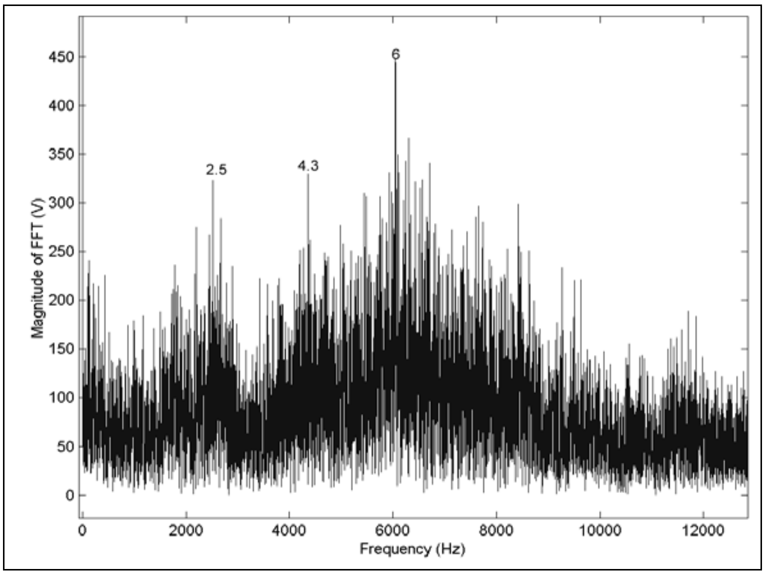


**Figure 7 - Frequency spectrum graph indicating three Major Dominant Frequencies in the recorded data with a sampling rate of 10 kS/s**

At a sampling rate of 10 kS/s, three MDFs were discernible of 2.5, 4.3 and 6 kHz. At 100 kS/s, seven MDFs are evident within the range of 16 kHz to 48 kHz. With a further increase to 150 kS/s, the same number of MDFs was evident though the range of MDF frequencies increased to 61 kHz. At 200 kHz, the MDFs were very similar to those found at 150 kS/s. It was noted that as the sampling rate increased, the strength of the MDFs compared to the background level was more discernible.

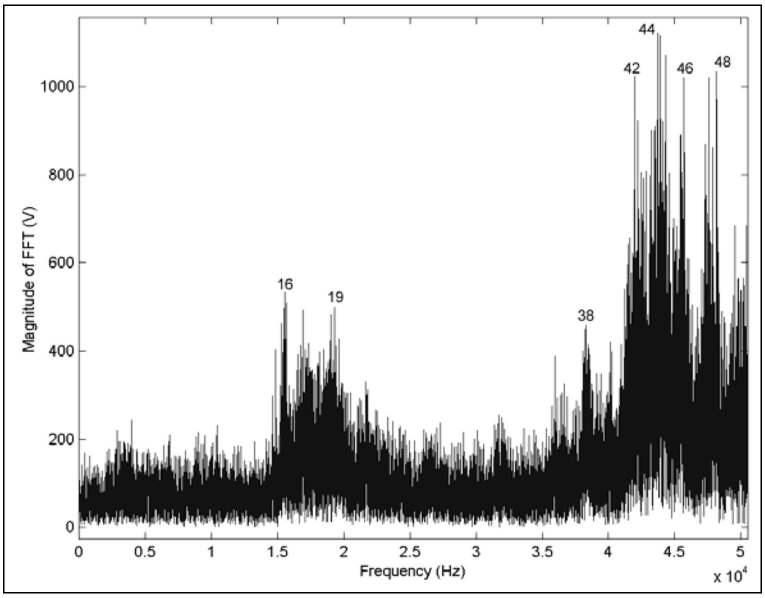


**Figure 8 - With an increase in sampling rate to 100 kS/s, seven Major Dominant Frequencies were evident**

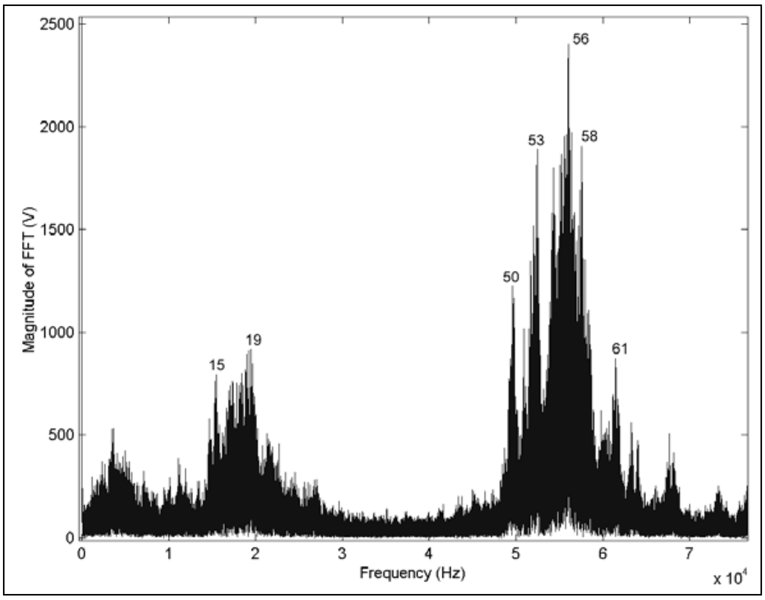


**Figure 9 - At 1 0 kS/s, seven Major Dominant Frequencies were again evident**

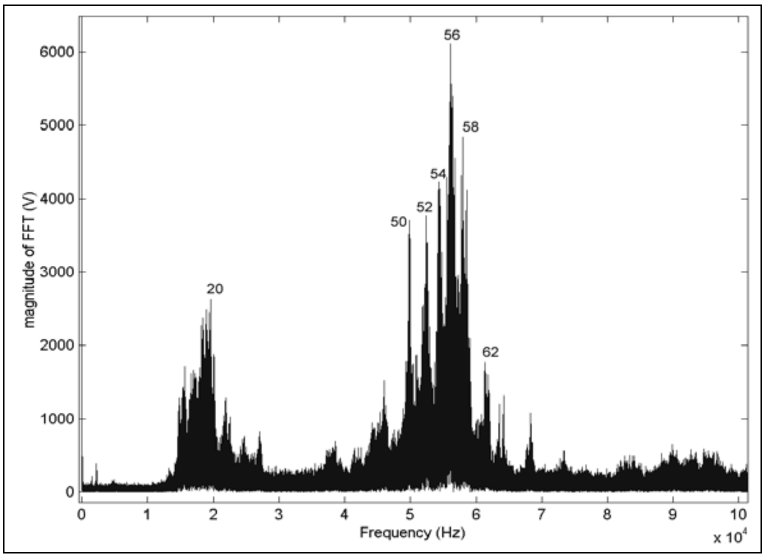


**Figure 10 - At a sampling rate of 200 kS/s, seven Major Dominant Frequencies were evident that were similar to those found at 150 kS/s**

It is also important to note that at 200 kS/s the highest MDF was 62 kHz which is roughly 60% of the folding frequency indicating that this sampling rate provides sufficient leeway for higher frequencies to be identified. It was decided to conduct all the experiments at a sampling rate of 200 kS/s corresponding to a folding frequency of 100 kHz.

### Cutting speed

The effect of a change in cutting speed on the nature of the acoustic signal was examined in sandstone, coal and plaster. Two cutting speeds were selected of 0.150 m/s and 0.846 m/s representing a five-fold difference in speed. The frequency analysis found little significant difference between the two speeds for all three materials with the same MDFs being identified.

### Depth of cut

Two levels of depth of cut were examined in sandstone (3 mm and 6 mm) and three levels in coal (3 mm, 6 mm and 9 mm). The MDFs in each set of results were compared. Again there was very little change in the MDFs with cutting depth for each material. Figures 11 and 12 show the frequency spectrum for 3 mm and 6 mm in sandstone respectively.

### Transducer location and attachment

The objective of this series of tests was to examine the effect on the acoustic signal of changes in the method of attachment of the acoustic transducer and its location with respect to the cutting tool.

In terms of attachment, beeswax and "super glue" were used. The frequency analysis indicated little difference in the MDFs between the two methods of attachment. There was though an appreciable difference in the amplitude of the acoustic signal indicating better coupling of the transducer and less attenuation of the signal when glue was used. This was reinforced by the need to use a higher gain setting on the pre-amp in the tests when using beeswax.

Location of the transducer was found to have a substantial impact on the frequency response in the acoustic signal. As with the method of coupling, a change in location affected the level of attenuation of the acoustic signal. Also there was a change in the level of noise in the signal, making it more difficult to define the MDFs in certain configurations.

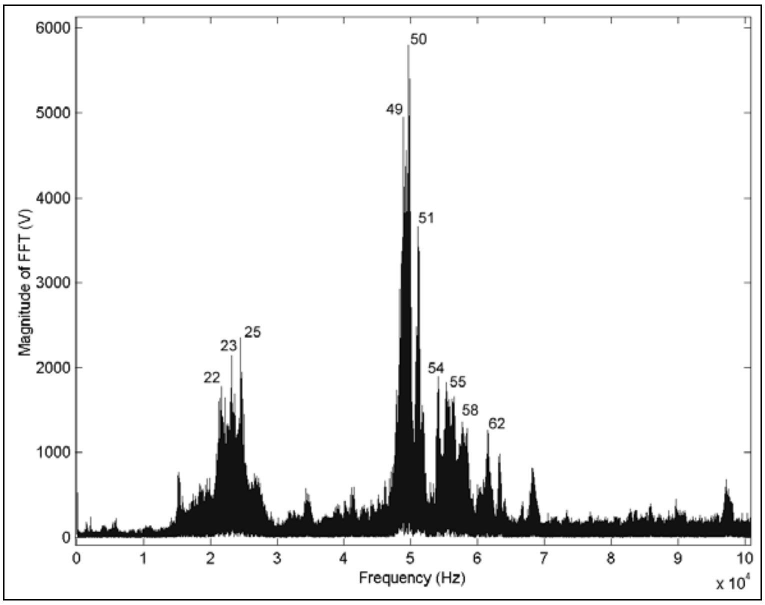


**Figure 11 - Frequency spectrum graph for a 3 mm depth of cut in sandstone with the transducer glued on the cutting tool**

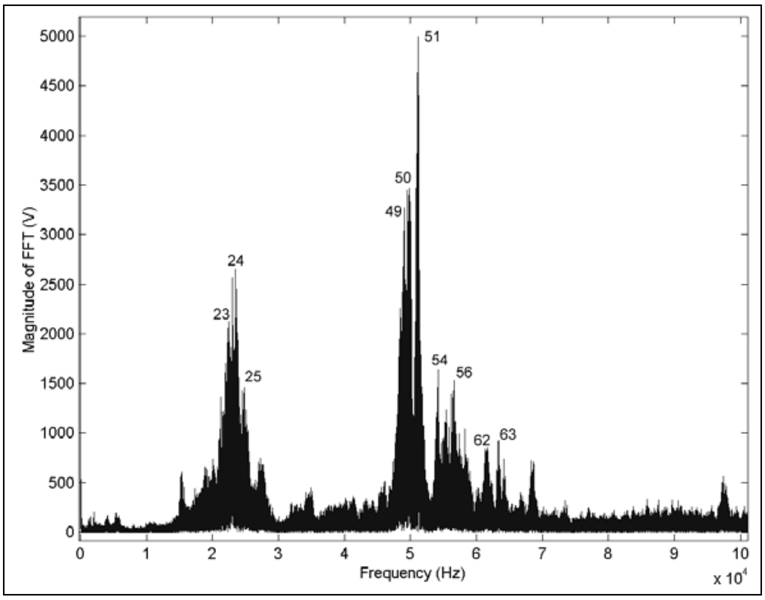


**Figure 12 - Frequency spectrum graph for a 6 m depth of cut in sandstone indicating a similar set of MDFs as that found for 3 mm. Transducer glued on the cutting tool**

The frequency spectrum graph shown in Figure 11 was for the case when the acoustic transducer was glued directly to the cutting tool post holder. Figure 13 shows the frequency spectrum graph for the same cutting configuration except the transducer was glued to the surface of the sandstone block. When comparing these two configurations it can be seen that:

- there was less attenuation in the acoustic signal when the transducer was mounted directly on the cutting tool;
- there was a clearer definition of the MDFs when the transducer was mounted on the cutting tool;
- there was a shift in the MDFs at the lower frequencies around 20 kHz between the two configurations with a slightly lesser change at the higher frequencies.

When the test was repeated using the coal sample, similar results were observed.

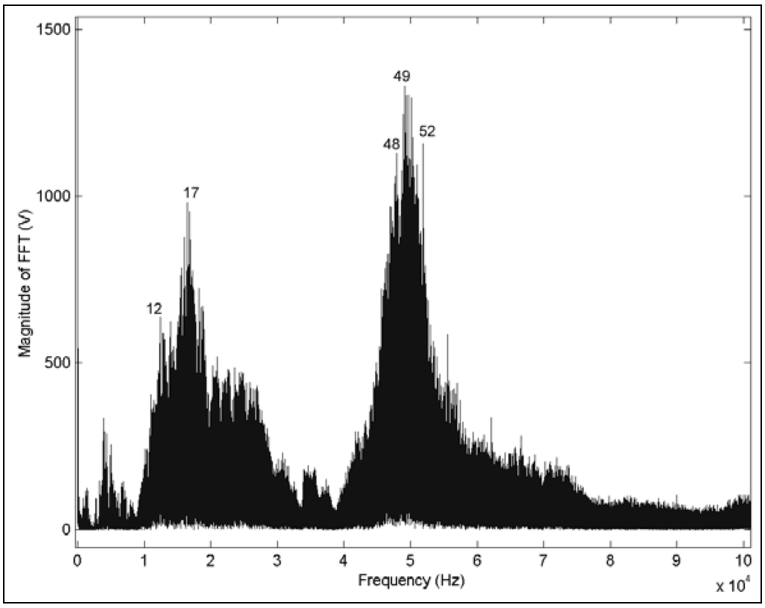


**Figure 13 - Frequency spectrum graph for a 3 mm depth of cut in sandstone with the transducer glued on the sandstone block.**

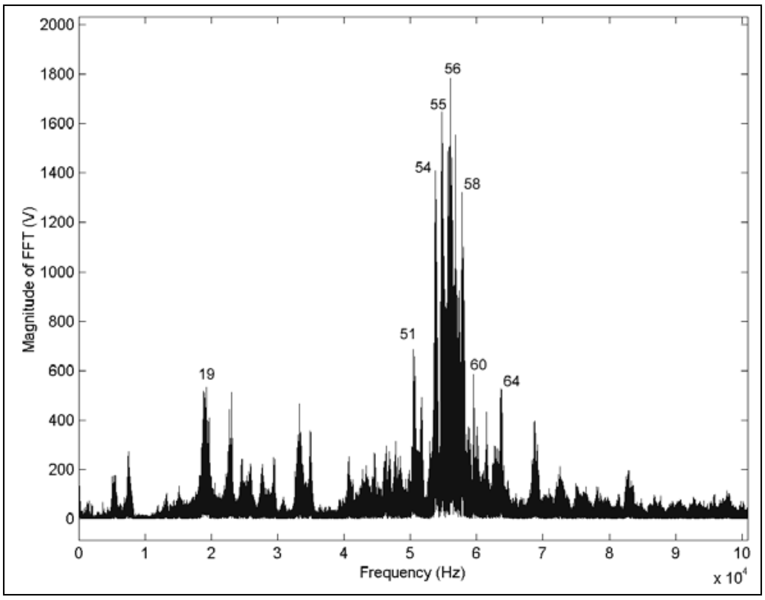


**Figure 14 - Frequency spectrum graph for a 6 mm depth of cut in coal with the transducer glued on the cutting tool.**

## Rock type

When comparing the test results for different material types, there were significant differences in the amplitude of the signal as well as the MDFs.

Figures 14 and 15 show the frequency spectrum when cutting in coal and in plaster. The difference in amplitude would be expected as they correspond to the differences in the energy of cutting between coal and plaster.

There was also a distinct difference in the set of MDFs especially when compared to that found when cutting in sandstone shown earlier in Figure 12.

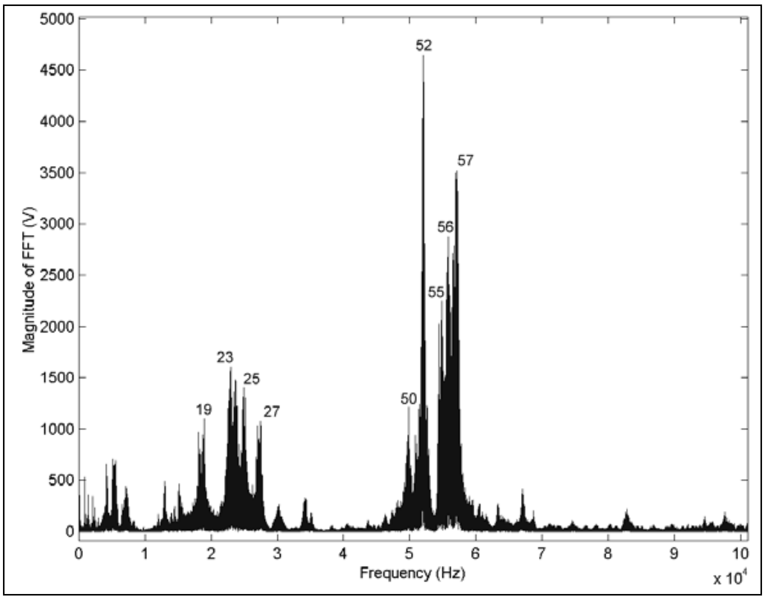


**Figure 15 - Frequency spectrum graph for a 6 mm depth of cut in plaster with the transducer glued on the cutting tool**

Following on from this, a distribution of the commonly occurring MDFs was compiled based on all the tests for each material. Figure 16 shows a graph of the frequency of occurrence of the MDFs for the different cutting configurations when cutting in sandstone.

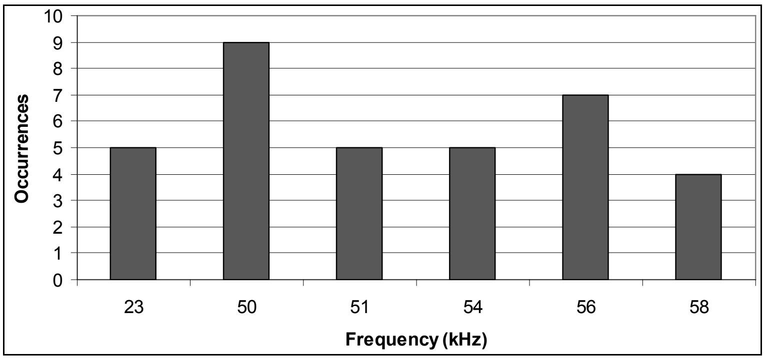


**Figure 16 - Distribution of the most common MDFs for the different tests when cutting in sandstone**

The MDFs were added, graphed and compared for each of the three materials. This was undertaken in order to determine the characteristic frequencies common to a particular cutting parameter.

The two most common MDFs were 50 kHz and 56 kHz for sandstone; 54 kHz and 55 kHz for coal; and, 56 kHz and 57 kHz for plaster. The number of tests used to determine each of the common MDFs for sandstone, plaster and coal were ten, seven and seven respectively.

## CONCLUSIONS

At a sampling rate of 200 kS/s, a set of Major Dominant Frequencies (MDFs) could be defined in an acoustic signal that can be used to characterise the Acoustic Emissions (AE) emitted under differing rock cutting configurations.

The MDFs only became evident at sampling rates in excess of 100 kS/s which is well above that which could be achieved with commercially available equipment in the 1980s and 1990s.

This sampling rate of 200 kS/s allowed for MDFs of up to 100 kHz to be identified. At this sampling rate the highest MDF was approximately 65 kHz.

Several different rock cutting configurations were examined of which some had more of pronounced effect than others.

In the case of the cutting depth and cutting speed there was very little significant effect on MDFs. Significant differences were observed though with respect to transducer location and method of attachment. The best signal was found with the AE transducer attached to the cutting tool using glue as opposed to being attached to the rock using beeswax.

In the case of cutting in three different material types (sandstone, coal and plaster), there were significant differences in the MDFs. These MDFs defined the signature for a cutting configuration and indicate that a monitoring system could be developed to maintain cutting within a certain rock horizon.

The objective of this project was to determine whether measuring AE during cutting could be used as a basis for monitoring machine performance. It was found that AE were more sensitive to changes in some rock cutting configurations than others. Further work is necessary to confirm the usefulness of this as for real-time application in machine control and when using multiple cutting tools on a cutting head.

## REFERENCES


Hardy H R, 1981. Application of Acoustic Emission Techniques to Rock and Rock Structures; A State-of-the-Art Review, in *Acoustic Emissions in Geotechnical Engineering Practice, STP 750,* V P Drnevich and R E Gray, Eds. pp 4-92 (American Society for Testing and Materials).

Hardy H R, 2003. Acoustic Emission / Microseismic Activity, Volume 1: Principles, Techniques and Geotechnical Applications, pp 1-256 (Balkema Publishers: The Netherlands).

Marshall A, 1989. Introduction of vertical guidance into the Nottinghamshire Area. *Mining Technology,* May, pp 135-144.

NASA, 1982. Longwall shearer guidance and control. Marshall Space Flight Centre, NASA TM-82455, NTIS:DOE/ET-75-I-01-9012.

Pazuchanics, M J and Mowrey, G L, 1991. Use of adaptive signal processing techniques to discriminate between coal cutting and rock cutting, USBM IC 9269 (USA Dept of Interior).

Shen H W and Hardy H R, 1996. Laboratory Study of Acoustic Emission and Particle Size Distribution during Linear Cutting of Coal, in *Rock Mechanics Tools and Techniques*, *2$^{nd}$ Nth American Rock Mechanics Symposium*, pp 835-841, (Balkema: Rotterdam).

Williams, E and Hagan, P C, 2006. Observations on the variation in acoustic emissions with changes in rock cutting conditions, in *Proceedings Coal 2006: 7$^{th}$ Underground Coal Operators Conference*, University of Wollongong, (AusIMM: Illawarra Branch).