DIESEL ENGINE PROBLEMS, ACOUSTIC EMISSION SIGNALS AND SIMULATED MISFIRE FAULTS

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This paper discusses commonly encountered diesel engine problems and the underlying combustion related faults. Also discussed are the methods used in previous studies to simulate diesel engine faults and the initial results of an experimental simulation of a common combustion related diesel engine fault, namely diesel engine misfire. This experimental fault simulation represents the first step towards a comprehensive investigation and analysis into the characteristics of acoustic emission signals arising from combustion related diesel engine faults. Data corresponding to different engine running conditions was captured using in-cylinder pressure, vibration and acoustic emission transducers along with both crank-angle encoder and top-dead centre signals. Using these signals, it was possible to characterise the diesel engine in-cylinder pressure profiles and the effect of different combustion conditions on both vibration and acoustic emission signals.

1. INTRODUCTION

Due to the number of components and sub-systems that together form an internal combustion engine, it is of no surprise that many engine parameters need to be monitored. Some commonly used engine condition monitoring (CM) techniques include oil analysis, exhaust gas analysis, cylinder pressure measurements and vibration analysis. Whist CM techniques such as these have been proven and are widely adopted in industry, in certain instances these CM techniques have been regarded as being impractical, unsuitable, or limited in their ability to deliver the desired condition monitoring or fault diagnosis capabilities.

In recent years the push to effectively apply condition based maintenance (CBM) practices to diesel engines has led to the continued development of diesel engine condition monitoring methods. These CM methods seek to effectively diagnose faults earlier and thus provide more scope for maintenance planning and scheduling.

AE based techniques in particular are thought to have a great deal of potential in monitoring both the performance, and mechanical condition of diesel engines even though the development, commercialization and industrial application of AE based diesel engine CM methods is still in the early stages.

In addition to presenting some interesting background information concerning common diesel engine problems, AE based diesel engine CM research and diesel engine fault simulation, this study seeks to document some initial results arising from the simulation of common combustion related fault, namely misfire.

2. DIESEL ENGINE PROBLEMS

Typically encountered diesel engine problems include the loss of power, overheating, excessive or unusual noise and changes in exhaust emissions. These problems can be thought of as the observable or measurable symptoms of an underlying fault. Due to the complexity of IC engines, these symptoms can result from many interlinked causes. The interrelation between original faults, intermediate faults and symptoms can make engine fault diagnosis difficult.

A substantial number of serious engine problems can be attributed to faults linked with three engine component groups in particular. The component groups are; fuel injectors, piston rings and cylinder walls, and the inlet and exhaust valves. As the component groups mentioned are directly involved in the combustion process, they are critical in terms of engine performance, efficiency and engine reliability.

Fuel injectors are responsible for the delivery of the fuel into the combustion chamber and so are crucial in ensuring good fuel atomization and mixing occurs properly within the combustion chamber. Fuel injector faults can lead to poor combustion, loss of power, excessive fuel use and undesirable emissions.

The piston rings are required to produce a good seal between the piston and cylinder wall in order to limit blow-by and prevent the flow of lubricant into the combustion region. Additionally, piston rings are required to have a low friction value in order to; reduce frictional losses, lower engine wear, retain the desired liner texture and have good resistance against hot erosion, chemical attack and mechano-thermal fatigue [1].

The inlet and exhaust valves allow the working fluids, namely the air and exhaust gases, to be transferred into and out of the combustion chamber at the correct times whilst sealing the combustion chamber during the compression stroke and against the high pressures generated during the power stroke. Due to the heat and chemical makeup of exhaust gas flows the exhaust valve in particular tends to be subjected to harsh operating conditions. In fact, a study carried out on a 2200KW, MAN 7L 400/500 marine diesel power plant [2] showed that the exhaust valves in particular were critical from a reliability viewpoint and had the highest failure rate of all the combustion related components.

3. SIMULATING DIESEL ENGINE FAULTS

The limitations associated with engine testing, particularly when quantifiable or repeatable experiments are required; make it necessary to simulate engine faults in order to carry out tests in a controlled test environment. Therefore not surprisingly, various studies have detailed a number of fault simulation techniques. Table 1 highlights a list of references along with the methods used for simulating various diesel engine faults. Of note is the number fault simulation techniques which relate to the critical component groups highlighted previously.

Table 1
Reference list showing simulation methods for various diesel engine faults

Ref	Simulated Faults	Details
[3] [4] [5] [6]	*Exhaust valve leakage (Burn-through)*	*Both small and large exhaust valve leaks simulated by grinding groove in valve sealing face*
[3] [4] [5] [6]	*Cylinder misfire*	*Misfire simulation carried out by Turning off fuel injection to cylinder*
[7] [8]	*Exhaust valve leakage*	*Exhaust valve leak simulated using a fine cut (200 microns deep) across Seat of valve lid*
[7] [8]	*Inlet valve leakage*	*Exhaust valve leak simulated using a fine cut (200 microns deep) across Seat of valve lid*
[7] [8]]	*Blocked fuel injector*	*One of four holes in the fuel injector nozzle was blocked*
[7] [8]	*Poor fuel atomisation*	*Fuel injector with faulty atomization pattern was used (Nozzle had a "slight dribble")*
[9]	*Loss of compression*	*Creating an inlet valve leak(using a fine cut about 200 microns deep across seat of valve lid)*
[9]	*Incorrect fuel injection*	*One of four holes in the fuel injector nozzle was blocked*
[10]	*Intake manifold leak*	*Two levels of manifold leakage were induced by drilling 2mm and 6mm holes into bolts which could be screwed into the inlet manifold plenum chamber*
[11]	*Injector Fault (spring fatigue)*	*Injector pressure was changed by inserting shims under the pressure*
[11]	*Exhaust manifold gasket leak (gasket burn-through)*	*Gasket material removed to form a channel near exhaust ports*
[12] [13]	*Piston ring/cylinder Liner scuffing*	*Scuffing/lubrication fault was induced by shutting off lubrication system*

Those faults relating to the piston ring and cylinder wall appear to be the most difficult to simulate accurately given the level of difficulty in inducing and quantifying ring/liner faults and the practical issues of needing to disassemble and reassemble the engine between tests as well as the high likelihood of severe engine damage.

4. EXPERIMENTAL MISFIRE SIMULATION

The aim of this experimental test campaign was to simulate a common combustion related diesel engine fault, namely misfire. Misfire occurs when combustion within the cylinder fails to take place. This can lead to a severe drop in power and engine stall. In broad terms, misfire can be caused by faults which lead to reduced compression ratios, poor quality fuels, and electrical problems and by injector/fuel system faults.

As misfire is directly related to combustion, it is of no surprise that from a performance monitoring view point cylinder pressure is highly effective in terms of detecting and misfire. From a condition monitoring point of view however cylinder pressure measurements lack information concerning fault diagnostics. Additionally, pressure sensors are intrusive and costly to install as they must be fitted within the combustion region.

The misfire fault was experimentally simulated using an electrical switch which when activated cut of fuel injection into the cylinder. The datasets generated were used to compare and characterise the resultant AE and vibration signals.

Two data acquisition systems were employed, the first system was used to record vibration, cylinder pressure, TDC and crank angle encoder signals, whilst the second system was used to record TDC, encoder and AE signals from the engine cylinder block and cylinder head.

4.1 Biofuels Engine Research Facility

The experimental misfire simulation was carried out using the Biofuels Engine Research Facility (BERF) located at Queensland University of Technology. This facility consists of a 5.9 litre, turbo-charged Cummins diesel engine coupled to a Froude water dynamometer. The test bed is controlled electronically via a Dynalog control system. The BERF is shown in Figure 1.

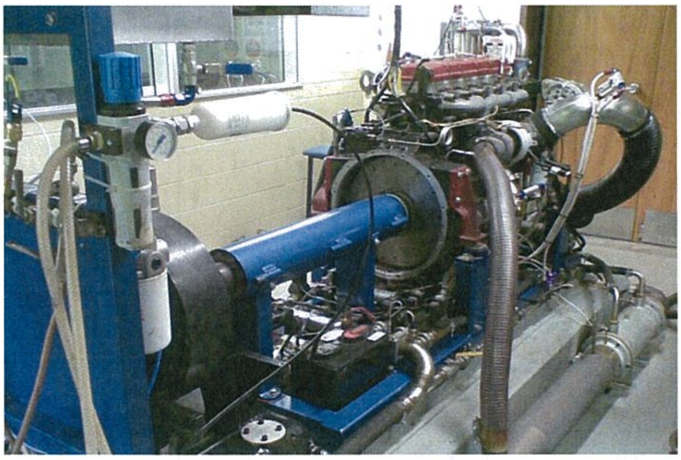

Figure 1: The Biofuels Engine Research Facility

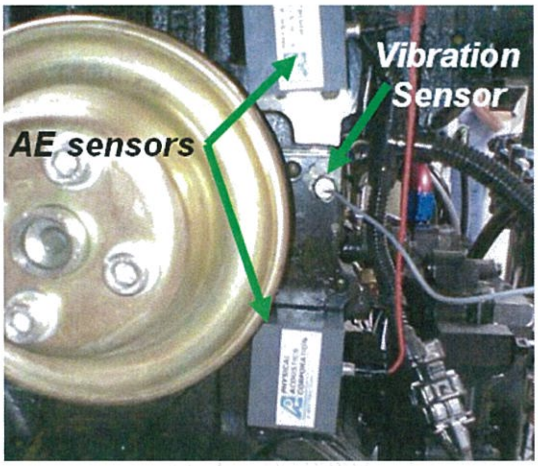

Figure 2: AE and vibration sensor positions

4.2 Experimental Procedure

As mentioned, two data acquisition systems were employed during the Cummins test campaign. The first system was used to record vibration, cylinder pressure, TDC and crank angle encoder signals whist the second data acquisition system was used to record TDC, encoder and the AE signals from the engine block and head.

As is seen in Figure 1, both the AE and vibration transducers were positioned on the front face of the engine with the closest cylinder being cylinder number one. The first AE sensor was placed on the engine block while the second AE sensor was placed on the cylinder head.

These AE sensor positions were used in order to investigative the effects of senor positioning upon AE signals. Cylinder pressure from cylinder one was recoded using a Kistler pressure transducer. The data acquisition system used for the vibration and pressure measurements is shown schematically in Figure 3 whist Figure 4 shows the data acquisition system used to capture the AE signals. The misfire test was undertaken at an engine speed of 1500 rpm and as load settings above 60% resulted in the engine stalling, the series of misfire tests was undertaken at half load.

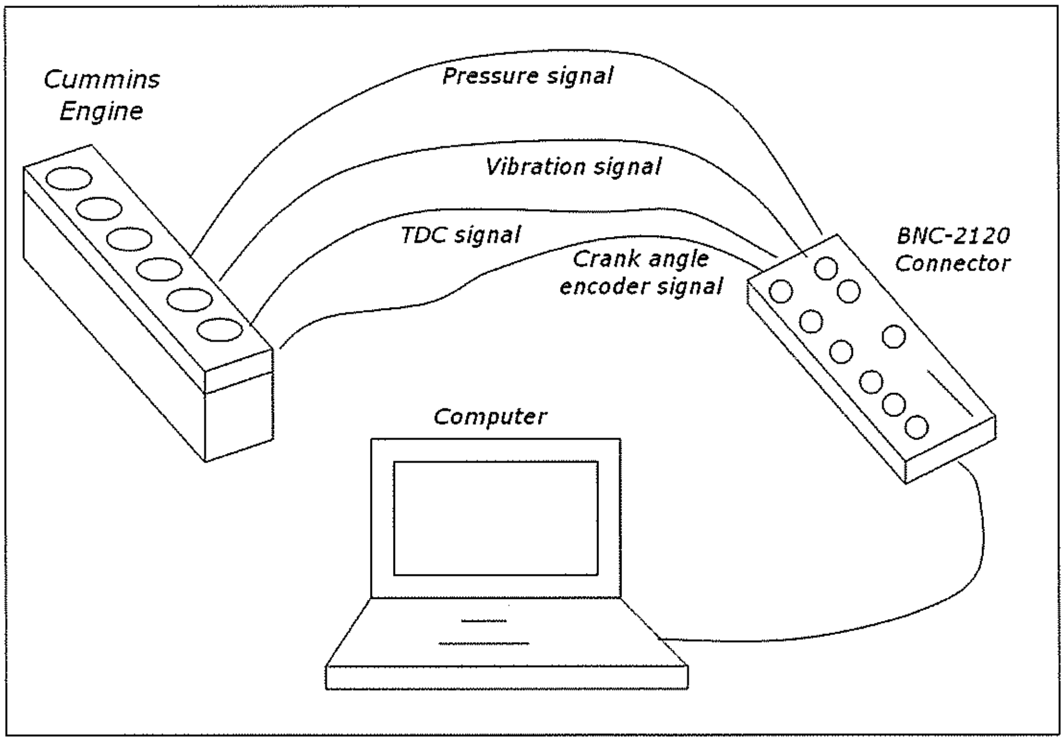

Figure 3: Diagram showing data acquisition system used to record cylinder pressure, vibration, TDC and crank angle encoder signals

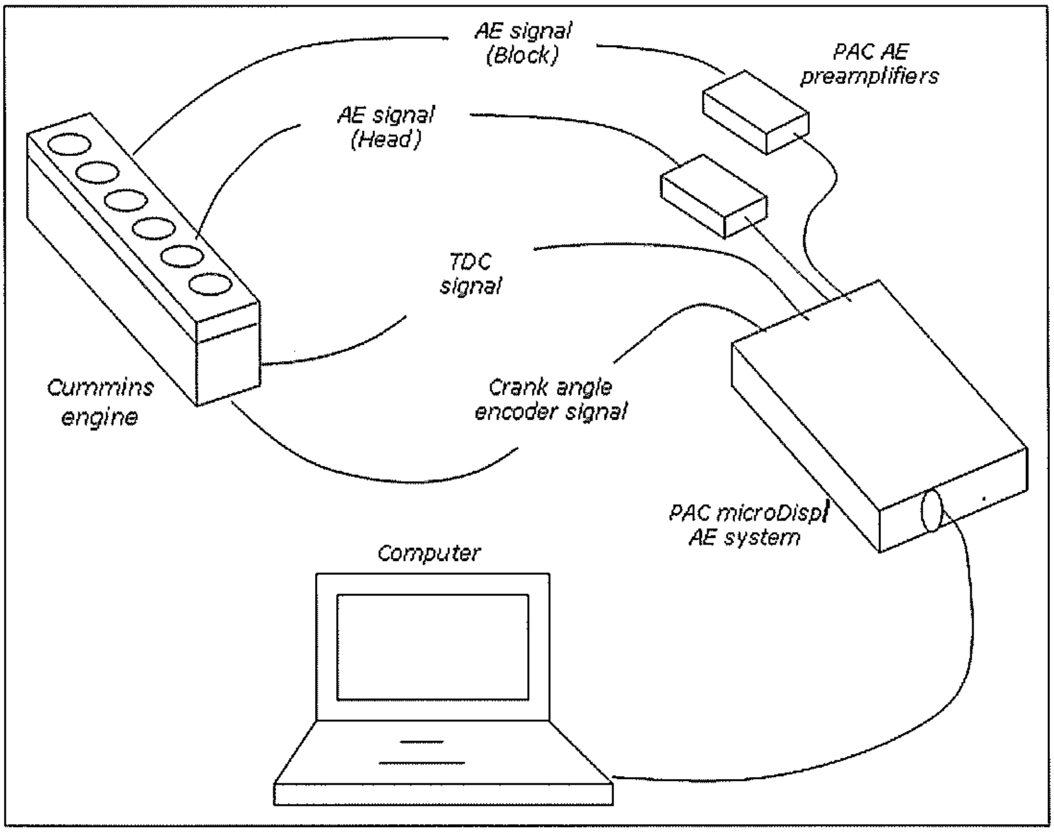

Figure 4: Diagram showing the AE data acquisition system used for the Cummins test

5. MISFIRE SIMULATION RESULTS

As misfire is directly related to combustion, it is of no surprise that cylinder pressure is highly effective in terms of detecting and qualifying the severity of the misfire. For this series of tests pressure traces are utilised to confirm the misfire situation. In addition both vibration and AE measurements have been recorded. The recorded vibration and AE signals have been re-sampled into the crank domain in order to facilitate accurate comparison between different engine cycles and speeds. The signals have also been analysed using frequency spectrograms. This method, using fast Fourier Transforms, allows the calculation of energy levels associated with various frequencies

5.1 Vibration Signals

As misfire is directly related to combustion, it is of no surprise that cylinder pressure is highly effective in terms of detecting and qualifying the severity level of the misfire. The difference between a normal combustion pressure trace and a misfire pressure trace is highlighted by the lower panels of Figure 5 and 6. The bottom panel of Figure 5 shows a pressure signal for one complete normal combustion engine cycle. As seen, at approximately 300 degrees of crank angle the green pressure curve begins to rise. This rise, peaking at approximately 360 degrees corresponds to the compression stroke.

The combustion or power stroke corresponds to that part of the pressure curve occurring between 360 and approximately 440 degrees. Of note is the increase in vibration signal amplitude seen during this interval and the corresponding increase in energy seen in the frequency spectrogram shown in the upper panel.

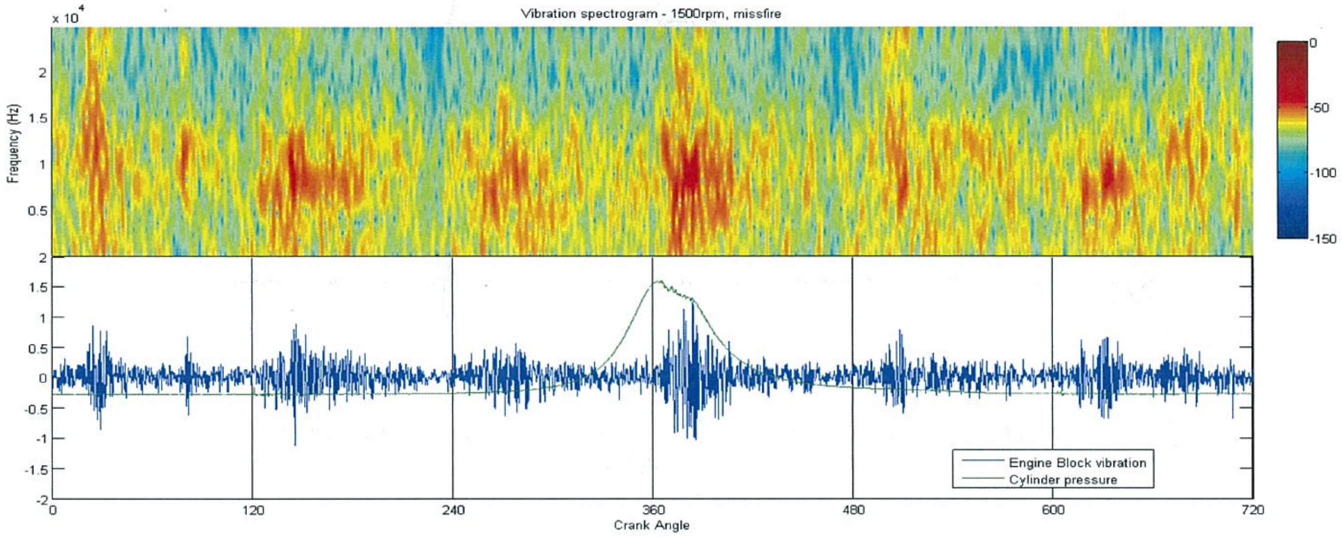

Figure 5: The upper panel shows frequency energy levels for the vibration signal. Lower panel shows cylinder pressure and vibration signals for normal combustion.

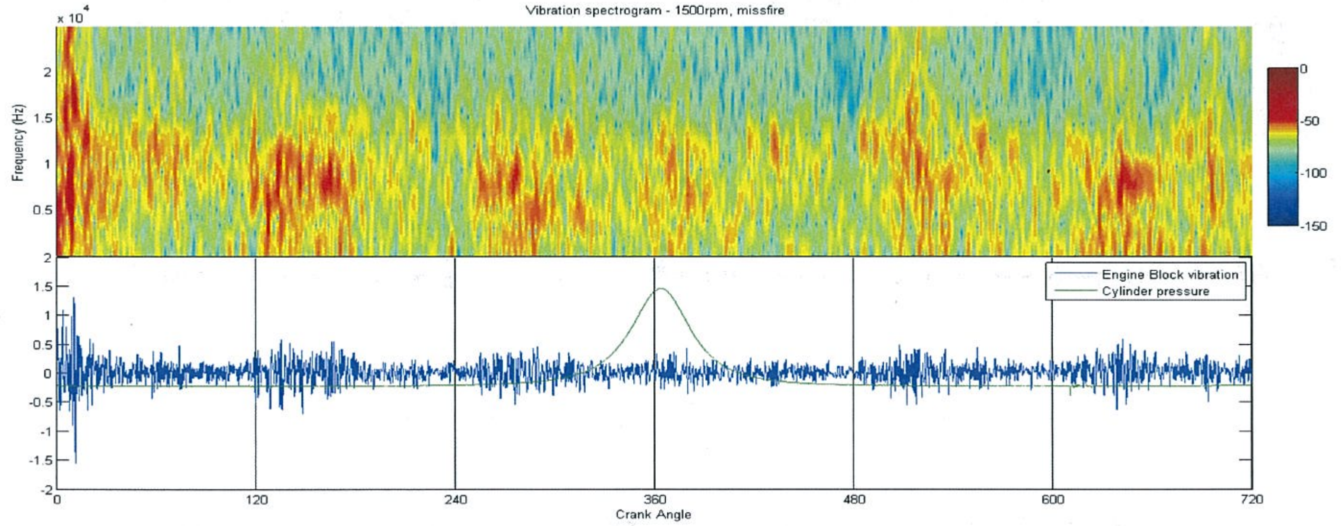

Figure 6: The upper panel shows the frequency spectrogram for the vibration signal. Lower panel shows cylinder pressure and vibration signals for misfire.

Figure 6 shows a pressure signal and the resulting vibration for one complete engine cycle for the misfire situation. As seen, at approximately 300 degrees of crank angle the green pressure curve begins to rise as before. Unlike Figure 5 however the curve between 360 and approximately 440 degrees mirrors the compression part of the curve. This indicates that the compressed air is simply expanding as the cylinder passes the top dead centre position and moves downwards. The misfire spectrogram shown in the top panel of Figure 6 also shows a distinct reaction as the signal energy levels are much lower for the corresponding portion of the spectrogram. These characteristics suggest that from a performance monitoring viewpoint, vibration based techniques are capable of detecting misfire.

5.2 Acoustic Emission Signals

As highlighted by Figure 7 acoustic emission signals can also be used to detect misfire. Figure 7 shows AE signals for two individual engine cycles. The top panel shows an AE signal recorded from the engine whist running normally. The Lower panel shows an AE signal recorded from a misfire engine cycle. There is a clear difference between the graphs for the interval between approximately 300 and 490 degrees of crank angle. This crank angle interval corresponds to the compression and combustion events for the cylinder closest to the sensors.

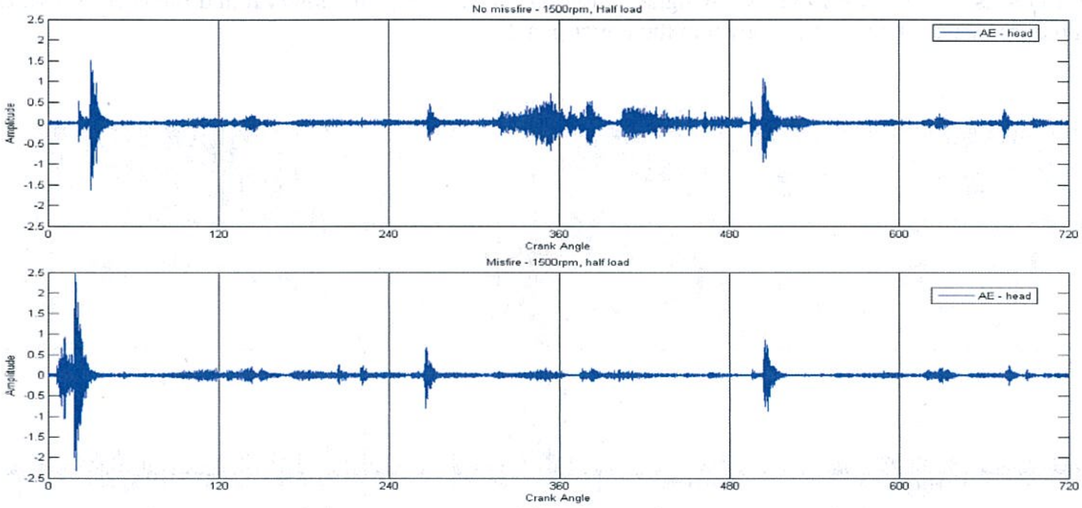

Figure 7: The upper panel shows an AE signal for a normal engine cycle. The lower panel shows an AE signal for a misfiring engine cycle.

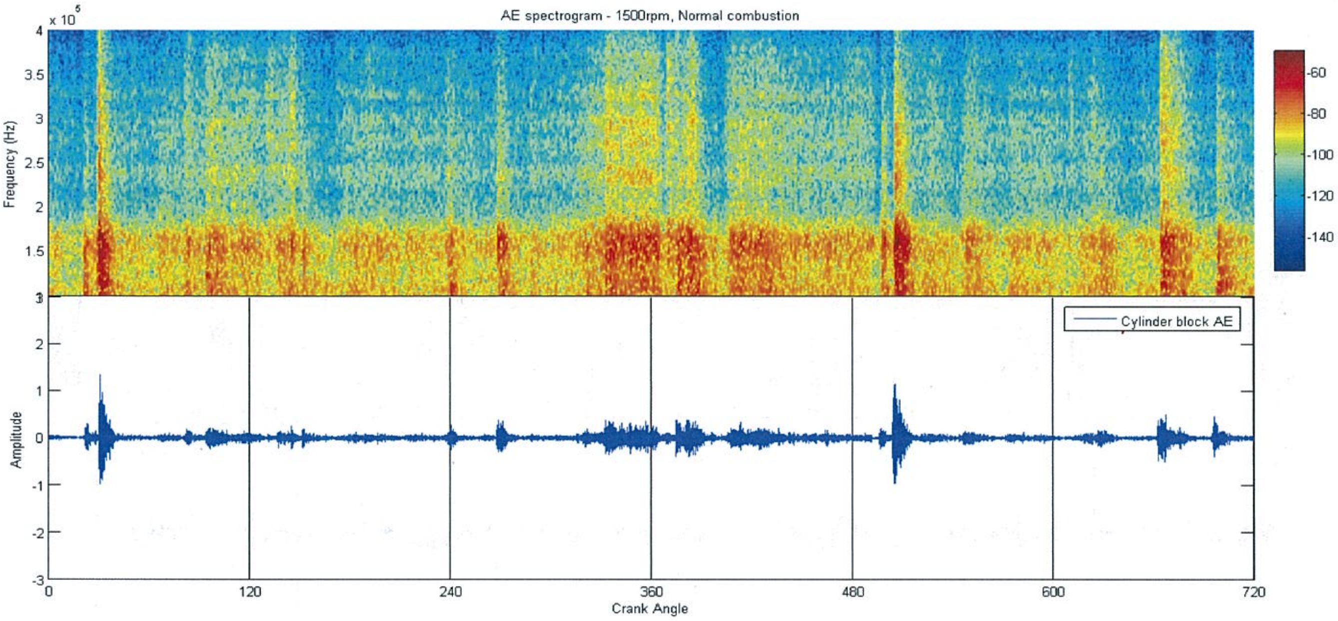

Figure 8: The upper panel shows the frequency spectrogram for one complete normally running engine cycle recorded from the engine block. The lower panel shows the corresponding AE signal.

The top panel of Figure 8 shows a frequency spectrogram of an acoustic emission signal recorded on the engine block for a normal engine cycle. The lower panel shows the corresponding AE signal in terms of crank angle. The piston top dead centre position at the start of the power stroke corresponds with a crank angle of 360 degrees and once again the interval between approximately 300 and 490 degrees of crank angle shows combustion occurring.

The top panel of Figure 9 shows a frequency spectrogram of an acoustic emission signal recorded on the engine block for a misfire engine cycle. And, as in the previous figure, the lower panel shows the corresponding AE signal in terms of crank angle. A distinctive difference in the interval between approximately 300 and 490 degrees of crank angle can be seen. As evidenced by the reduced energy levels, the difference between normal combustion and misfire is also seen when comparing the spectrograms from Figure 8 and Figure 9.

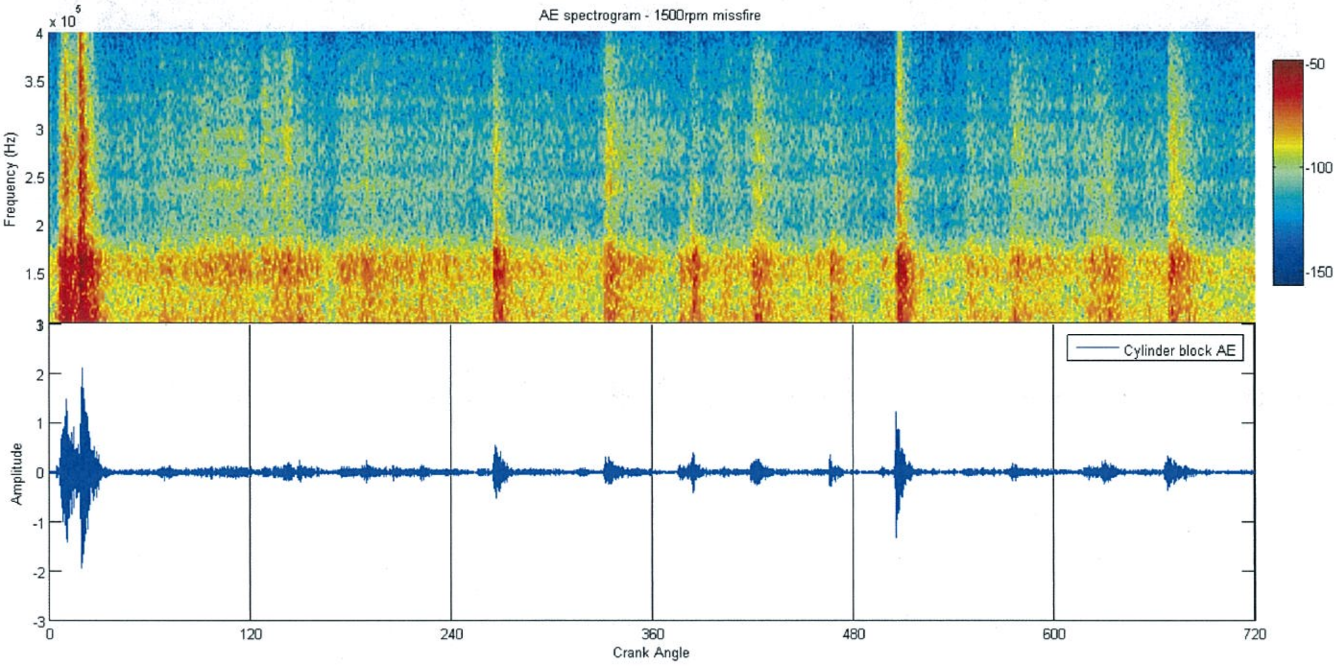

Figure 9: The upper panel shows the frequency spectrogram for one complete misfire engine cycle recorded from the engine block. The lower panel shows the corresponding misfire AE signal.

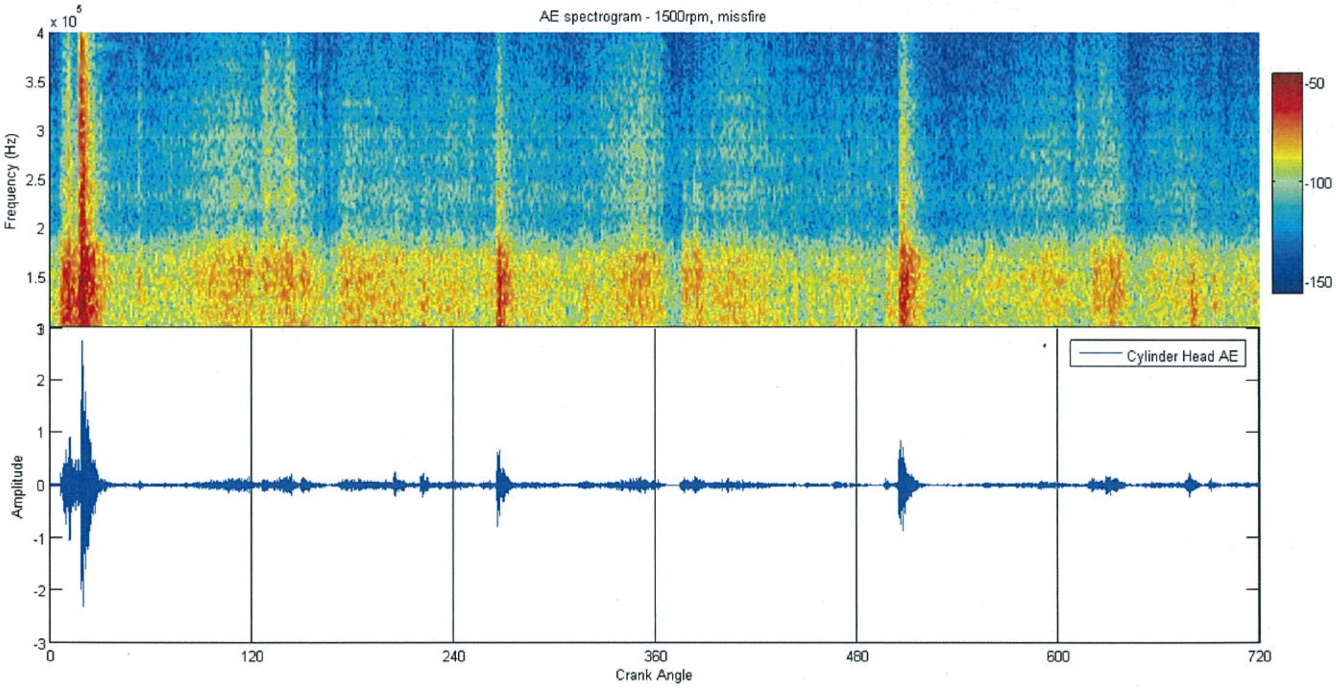

Figure 10: The upper panel shows the frequency spectrogram for one complete misfire engine cycle recorded from the engine head. The lower panel shows the corresponding misfire AE signal.

The distinctive difference between misfire and normal combustion in the interval between approximately 300 and 490 degrees is highlighted even further by Figures 10 and 11. In these figures the same normal and misfire engine cycles were recorded using a sensor positioned on the head of the engine. As seen, the difference between normal combustion and misfire is even clearer. This extra signal clarity may be due to a reduction in AE wave reflections due to the isolating effect of the head gasket and the reduction in noise from auxiliary components mounted to the engine block.

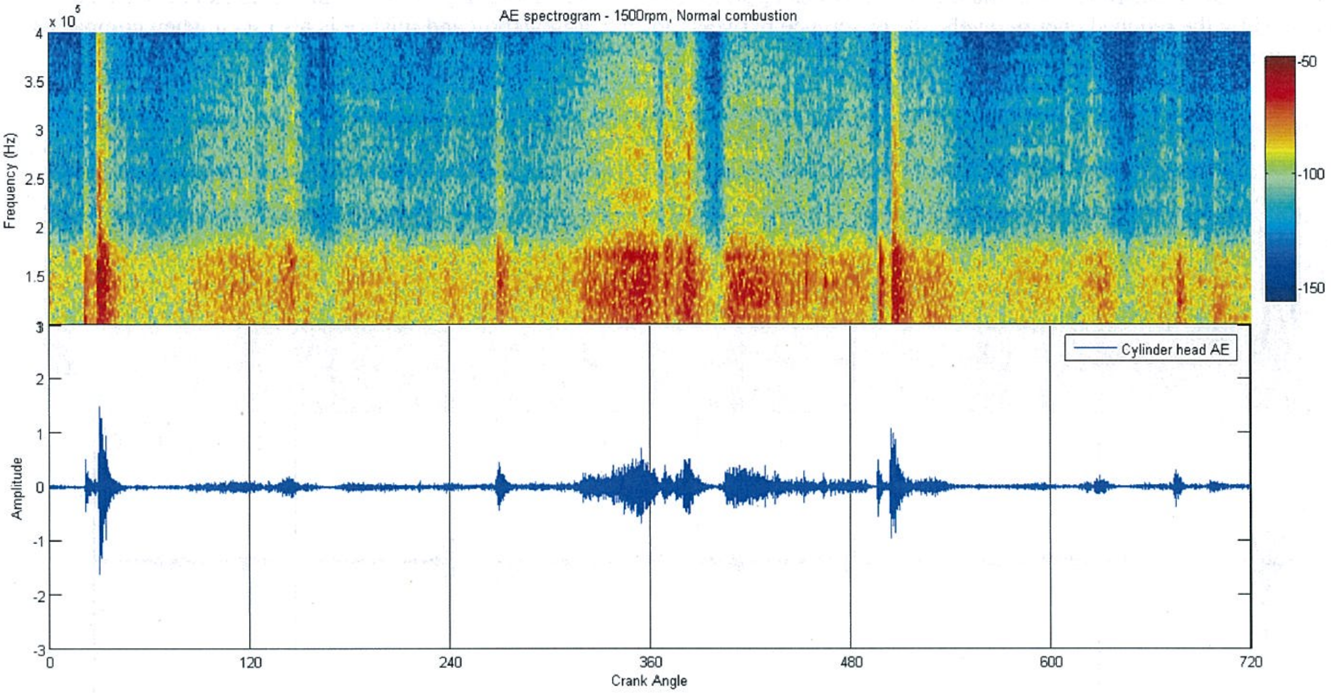

Figure 11: The upper panel shows the frequency spectrogram for one complete normal combustion engine cycle recorded from the engine head. The lower panel shows the corresponding AE signal.

6. CONCLUSIONS AND FUTURE WORK

The recorded vibration and AE signals showed that diesel engine misfire can be clearly identified using both signals but the misfire event appeared more distinct when considering the AE signal. The majority of the AE signal energy was concentrated in a frequency band from the lower cut-off frequency of 100 KHz up to approximately 200 KHz. The combustion event produced a distinctive "broadband" event with increased energy levels appearing up to 350 KHz. Other peaks in the AE signal, such as the peak shown at 30 degrees crank angle thought to be mechanical events. These events also showed elevated signal energy at frequencies up to the 400 KHz limit.

It was also noted that the AE measurements taken from the engine head appeared to contain less noise. Possible reasons for this were; a reduction in AE wave reflections due to the isolating effect of the head gasket and the reduction in noise from auxiliary components mounted to the engine block. These initial observations show that AE signals are superior to vibration measurements in terms of misfire detection and possibly hold a substantial amount of information regarding other events and processes occurring in diesel engines.

Whist the initial observations outlined detail some interesting results, a great deal of work remains to be done. In addition to further analysing and comparing vibration and AE measurements from misfire and normal engine cycles, the continuing analysis will seek to find the AE signal characteristics which best relay misfire information. In addition, further analysis will be undertaken to identify the specific events which cause the distinctive peaks witnessed in the AE signal plots

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