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The Analysis of Acoustic Emission Signals from the Cylinder Head of a Diesel Engine for Fault Detection

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Abstract

There are many acoustic emission (AE) sources in a diesel engine. During an engine cycle, fuel injection, onset of combustion, valve impacts and piston slaps all produce AE effects. Because these events happen around the top dead centre, it is difficult to separate them for the purpose of combustion monitoring. This study focuses on characterising AE signals measured on the cylinder head of a diesel engine for injection fault diagnosis. Firstly, AE signals are analysed to understand AE signals in association with engine operating conditions and sensor placement. Then, faulty injectors are tested to evaluate AE based injection fault detection. The results from joint angular and frequency analysis has shown that AE can clearly monitor the changes in the combustion process due to its high signal to noise ratio in the high frequency range from 10kHz to 45kHz where other vibro-acoustic sources have little influence.

Keywords: diesel engine, fuel injection, misfire, misfire detection, acoustic emission.

1. Introduction

Today's diesel engines must meet both fuel economy requirements and pollutant emissions regulations, which have become more and more stringent moving from euro V to Euro VI and beyond. Faults in fuel injectors cause not only low engine efficiency but also high and sometimes even unacceptable level of unburned hydrocarbons due to levels poor air fuel ratio's. In addition, injector faults increases noise and vibration which may cause damage to engine components. Therefore, the detection injector faults at their early stage and maintain combustion performance is one of key tasks in controlling pollutant emission as an engine ages and not just its early life performance.

Many previous researchers have been carried out for engine fuel injection diagnosis [1, 2, 3] based on airborne acoustics and structural borne vibration. However, because of complexity of vibro-acoustic sources in a diesel engine, it is difficult to obtain detailed information regarding to fuel injection for reliable fault diagnosis. In contrast, acoustic emission (AE) from engines usually may be a more effective approach to detecting injection related faults because it is measured in high frequencies such as 100kHz above and hence has the good localisation performance.

AE measurement on the cylinder head is a non-intrusive method and has been successfully implemented for monitoring diesel engines [4, 5, 6]. Various signal processing techniques of the AE signals are used to extract features sensitive to faults. These

investigations have shown that the AE signals have a very high signal-to-noise ratio and the faults of interest can be extracted with certain effort in signal processing.

The measured AE signals on the diesel engine depend on the excitations and the propagation path. The main sources of excitation are likely to affect the engine AE response, include impacts due to piston clearances (piston slaps), fuel injection, high rise of gas pressure during combustion and the impacts of inlet and exhaust valves. Some of these faults affect the AE signal simultaneously and during a limited portion of the engine cycle. A fault is usually detected by comparing the AE signal of the faulty engine to the reference signature. In the angular domain, the presence of several simultaneous faults makes the separation of the sources a difficult task. Fourier spectrum is more useful for the analysis of stationary signals associated to reciprocating machines. For non-stationary engine AE signals, the spectrum tends to smear frequency components. Joint angular-frequency analysis has more potential for source separation since both the frequency content and time varying profile of the signal can be investigated simultaneously.

In this paper, the potential for early detection of injector faults using AE signals is investigated experimentally. In the experimental work, a four-stroke, four-cylinder, in-line diesel engine has been used. AE signals have been recorded under different healthy conditions and analysed correspond in the angular, frequency and joint angular-frequency to extract key characteristics from the raw AE signals for differentiate different engine conditions.

2. AE Sources in Diesel Engines

There many possible AE sources in diesel engines. Previous studies [8, 9, 10, 11] have shown that AE measured at cylinder head contains major AE events from combustion, fuel injection piston slaps and valve impacts. In the following, possible AE sources of a diesel engine, as well as the mechanism of propagation of these sources to the engine structure are reviewed for best understanding of AE signals measured from different engines at different locations.

2.1 Combustion

During the phase of combustion a significant and rapid increase of the in-cylinder pressure occurs to force piston moving down. Because of the high pressure rise rate, this combustion force can be described as comparable to a hammer hit and hence can cause wideband responses on the cylinder and cylinder head. Obviously, at higher engine conditions, higher impacts will be resulted by higher pressure increases. Previous studies confirmed that this excitation is periodic according engine working cycle and spreads to wide frequencies as high as several kilo-Hz.

As the impact of the combustion pressure applies a direct excitation on the cylinder head. This path constitutes the first way of propagation and can be observed easily by placing AE sensor on cylinder head

2.2 Piston Slap

Piston slap is another important source of acoustic emission in diesel engines. It is caused by the inversion of the inertia forces acting on the piston as the piston changes direction at top dead centre TDC and bottom dead centre BDC. This effect is most prominent when the force from the combustion process is acting on the piston. Piston slap results from the succession of two strong impacts. One impact is applied by the upper part of the piston near the crown while the other impact is applied by the lower part of the piston skirt. The upper impact is usually higher than the lower due to high gas force in combustion cycle. The piston slap impacts also cover a wide range of frequencies and vary significantly with engine operating conditions. The dimensions of clearance between piston and cylinder are the most decisive factor of the impact intensity and hence these types of AE events may not be observed directly when the clearance is small. Nevertheless, it is very close to TDC and may be masked by combustion event.

2.3 Fuel Injection

The fuel injection process in a diesel fuel is driven by a high pressure (several hundred bars) in short time duration (several micro-seconds). It causes both mechanical impacts and flow friction. During fuel injection the high pressure fuel wave makes the needle valve opening and closing, which produces the mechanical impacts due to the valve motion and hence possible AE events. In the mean time, a high speed flow formed in the orifices of injector may also produce AE signals due to complicated hydrodynamic processes such as fuel atomization, interaction between the flow jet and orifices. This fuel injection related AE's occur before TDC and have much smaller amplitude compared with combustion induced AE.

2.4 Valve Impact

Closing and opening of intake and exhaust valves is achieved by a camshaft and a valve spring operating in precise synchronisation. AE events from the valves in a diesel engine arise from two sources of distinctly different origin and character, namely:

1- Mechanical impact is generated by the colliding of various surfaces, in particular those of the valve and valve seat, and of the rocker arm with push rod or valve stem. Valve impact is considered to be the predominant source of AE events from the valve.

2- Aerodynamic friction is created by the high speed gas passing between the valves and their seating, and gas flow over the valve face.

Valve impact plays a significant role in the AE of diesel engines and these impacts on the valve seat on valve closure, and the degree of impact depends on the valve closing velocity, which is controlled by the dynamic behaviour of the valve train, particularly the force exerted on the valve by the valve spring.

Moreover AE transmission paths also distort AE signal considerably [9, 10]. Besides internal damping effect, AE waves travelling in engine structures can undergo

reflection, scattering, mode conversion and diffraction, and many of these are discontinuous Therefore, the intensity of AE signal has to be examined in association with the effect due to distance between source and sensor.

3. AE Measurements

AE signals studied in this paper are from an in-line four-cylinder diesel engine, whose combustion sequence for each cylinder is 1-3-4-2. Full operating parameters and characteristics of the engine are given in Table 1.

A wide band frequency AE sensor was placed on the front side of cylinder head so that AE characteristics from Cylinder 1 can be studied with great details, as shown in Figure 1. The output or AE sensor is amplified and sampled at 2MHz for more accurate waveform analysis. Raw AE signals were collected under constant engine speed: 1000rpm and 4 different load conditions: 0, 50Nm, 100Nm, 150Nm.
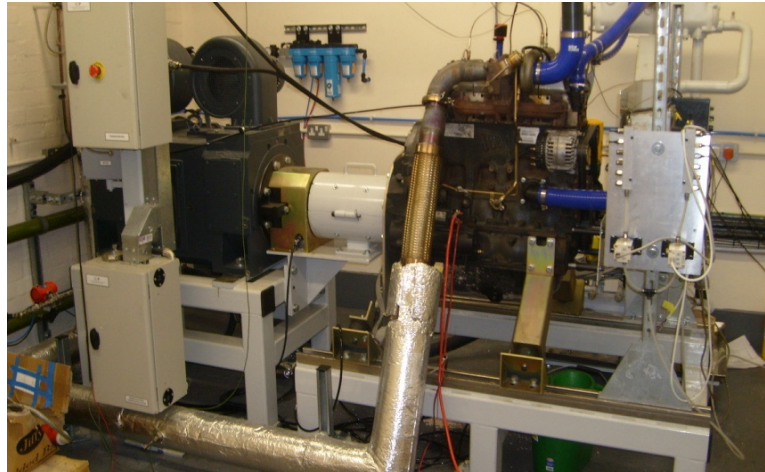

Figure 1 JCB Engine Test Rig

Table 1 Description of JCB Engine

Type of engine	Turbocharged diesel engine
Number of cylinders	4
Bore	103mm
Stroke	132mm
Inlet valve diameter	36.5mm
Exhaust valve diameter	33.2mm
Compression ratio	18.3
Number of valves	16
Injection system	Direct injection
Displacement	4.399 litre
Speed range	850 – 2200 rpm
Recommended speed	850 rpm
Compressor speed	60,000 – 220,000 rpm
Maximum power	74.2 kw @ 2200 rpm

For a study of AE signal based engine fault diagnosis, three tests were conducted under different engine conditions. Test 1 is for the baseline AE data collected when the engine is healthy. Test 2 is for a small fault in cylinder 1 under an abnormal fuel injection pressure induced by setting it 15% lower than the nominal injection pressure of 270bar. Test 3 is for a large fault induced by disconnecting fuel supply to cylinder 1 completely to simulate a full misfired engine.

4. Signal Analysis and Result

4.1 Analysis in the Angular Domain

Based on the raw AE signals measured, the engine speed is estimated and corresponding crank angles are calculated based constant speed operation. Figure 2 presents the AE signals aligned in the angular domain under different loads at 1000rpm. In addition, the events relating to inlet valve opening (IxO), inlet closing (IxC), exhaust valve opening (ExO) and exhaust valve closing (ExC) are also illustrated based on their corresponding nominal values. It can be seen that there are four major AE events can be observed clearly in one full engine cycle for this four cylinder engine. This alignment is just based on the amplitude trend with engine load without the measurement of TDC signals. In particular, the amplitude change in is more consistent with the increasing in engine load and hence with AE generation mechanisms, i.e. a higher load generating a high combustion AE event. In contrast, other AE components maintain nearly constant with load, showing that they are mainly come from valve events. Besides a small AE event showing around 190º is also consistent with the closure of inlet valve 1.
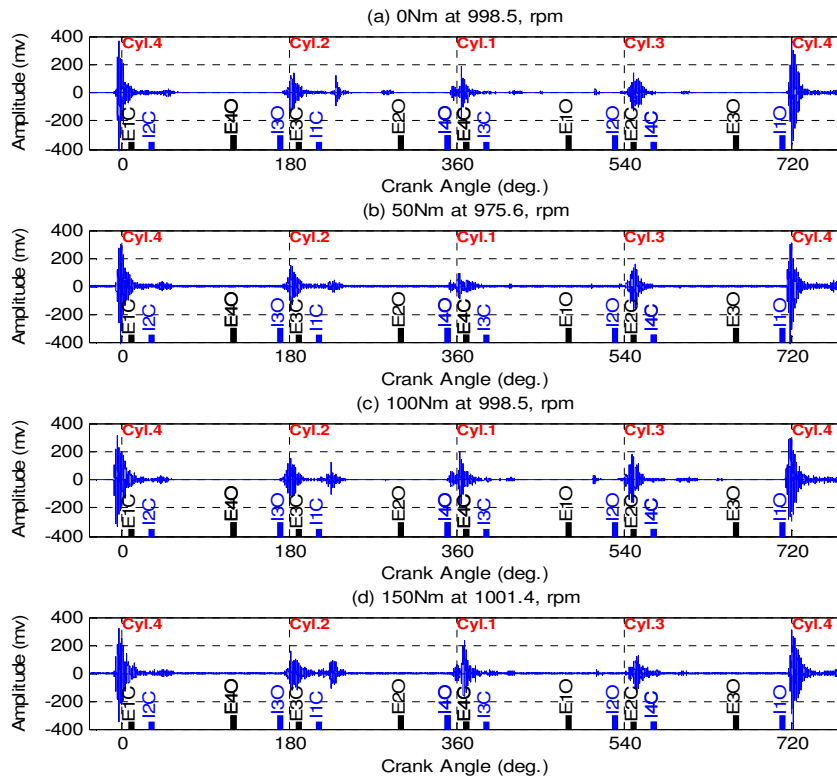

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Figure 2 AE signals in the angular domain under different loads

However, the largest event is aligned with the event due to the opening of inlet valve in cylinder 1 and its amplitude is similar over different load conditions. This observation is different from previous study that the combustion is the largest AE event [8, 9, 10], which demonstrates that AE characteristics are very different between different engine designs.

This new large AE event could be caused by damage to the main engine bearing on the crank shaft or the journal bearing on the connecting rod or large clearances at the gudgeon pin. This damage could lead to excessive movement and lead to high energy impacts of the components. These impacts could propagate through the engine and cause the large AE event measured on the engine.

Figures 3 and 4 show the comparison of healthy AE signals with that from the two seeded faults respectively. For the reduced injection pressure fault, a clear difference just before 360º, shown in Figure 3(a), can be seen under no load operation whereas they are very similar for other load conditions. Even though, the rapid transient event of the no load condition indicates that an obvious injector valve impact due to the pressure reduction. However, for other load conditions this feature is not so clearly observed in this angular domain presentation. This shows that more advanced analysis is required to achieve full fault diagnosis.
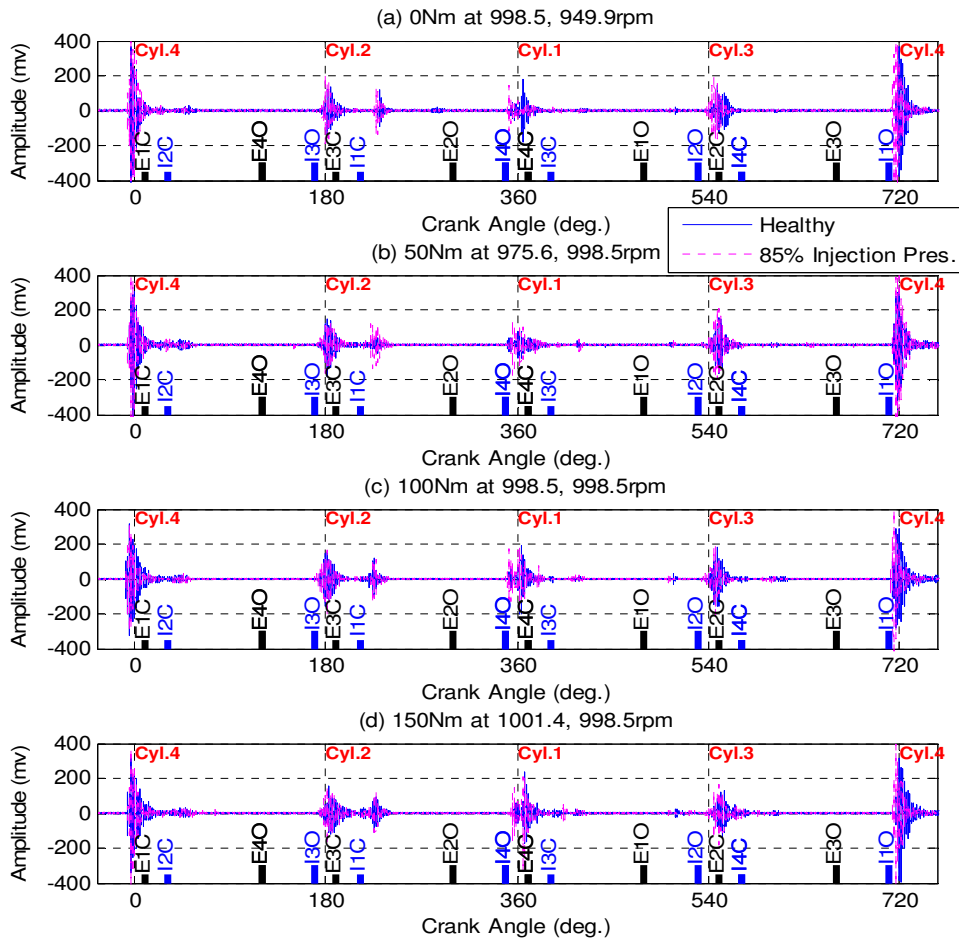
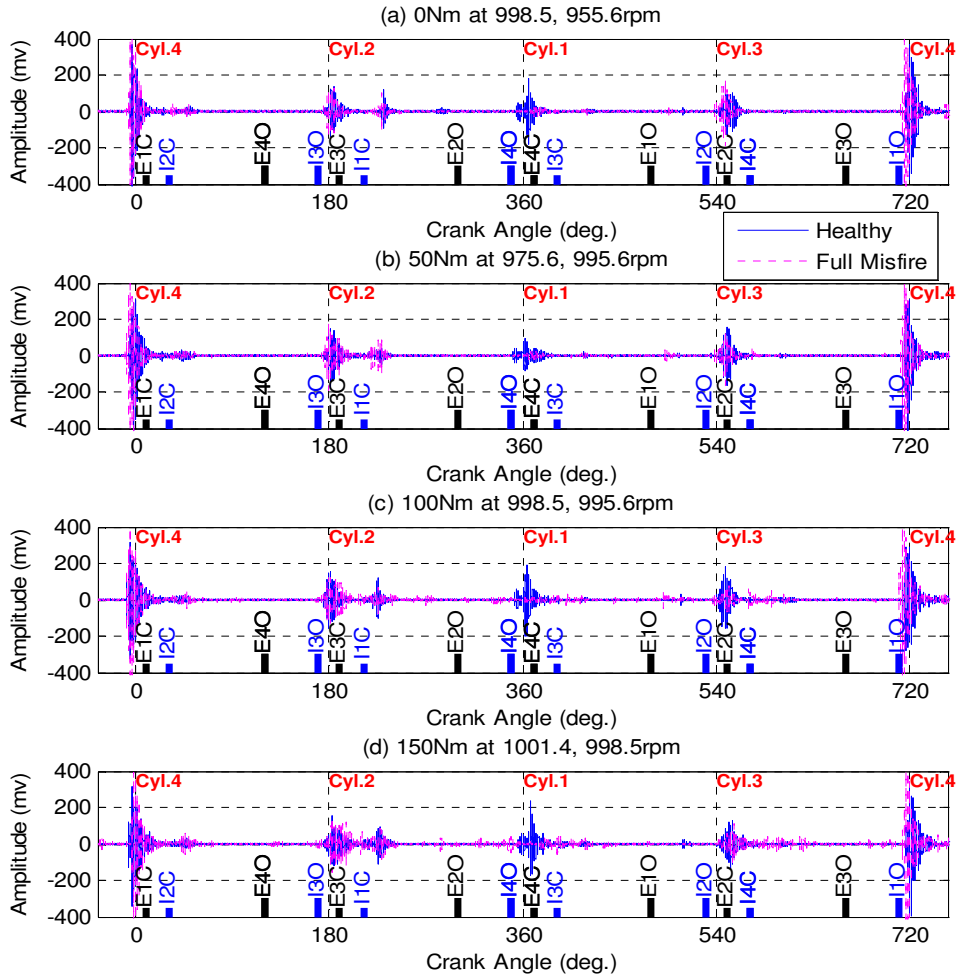**Figure 3** AE signals in the angular domain (85% injection pressure).

Figure 4 AE signals in the angular domain (full misfire).

For the full misfired cylinder, AE signal in Figure 4 show no clear AE event for all load condition tests and hence allows the misfire to be detected straightforward in the angular domain.

4.2 Analysis in the Frequency Domain

The AE signals in the frequency domain are obtained by applying the Fast Fourier Transformation (FFT) to raw AE signals. Figures 5 and 6 give spectral comparison for two faulty cases respectively. It can be seen that high AE energy is mainly in a frequency range from 10kHz to 45kHz and there is clear change can be observed in the spectrum between the healthy and faulty cases. For both two faulty cases, the main frequency components shift slightly to higher frequency bands. It may indicate that engine behaves with sharper impacts or more violent flow processes, which are basic symptoms of the faulty operation.

However, it is impossible to determine which cylinder has a faulty injector from the spectrum and to differentiate between the two faulty cases.
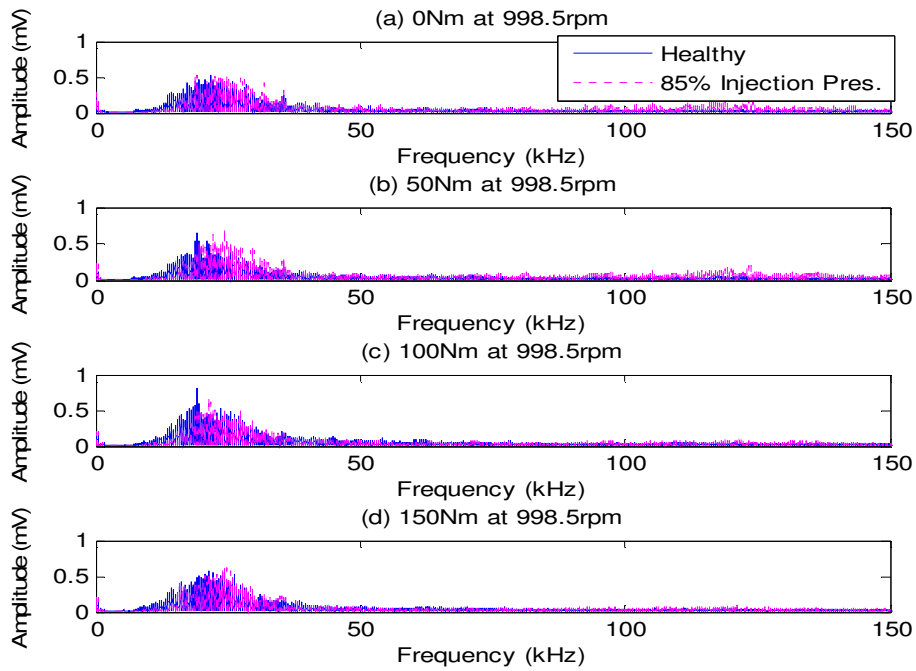

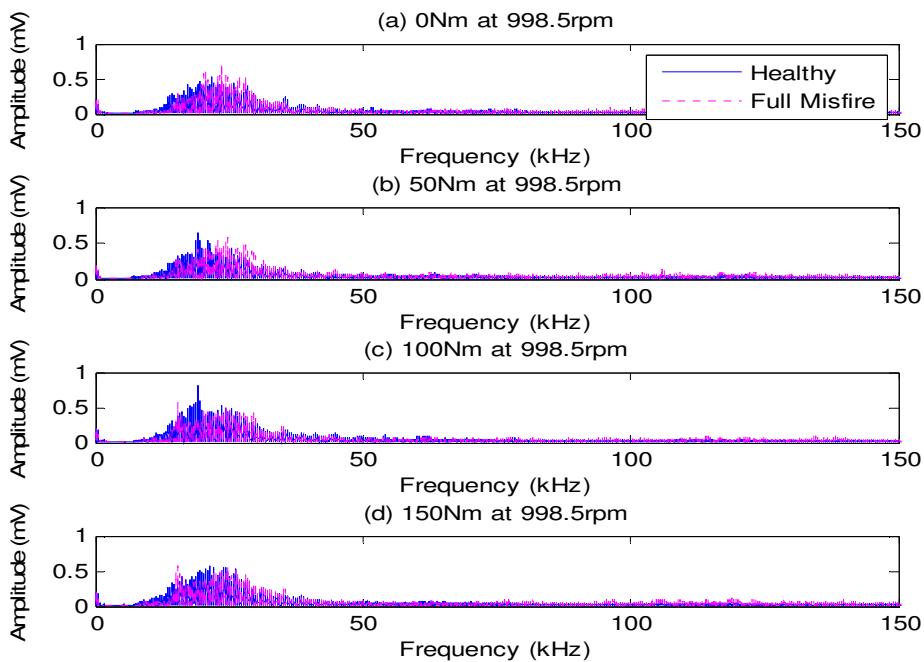**Figure 5 S**pectra of the AE signals for 85% injection pressure

Figure 6 Spectra of the AE signals for full misfire

4.3 Analysis in the Angle-Frequency Domain

Above analysis shows that AE signals in the angular domain can produce diagnosis results for no load condition but not for higher load conditions whereas spectrum presentation allows fault deletion for all cases but not diagnosis. To combine the capabilities in both the angular and frequency domains, joint angular-frequency analysis is applied to the AE signals. Previously work in [1, 2,] shows that smoothed Wigner distribution is effective in analysis injector impact induced vibration. However, recent advances in signal processing show that wavelet transforms is more suitable in analysis highly non-stationary signals such as AE from engines. Therefore, the measured AE signals is analysed with a continuous wavelet transform (CWT) using a Morlet wavelet. For more detailed study, CWT results are presented around the combustion TDC of cylinder 1.

The top two graphs in Figure 7 show CWT results of healthy engine under no load and a high load respectively. It can be seen that combustion AE events occurs around 365º and its frequency content become higher under high load condition. In addition, its amplitudes also increase. The AE event due to fuel injection happen around 355º and both its frequency range and amplitude increase with load.
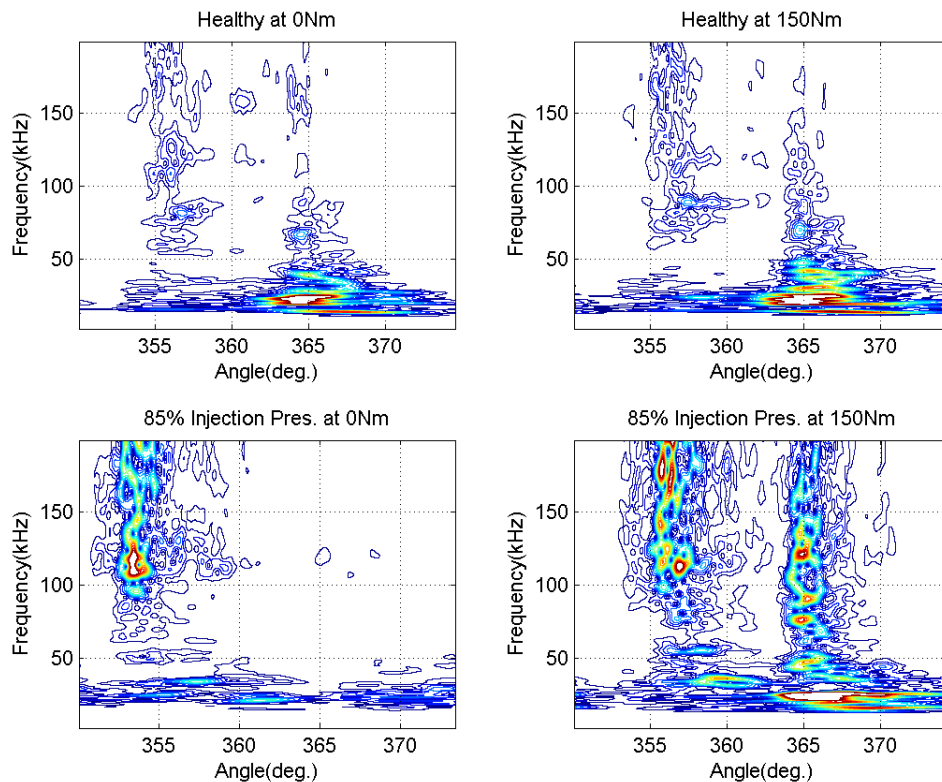

Figure 7 Angular-frequency representation of healthy and 85% injection pressure

For the small fault of the lower injection pressure, CWT results change significantly from that of healthy case. CWT results shown by bottom graphs have higher AE amplitudes, indicating higher impact from needle valve opening due to reduced injection pressure. For the no load case, it shows little combustion AE event whereas

around 365º, indicating poor combustion occurring in the cylinder. In contrast, the high load condition show a very high AE combustion event with wider frequency range. This shows that the combustion occurs violently because of poor fuel atomization and more fuel injected caused by reduced injection pressure.

These significant changes due to the fault in CWT shows that it is possible to differentiate the small injection fault from healthy and achieve diagnosis under both high and low load conditions.
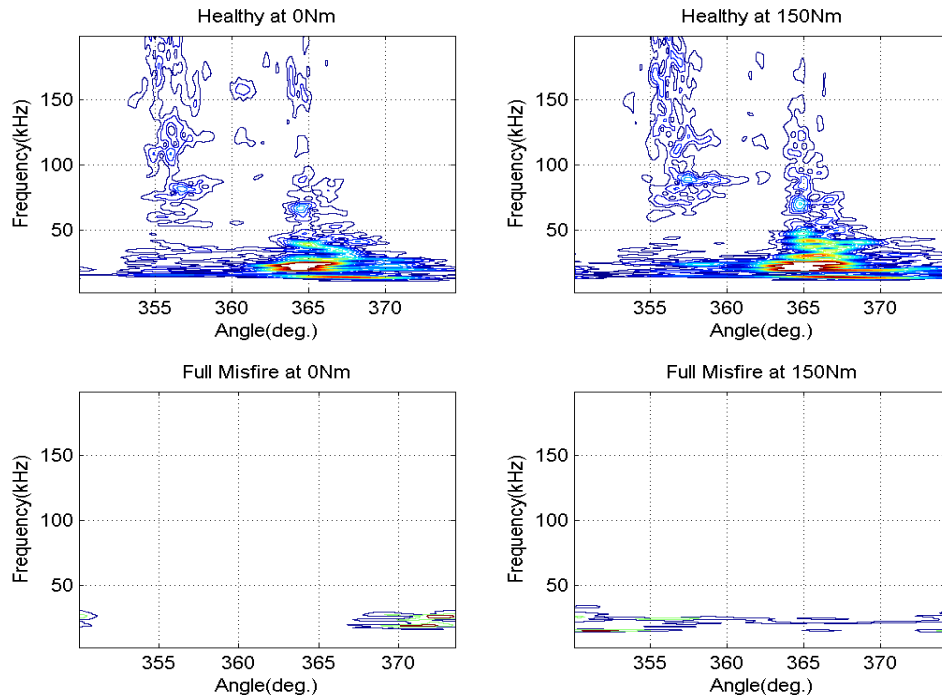

Figure 8 Angular-frequency representation of healthy and full misfire

Figure 8 present the comparison of CWT results between the healthy case and the full misfire under both low and high load conditions. It is obvious that neither combustion AE event nor injection shows on CWT results and hence this fault can be detected and diagnosed without problems.

5. Conclusion

This experimental study has shown that AE signals from a four cylinder diesel engine are predominately caused by inlet valve opening. It is then demonstrated that advanced data analysis allows a full fault diagnosis, even though measured AE signals are combined with different AE sources of different cylinders.

In particular, the analysis in the angular domain provides a straightforward method to identify small malfunctions of the injector only under no load operations. The analysis in the frequency domain can produce fault detection for both faults but cannot identify differences between different sources and types of faults. The joint angular-frequency

analysis can provide both detection and diagnosis for both the small and large injection faults and their original cylinder.

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