Online Monitoring of Engine Oil Quality Based on AE Signal Analysis

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ABSTRACT

This paper studies online condition monitoring of engine oil by analysing the acoustic emission (AE) signals. The AE signals were measured using an AE sensor mounted on the thrust side between second and third cylinders in a four cylinder diesel engine. The signals were then filtered and transformed to the frequency domain, where the amplitudes of the different frequency components of the AE waveforms were analysed and compared to the AE baseline signatures. The mean amplitudes of the spectral components in the frequency band 10kHz to 50kHz were found linearly proportional to the engine speed and load. It was also found that the RMS values of this frequency band were affected by the oil viscosity. These results show that it is possible to use AE measurement to predict the quality of lubrication.

Keywords: Acoustic Emission Monitoring, Condition Monitoring, Diesel Engine, RMS Value.

1. INTRODUCTION

Diesel engines have become a common source of power in many fields because they are fuel efficient, robust and reliable. Mechanical impacts induced piston slap impacts, timing gear rattle, bearing impacts, fuel injection system operation, valve system and accessories impacts. Acoustic emission (AE) has proven to be very useful in monitoring reciprocating machines both for faults and for running conditions. Piston slap event is the most prevalent source among the mechanical impact AE sources. Piston slap plays an important role in the horizontal AE of the diesel engine and is defined as an impact phenomenon between the piston and cylinder wall caused by changes in the side force acting on the reciprocating piston. The sudden movement of the piston across the clearance between the piston and the cylinder wall usually takes place four times per cycle, close to, but not necessarily at the top and bottom dead centre positions [1]. The impact force on the cylinder wall by the piston causes either mechanical impacts or impulsive hydraulic pressure in the lubricating oil film which transmits through the engine block. Transmission can also occur through other parts of the engine, such as the connecting rod and crank shaft. In any case, the result is AE event and engine performance deterioration [2].

It was found that the thickness of the oil film in the clearance is very important in reducing piston slap. Ungar and Ross [3] developed theoretical descriptions to determine the crank angles at which piston slap occurs and to predict the acoustic emission. The descriptions were based on the initial assumption that the lateral kinetic energy of the piston was imparted to the block as AE energy.

This study is an attempt to extract useful information about the engine lubricating oil quality and condition by analysing the measured AE signals caused by this kind of source (piston slap) and to investigate the effects of load, speed variation and temperatures. The study was carried out by measuring the AE signals at different operating conditions using different lubricants.

2. CHARACTERSTICS OF AE DUE TO PISTON MOTION

AE acquired from diesel engines include events of both burst and continuous types that originate from mechanical and fluid processes within the engine [4]. In particular, piston motion is the major excitation of AE and can be understood in several aspects:

1. Friction between piston and liner

Friction refers to the forces acting between mechanical components due to their relative motion and to forces on and by fluids when they move through the engine. A percentage of power generated within the engine cylinders are lost due to friction that causes some reduction in the resulting brake power obtained off the crankshaft. A significant part of the total power loss in the diesel engine is due to piston assembly friction. This friction contributes about half of the total friction and can be as much as 75% at light load.

2. Interaction between piston ring and liner

There are a number of processes occurring at the ring/liner interface that provide possible source mechanisms for the AE events and these primarily consist of asperity contact, blow-by hydrodynamic lubrication. The friction attributable to the oil-control ring is significant; estimated at between 50% and 75% of the total ring-pack friction by Richardson [5] with the other main components being elastohydrodynamic viscous friction and friction due to asperity contact at top and bottom dead centres.

3. Asperity contact

The relationship between AE activity and piston velocity means that asperity contact between compression rings and the liner is unlikely to be the major AE source because away from the dead centres the compression rings benefits from elastohydrodynamic lubrication with maximum effect at around mid-stroke, hence the possibility of asperity contact, and any resultant AE is minimal. However, it is possible that the AE source is associated with fluid processes within the elastohydrodynamic lubrication regime at the compression rings.

4. Lubrication flow

Within the elastohydrodynamic lubrication process there are several source mechanisms that could produce AE, for instance, oil flow characteristics such as oil shear and oil-film cavitation. We can say that the fluid processes within elastohydrodynamic lubrication are not major source origins of AE.

5. Lubrication blow-by

The blow-by would be expected to occur most severely in the presence of large pressure differences over the rings i.e. at around TDC on compression/expansion strokes and not at around mid-stroke every stroke, therefore, blow-by is considered highly unlikely to be the source in normal running.

6. Scuffing between piston ring and liner

In studies [6, 7] AE generation during sliding contact was observed and relationships between AE activity and sliding speed, applied load, wear rates, etc., were developed. These findings prompted work that specifically investigated the occurrence of scuffing between samples of piston rings and cylinder liners in a reciprocating rig [8], where it was possible to differentiate between three different stages of scuffing; scuffing origin, irreversible scuffing and severe scuffing.

7. Wear

The three important wear mechanisms mentioned over the years are: corrosion, abrasion and adhesion. Corrosion is the dominant mechanism when the engine runs either very cold or very hot. There are other wear mechanisms, such as oxidation and splat delaminating as well. Generally, corrosion has been successfully reduced by the use of thermostats and by the addition of corrosion inhibitors to engine oils. The real wear progression of the piston ring/cylinder bore system is quite complex and is a function of several factors, such as metallurgy of the contacting materials, surface finish and integrity, operating conditions of the components and lubricant properties.

8. Piston slap

The piston slap is one of the most important sources of AE event, which is produced by impacts between the piston and cylinder wall. These impacts cause the engine outer surface to generate AE, vibration and consequently radiate airborne noise. Oil film thickness is the most important factor affecting the piston slap and some of the major parameters affecting the oil film thickness are piston speed, lubrication viscosity, ring face profile, boundary conditions surface roughness and ring flexibility.

3. TEST SETUP AND METHOD

AE signals studied in this paper are from an in-line four-cylinder, four stroke, direct injection, heavy duty, off-road diesel engine, whose combustion sequence for each cylinder is 1-3-4-2. This work details a series of tests on diesel engine with a range of specifications, given in Table 1.

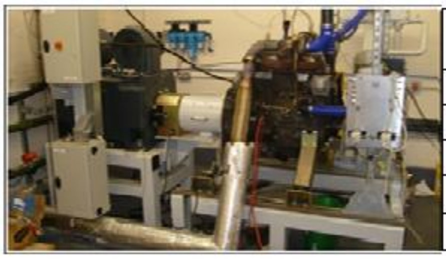
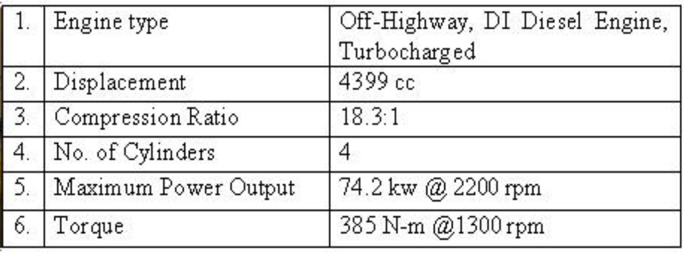


Figure 1 JCB Engine Test Rig



1.	Engine type	Off-Highway, DI Diesel Engine, Turbocharged
2.	Displacement	4399 cc
3.	Compression Ratio	18.3:1
4.	No. of Cylinders	4
5.	Maximum Power Output	74.2 kw @ 2200 rpm
6.	Torque	385 N-m @1300 rpm

Table 1 Description of JCB Engine

3.1 TEST ENGINE LUBRICANTS

Test engine lubricants used in the experimental study are as follows;

Used oil

Oil SAE 10W-30

Oil SAE 15W-40

Oil SAE 20W-50

Both engine lubricants are commercially available, complying with API CG-4 performance category level. It is to be noted that used engine oil was taken as the baseline engine lubricant for friction studies.

3.2 ENGINE TEST BENCH DETAILS

A test engine coupled with the appropriate AC dynamometer and instrumented with fuel consumption measurement unit, pressure sensor, angle encoder, speed sensor, temperature indicators etc was used for the study as seen in Figure 1. Engine tests were conducted at two speeds and four loads for each engine lubricant, details of operating condition are given in Table 2. Pressures at each operating speed and load were recorded at each operating point for four oils.

Table 2 Engine test operating conditions

Operating Conditions	**Values**
Speed (rpm)	1000 and 2000
Torque (Nm)	50, 100, 200, 300
Temperature oil (^{o}C)	90 ± 5
Temperature Coolant (^{o}C)	85-90

3.3 AE SENSOR AND DATA ACQUISITION SYSTEM

The acoustic emission signals were measured using a Wideband sensor model WD as shown in Table 3. This type of sensor made by Physical Acoustics Corporation has a differential output to decrease the influence of noise. The Wideband sensor includes the frequency range of most engine events. An acoustic emission sensor has been used for the acquisition of the acoustic emission signal. The AE sensor was mounted near the TDC of third cylinder of the engine to collect the AE signals generated during the operation of engine. To obtain good signal conductivity, vacuum grease was used to couple the AE sensor with the measurement surface. One of the data streaming technologies available for AE data acquisition is the PCI-2 board, provided by Physical Acoustics Cooperation. This board is connected to a computer through the industry standard high-speed (138MB/sec) PCI bus and the sampled AE waveforms can be continuously transferred to the hard disk. Hence the AE signal can be saved as long as the capacity of the hard disk in the computer. The AE measurement system developed in this research is based on the PAC PCI-2 card, which is specially designed for the high-speed data acquisition of AE signals. The AE sensor converts the AE signal to an electrical signal and sends it to the pre-amplifier.

Table 3 Acoustic Emission sensor details

S.NO	Parameters	Value
1	Operating frequency range	100-1000 KHz
2	Peak sensitivity	55^{+} V(m/s)(dB)
3	Operating temperature	-65 to 177^{o}C
4	Dimensions (dia X ht) mm	18X17

The methodology for conducting experiment test engine was tuned as per the OEM’s recommendations before start of the test.

- Engine oil was drained and flushed to remove the surface active chemistry of the previous oil.
- AE signals were taken at each test operating points.
- Engine oil and coolant temperatures were controlled within the range of 90^{o}C ± 5 and 85-90 respectively at all test points
- Initially the baseline engine oil was charged into an engine for its test run and then new oils were used for the study. For each oil a new oil filter was used.

4. DATA ANALYSIS AND DISCUSSION

4.1 Analysis in the Angular Domain

Based on the raw AE signals measured, the engine speed was estimated and corresponding crank angles were calculated based on constant speed operation. Figure 2 presents the comparison of AE signals aligned in the angular domain under four different loads at 1000rpm for used and new 10W30 oil types.

In addition, the events relating to inlet valve opening (IO), inlet closing (IC), exhaust valve opening (EO) and exhaust valve closing (EC) are also illustrated based on their corresponding nominal values. Four major AE events can be observed clearly in one full engine cycle for this four cylinder engine. This alignment is based only on the amplitude trend with engine load without the measurement of TDC signals. In particular, the amplitude change in is more consistent with the increase 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 remain almost constant with load, showing that they mainly come from valve events. A small AE event showing around 190º is also consistent with the closure of inlet valve 1.

Figure 2 shows the AE signals around cylinder 2 for exhaust valve closing of cylinder 3 (about 190º) and the inlet valve closing of cylinder 1 (about 210º). A clear difference, shown in figure 3, can be seen under no load operation whereas they are quite similar for other load conditions.

For the fuel injection event, just before 10º TDC, there was a clear difference between used oil and 10W30 as seen in figure 2 at no load, while they were almost similar for other loads. Even though the rapid transient event of the no load condition indicates an obvious injector valve impact, for other load conditions, however, this feature was not so clearly observed in this angular domain presentation.

Figures 3 and 4 show the comparison of AE signals in the angular domain under different loads and speed of 1000 rpm for used oil and 15W40 and 20W50 respectively. From the figures, a clear difference 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 high impact combustion force, for other load conditions, however, this feature is not so clearly observed in this angular domain presentation. This shows that more advanced analysis is required to achieve full monitoring.

Also it was observed that at low speed, for load points, oil 10W30 was having slightly higher peaks, which indicates that there was more asperity contact between piston ring and liner when the engine was running with lower viscosity oil grade at low speed.

The angular domain analysis shows that AE signals in the angular domain can produce diagnosis results for no load condition, but not for higher load conditions.

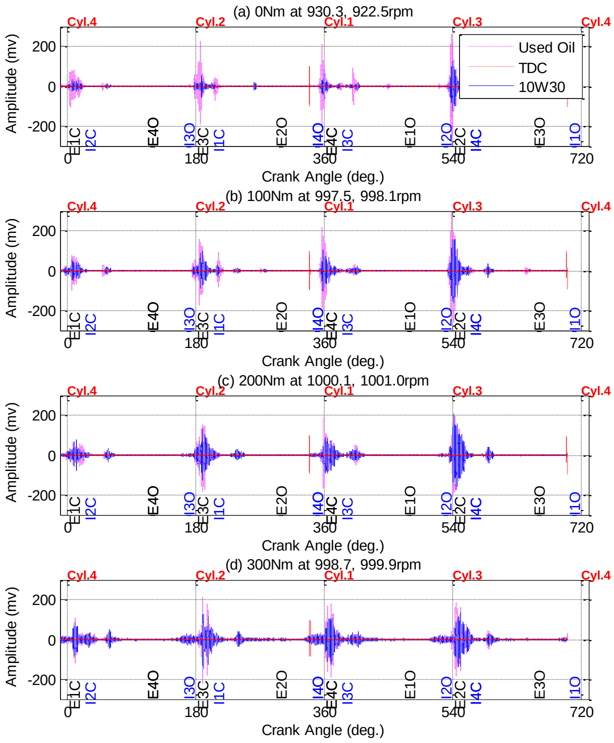


Figure 2 AE signals for used and 10W30 oils in the angular domain under different loads

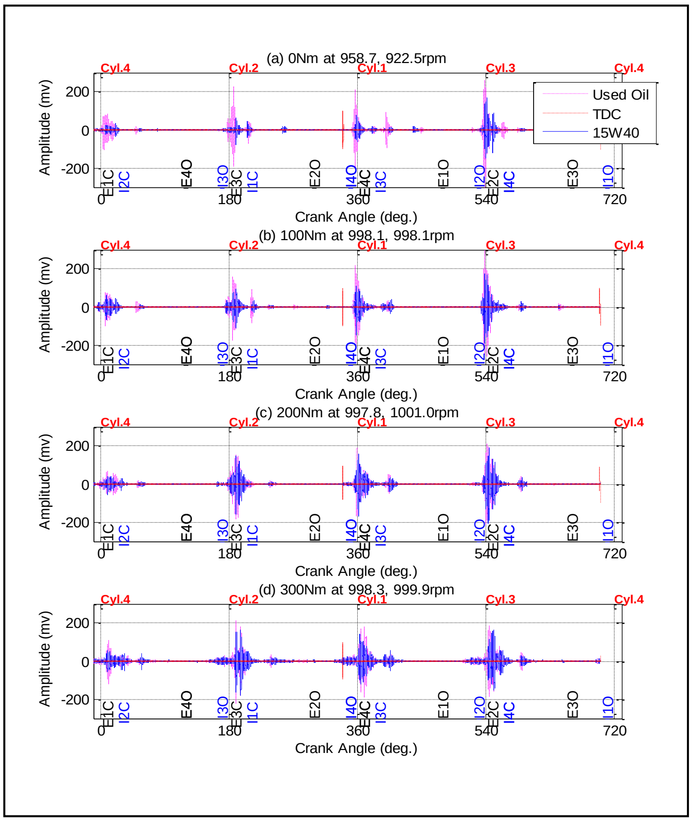


Figure 3 AE signals for used and 15W40 oils in the angular domain under different loads

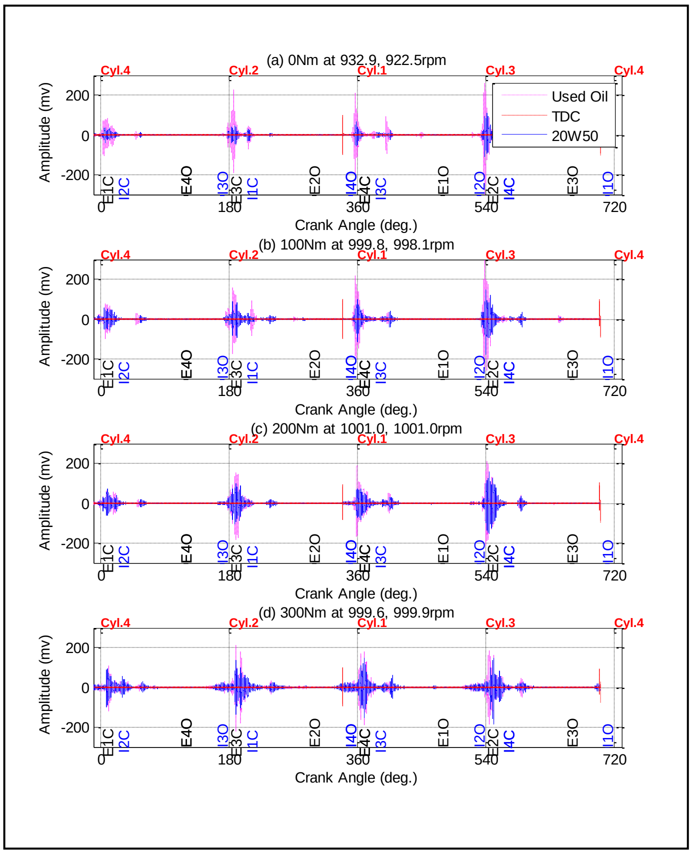


Figure 4 AE signals for used and 20W50 oils in the angular domain under different loads

For satisfactory lubrication of the engine the oil should possess some functional properties of which viscosity of oil is one of the most important properties, as it brings out the oil's capacity to lubricate. Oil viscosity effects on the piston slap induced AE signals were studied by changing the oil viscosity using three different types of engine oil, 10W-30, 15W-40, and 20W-50 and used oil.

The engine speed was set to 1000 rpm and 2000 rpm, and the AE signals were recorded at different oil temperature and loads. It was difficult to detect any effects of the oil type on the cylinder pressure waveform; also no change could be observed in the spectrum.

By filtering the signals using a digital filter between 10 kHz and 50 kHz and calculating the RMS values of the signals, clear differences could be observed between the used oil and the other three new oils (at 1000 rpm a bigger difference than 2000 rpm) especially at loads less than 200 Nm where the viscosity had a lower effect by the load as seen in the figure. There was also a clear difference between the three different new oils, especially between 100 Nm and 300 Nm, where the oil viscosity was affected much more by the load as shown in Figure 5. The intensity of the impacts was less when using higher viscosity oil, especially at 1000 rpm, because of the higher damping characteristics.
The RMS values in the case of 20W-50 were less, especially at 1000 rpm and below 200 Nm at 2000. At higher loads the effect of the oil viscosity could be observed, especially at speeds of 1000 rpm, which signifies the low friction with low viscosity grade oil. However, it was felt that more advanced signal processing techniques were needed to extract these small differences.

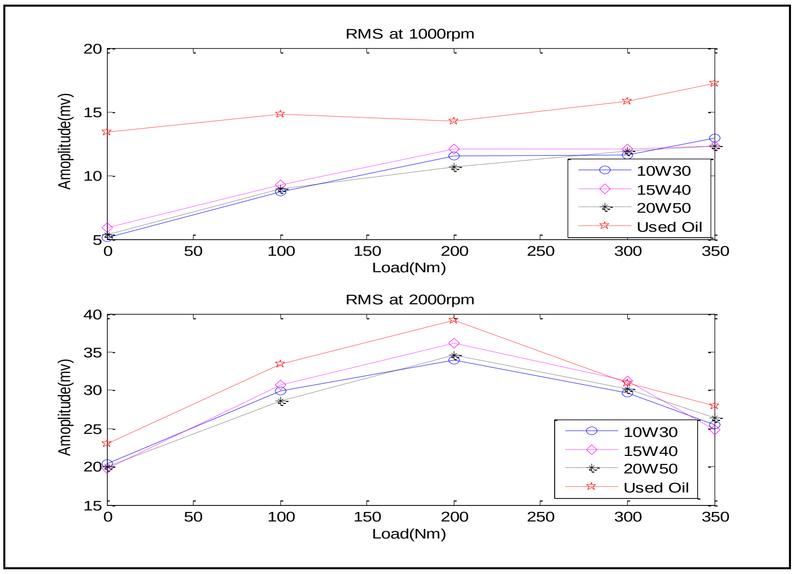


Figure 5 AE RMS values

5. CONCLUSION

This experimental study has found that the condition of the engine lubrication in terms of oil quality has a noticeable influence on acoustic emission signals from a four cylinder diesel engine. The analysis in the angular domain provides a straightforward method to identify the clear difference of the used oil and the new oils (three different types) especially under no load operations. In general, the use of poor quality oil (used oil) causes an increase in AE energy. The peaks on the frequency range between 10 kHz and 50 kHz were found to be associated with the oil quality, in other words the piston slap excitations. Although the AE signals were measured and affected by different AE sources and gave acceptable results.

Further research work will be conducted to extract more features from more advanced analysis techniques (angular-frequency results using different methods) to achieve full lubricating monitoring. The engine AE events may then be identified using these features.

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