Proceedings of the 21st International Conference on Automation & Computing, University of Strathclyde, Glasgow, UK, 11-12 September 2015

Characterisation of Acoustic Emissions for the Frictional Effect in Engines using Wavelets based Multi-resolution Analysis

Nasha Wei[1,2], Fengshou Gu[1,3], Tie Wang[3], Guoxing Li[3], Yuandong Xu[3] , Longjie Yang[3], Andrew D. Ball[1]

[1] Centre for Efficiency and Performance Engineering, University of Huddersfield, HD1 3DH, UK

[2] Department of Economics and Management, Taiyuan University of Science and Technology, Shanxi, P.R. China

[3] Department of Vehicle Engineering, Taiyuan University of Technology, Shanxi, P.R. China

F.Gu@hud.ac.uk , Nasha.Wei@hud.ac.uk

***Abstract*—The friction between piston ring-cylinder liner is a major cause of energy losses in internal combustion engines. However, no experimental method is available to measure and analyze the fictional behavior. This paper focuses on the investigation of using acoustic emission (AE) to characterize the friction online. To separate the effect relating to friction sources, wavelets multi-resolution analysis is used to suppress interfering AE events due to valve impacts and combustion progress. Then a wavelet envelope indicator is developed to highlight AE contents from friction induced AE contents. The results show that the AE contents in the middle strokes correlate closely with viscous friction process as their amplitudes exhibit a continuous profile similar to piston speed. Furthermore, the AE envelope indicator proposed can distinguish the differences between two types of lubrication oils, showing superior performance of AE based online lubrication diagnosis.**

Keywords- diesel engine; acoustic emission; piston-cylinder system; wavelet multi-resolution analysis; envelope analysis

I. INTRODUCTION

Diesel engines, which are primary components of the transportation system, have attracted much attention due to their wide usage and higher thermal efficiency. Previous research has shown that the piston-cylinder system, as a main working part of the engine, is a significant source of mechanical losses in internal combustion engines [1] [2]. Therefore, considering the reliability and economy of engine system, it is important to monitor the operation condition of the piston-cylinder system.

Acoustic emission (AE), as a very useful tool of non-intrusive test, has been used to monitor the engine condition. The high spatial and temporal fidelity of the AE signals acquired from engines in service make it possible to detect individual events and processes [3]. The frequency of AE signal is, usually in the range from 100 kHz to 1 MHz, higher than the frequency of vibration signal which is generally from 20Hz to 20 kHz. Consequently, the AE signal has a very high signal-to-noise ratio to avoid the influence of mechanical noise. Moreover, the AE sensors which could be placed on the surface of an engine body are less likely to suffer from the harsh environments (high pressure and high temperature) and none detrimental effects in the engine structure compared to pressure and temperature sensors. Therefore, AE signal is effective to assess the engine conditions such as combustion quality, valve performance, wear degrees inside engines for earlier fault detection and diagnosis.

Previous research has shown that the obvious bursts of AE for engines are related to valve landing and combustion progress. References [4] and [5] investigated the suitability of acoustic emission (AE) technique for the condition monitoring of diesel engine valve faults. Sharkey et al. [6] developed an engine fault diagnosis approach for combustion process using acoustic emission sensors. These researches indicate that the obvious bursts of AE events are caused by valve impacts and combustion. Douglas [7] reported that the continuous AE possibly induced by the ring/liner interaction related to asperity contacts between the ring-pack and cylinder liner. And the AE activity was found to be proportional to piston speed and pressure, indicating that the boundary friction acting upon the oil-control ring was the most likely AE source. Mishra et al. [8] presented that the total friction is addition of contributions made through viscous shear and asperity interactions. They also reported that viscous friction contribute main losses during suction and exhaust strokes and also accounts for sizeable friction losses in power strokes. Therefore, the friction between piston ring and cylinder liner is composed of asperity friction and viscous friction that will generate AE events during four strokes. It shows that less attention has been paid to the enhancement of AE signal quality for more accurate monitoring the frictional effect of piston-ring and cylinder liner.

This paper reports a method to monitor the engine friction online based on characterization of AE signals. As AE signals have strong nonstationary contents and there are a number of distinctive AE sources in the engine, wavelets based multi-resolution analysis (WMRA) including denoising techniques is used to extract the weak AE events that are relating to friction process. The key WMRA parameters are tuned based on the behavior of viscous friction in engine operation cycle. Then the envelope of extracted signals is used to develop diagnostic parameters for monitoring engine lubrication condition.

II. ACOUSTIC EMISSION GENERATION OF PISTON ASSEMBLY

Originally, AE signals are sourced from the generation and propagation of cracking and fracture, slipping and

The project of this paper is supported by Natural and Scientific foundation of China.(NO. 51375326).

elastic plastic deformation in the point view of engineering material failures. By sharing similar mechanisms the major AE sources in an engine can be understood to be from three physical processes including friction and wear, rapid pressure oscillations and mechanical impacts.

Friction and wear processes are generated between two sliding surfaces caused by the synthetically effects of adhesion, deformation, material fracture, heat and chemical process. These processes of friction and wear generate high-frequency AE stress waves predominantly pseudo-continuous with superimposed burst emissions due to sporadic high-amplitude events such as single asperity fracture, particle interactions [9]. The excessive friction and wear on pistons, cylinder liners and piston rings are also sources of AE. Shuster et al. [10] demonstrated the usefulness of acoustic emission RMS measurements for studying the piston ring cylinder liner scuffing phenomenon based on the understanding that the AE can be induced by the friction between piston ring and cylinder liner segments. Douglas et al. [7] used AE RMS and AE energy RMS measurements to provide information pertaining to the interaction between piston rings and cylinder liners in a range of diesel engines. However, the original AE signals processing methods mentioned above were hard to extract the feature about tribology of piston and cylinder system to detect the type of the friction.

The RMS value of AE signal is well correlated with the pressure signal in the time and frequency domain [11]. Vibrations and deformations between contact surfaces are induced by alternating low and high pressures in the piston ring against the cylinder wall. The excessively high cylinder pressures also generate the high pressures between piston ring and cylinder wall, and cyclically varying sealing force exerted by the in-cylinder pressure on the piston rings was found to influence the resultant AE activities [7].

Because of the elastic plastic deformation and stain of metal material, the AE signals could be excited by the mechanical impacts between different engine components. In particular, the valve events from air intake exhaust and fuel injections can cause strong impacts. Hence, a number of acoustic emission based studies have been carried out to detect the faults of valve opening and closing impacts [4] [12] and needle impacts of injection [13] [14].

Based on these advancements in AE studies, AE from engines friction effect are much weaker and occurring throughout full engine cycle. On the other hand, AE from other two mechanisms are very strong but present only in certain crank angle positions. Based on these differences, it is likely to separate these sources to perform diagnostics for different purposes.

III. WAVELETS-BASED MULTIRESOLUTION ANALYSIS

A. Wavelet Transform

Wavelet transforms are particularly effective to analyse signals that contain non-stationary phenomena [15] which is the typical feature of engine AE signals. It has been used for numerous studies in fault diagnostics such as engines [16], bearings[17] [18], gears [19] [20] [21], and also has been applied to the feature extraction in acoustic emission study.

The continuous wavelet transform of a signal $f(t) \in L^2(R)$ ($t = 1, 2, ..., N$) is defined as

$$CWT(a,b) = \int_R f(t) \frac{1}{\sqrt{a}} \psi^* \left(\frac{t-b}{a} \right) dt \qquad (1)$$

where the mother wavelet function is $\psi_{ab}(t) = \frac{1}{\sqrt{a}} \psi \left(\frac{t-b}{a} \right) \quad a,b \in R; a \neq 0$.

in which a represents dilation index, b is translation index, and $\psi^*(t)$ represents the complex conjugate of function $\psi(t)$.

Similarly, discrete wavelet transform (DWT) is a discretization of the CWT which has a huge number of applications in science and engineering with the discretized scales and positions. The expression of DWT is defined as

$$Wf(j,k) = \int_R f(t) \frac{1}{\sqrt{2^j}} \psi^* (\frac{t}{2^j} - k) dt . \qquad (2)$$

The discrete mother wavelet function is

$$\psi_{j,k}(t) = \frac{1}{\sqrt{2^j}} \psi(\frac{t}{2^j} - k) , \qquad (3)$$

and the discrete father wavelet function is

$$\varphi_{j,k}(t) = \frac{1}{\sqrt{2^j}} \varphi(\frac{t}{2^j} - k) . \qquad (4)$$

where parameters 'a' and 'b' are replaced by $a = 2^j$, $b_{j,k} = 2^j k$, $j,k \in Z$ respectively to represent the time shift indices $k = 1, 2, ..., N/2^j$ and decomposition levels $j = 1, 2, \dots, J$. Consequently, the wavelet transform of $f(t)$ can be obtained by using (5) and (6) [22]:

$$a_{J,k} = \int f(t) \phi_{J,k}(\mathrm{t}) dt \qquad (5)$$

$$d_{j,k} = \int f(t) \varphi_{j,k}(\mathrm{t}) dt \qquad (6)$$

and $a_{J,k}$ is the the approximation coefficients reflecting the low frequency content of the sigand whereas $d_{j,k}$ is detailed coefficients reflecting the high frequency content.

B. Wavelet Multi-Resolution Analysis

The wavelet multi-resolution analysis (WMRA) implements discrete wavelet transforms with filters and decomposes the signal into several sub-signals at different levels of resolution [23]. A mathematical model of WMRA and its practical application were introduced for the first time by Mallat [24]. A signal can be represented by WMRA in terms of the scaling and the wavelet functions mathematically presented as: [22] [25]

$$f(t) \approx \sum_k a_{J,k} \phi_{J,k}(t) + \sum_k \sum_{j=0}^{J-1} d_{j,k} \psi_{j,k}(t) . \qquad (7)$$

Consequently, $f(t)$ can be reconstructed by the approximation signal $A_J(t)$ and the detail signals $D_j(t)$ at each level j which are expressed by (8) and (9) respectively:

$$A_J(t) = \sum_k a_{J,k}\phi_{J,k}(t), \qquad J,k \in Z \tag{8}$$

$$D_j(t) = \sum_k \sum_{j=0}^{J-1} d_{j,k}\psi_{j,k}(t), \qquad j,k \in Z \tag{9}$$

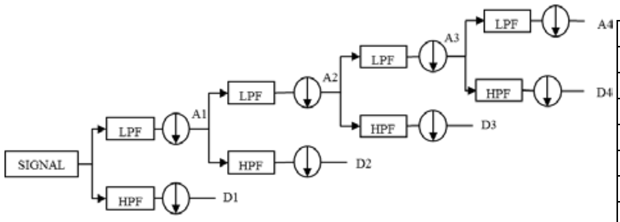


Figure 1. WMRA decomposition with 4 levels

For ease of understanding WMRA, a decomposition of a signal into four levels is illustrated in Fig. 1. The WMRA decomposes the original signal $f(t)$ with a low-pass filter (LPF) and a high-pass filter (HPF) in every decomposition level. At level j, $D_j(t)$ is the detail coefficients produced by the HPF, and $A_J(t)$ is the approximation coefficients produced by the low pass filter LPF. Therefore, the merits of WMRA are its ability to produce a good time resolution at high frequencies and good frequency resolution at low frequencies. Moreover, as the samples of wavelet coefficients at high levels are much smaller than the original signal, further analysis on them will be more efficient. This merit is very useful for processing AE signals acquired at MHz ranges and huge number samples.

However, the wavelet types and decomposing levels are usually needed to be selected appropriately in order to achieve high performances in its typical applications such as signal denoising and data compression. In this study, they are determined based on the friction behavior of engines which will be depicted in section 5.

IV. The Facility for Experimental Studies and Methodology

To investigate the AE based friction diagnosis, a single cylinder diesel engine was used for experimental studies. It has less AE events, compared with a multiple cylinder engine and it allows more accurate charactering the weak AE signals from frictions. Photos in Figures 1 and 2 show the basic structure of the engine, engine test bed and location of AE sensor. In addition, Table I provides the key specification.

A SR800 AE sensor from Soundwel Technology Co., Ltd is used for AE measurement, which has a flat frequency response over a range of 50 - 800 kHz. The AE sensor was located on the engine cylinder body surface by a magnetic hold-down as shown in Fig. 3. The sensor position is closer to the friction source between the ring and cylinder liner but relatively farer from other sources including valve impacts and combustion. The output voltage of an AE sensor is usually very low. So a preamplifier is used to amplify the signal so that it can be acquired adequately by a SEAU2S two channel AE measurement system. Simultaneously, a crank encoder signal is also acquired by this data acquisition system in order to mark the top dead centre (TDC) which can be used to align the AE signal with crank angle signal and to obtain the speed of the engine for performing angular domain based analysis.

TABLE I. Specification of the Test Engine

Manufacturer	Anhui Quanchai Engine Co., Ltd., PR. China
Engine type	QCH1110II
Number of cylinders	one
Combustion system	Direct injection, vertical type
Bore/stroke	110/115 mm
Displacement volume	1.093 L
Compression ratio	18:1
Rated power	14.7/2400 kW/r/min
Max. torque	67/1920 Nm/r/min

Figure 2. The photo of the diesel engine test rig

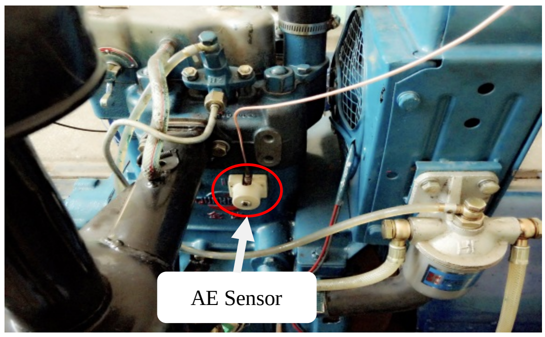


Figure 3. The installation of AE sensor on the engine body

To examine the effect of engine operation and lubrication oil conditions, two types of engine lubricant oil were tested when the engine operated under the conditions shown in in Table II. More speed setpoints were tested as the friction effect is more influenced by velocity variation than by the load. Table III shows the decisive parameter; viscosity values of the two types of oils at two different temperatures, which were measured before the engine tests. Note that the measurement instrument produced high diversity results at temperature 40°, showing that it is difficult to obtain reliable oil property measurement.

The AE signal measurements for each type of lubricating oils were repeated twice for all the operating conditions. More than 8 MEG data points were obtained at a sampling rate of 800kHz for each AE measurement, which covers over 100 engine cycles to be averaged for obtaining reliable results.

TABLE II. ENGINE OPERATING CONDITIONS

Engine speed (rpm)	**Load (Nm)**	**Running time (min.)**
Warm-up running (1000)	0	20~30
1000	10/40	5/5
1200	10/40	5/5
1400	10/40	5/5
1600	10/40	5/5
1800	10/40	5/5

TABLE III. VISCOSITY-TEMPERATURE COMPARISON OF DIFFERENT LUBRICATING OILS

Grade	**Viscosity(mPa·s)**			
	Test 1		***Test 2***	
	40°C	***100 °C***	***40 °C***	***100 °C***
10W30	35.54	3.53	76.46	9.93
20W50	174.2	20.27	165.1	18.33

V. WMRA ANALYSIS AND RESULTS

A. *WMRA Analysis*

The measured AE signals in the timed domain are firstly converted into the angular domain based on the TDC marker signals. Thus, it is easier to identify various AE events in association with the engine operation process. Fig. 4 shows a typical AE signal in the angular domain. It can be seen that for one working cycle of the four stoke engine there are a number of significant AE bursts. Based on the engine operation process, it is straightforward to identify the events that correspond sequentially to inlet valve opening (IVO), exhaust valve closing (EVC), inlet valve closing (IVC), fuel injection and combustion. However, it is difficult to see the exhaust valve opening due to that the valve is a bit far away to the AE sensor. Therefore, there are many other AE contents cannot be identified unquestionably. Particularly, the events assumed to be cylinder friction closing are very unconvinced because they show little characteristics relating the friction process.

To ensure that the AE signal contains friction information, the angular domain signals are decomposed onto successive wavelets levels. There are 144000 data points. The maximum level *J* could be 17. However, by a trial and error approach with using different types of wavelets including, Daubechies wavelets and Symlets wavelets families, it has found that Symlets of order 9 wavelet at level J=4 is sufficient so as to enhance the AE signal to show the friction effects in that the viscous friction exhibit higher amplitudes in the middle of the each stroke, which has been investigated in [5, 6, 23] about friction effects between piston ring and cylinder liner. In general, the continuous characteristics of the AE signals indicated by the viscous friction agree with the piston velocity profile and load variation.

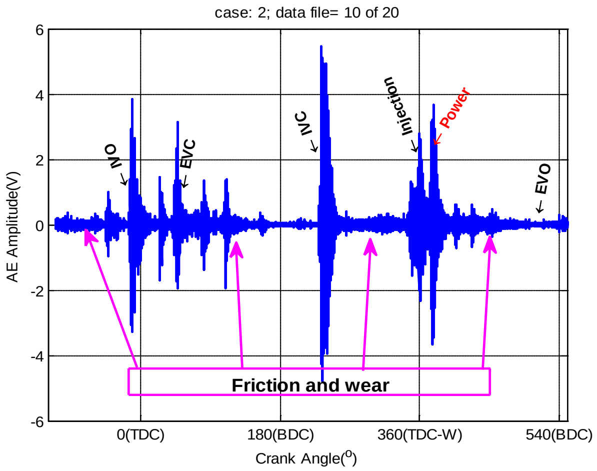
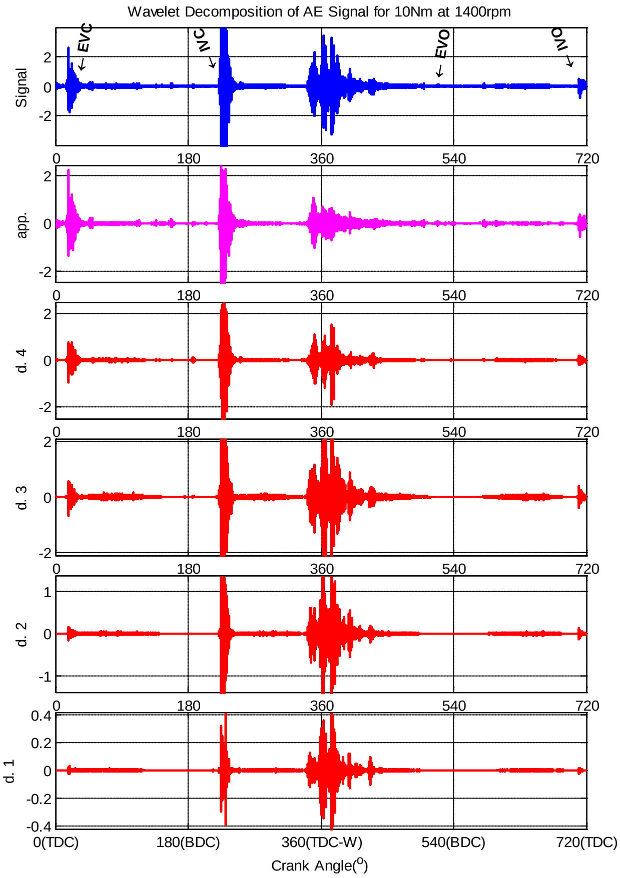


Figure 4. Raw AE signals from the engine cylinder body

Figure 5. Wavelet decomp



osition results of AE signal

As shown in Fig. 5, the decomposition with all detailed coefficients shows an effective enhancement of the friction characteristics. Particularly, d3 and d4 based decompositions produce higher amplitudes in the middle of engine stokes, compared with that of d1 and d2, which is more consistent with that of viscosity induced friction. Therefore, the decomposed signal from d3 and d4 are taken as the candidates for developing quantitative diagnostic features.

B. Wavelet based Envelope

However, because of the wide band characteristics, the AE events due to valve impacts, fuel inject and combustion spread across all different levels, which may influence the accuracy of quantitative features. Therefore, a wavelet denoise approach is used to suppress these dominant events. It is realized by applying a hard threshold of 0.25 to wavelets coefficients at to exclude the wavelet coefficients due to the dominant events and then reconstruct the signal with d4 coefficient only as it less influenced by these large events. Furthermore, the envelope of reconstructed signals are calculated for each engine cycle and an average is performed over different envelope signals over different cycles, which allows the random variation of viscous friction to be aggregated more effectively, compared with that of averaging the decomposed signals directly.

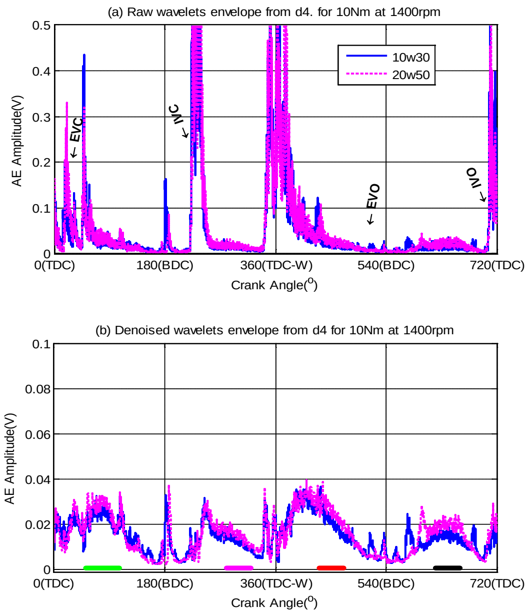


Figure 6. Envelope signals of decomposed signal with d4 coefficient

Fig. 6 presents typical envelope signals with and without denoise processing. It can be seen that the denoised envelope signal allows a clearer representation of the frictional characteristics. Especially, the AE amplitudes are very distinctive in the middle of each stoke, which allows the frictional effect to be examined more accurately. As shown in Fig. 6(b), the oil with higher viscosity produces higher AE amplitudes, which agrees with theoretical prediction in that higher viscously causes more viscous friction. Therefore, it is possible to use AE for indicating the engine lubrication condition.

C. Results and Discussion

Based on above analysis, four envelope indicators can be obtained by averaging amplitudes with respective to the four angular ranges illustrated by the bold horizontal lines in Fig. 6(b) to represent lubrication condition in corresponding strokes. As these four amplitudes are calculated around the mid stroke where the AE envelope has high signal-to-noise ratio, they can best reflect the viscous friction characteristics under different operating conditions.

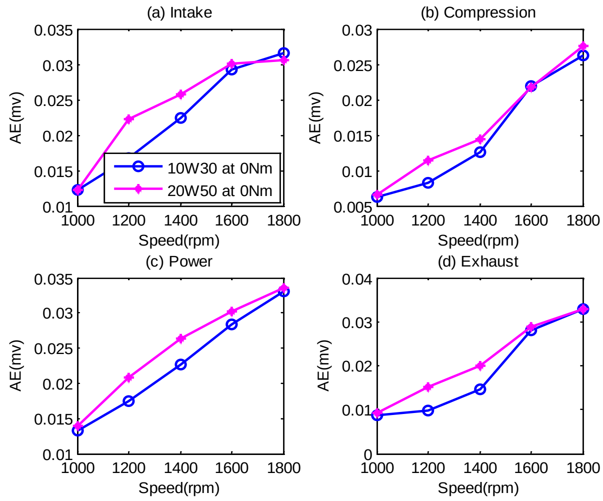


Figure 7. Average AE envelope indicator for no load operating.

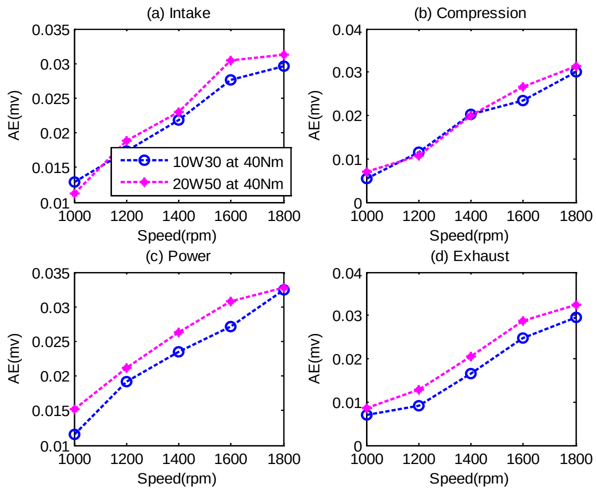


Figure 8. Average AE envelope indicator for higher load operation

Fig. 7 shows the AE envelope indicator at different speeds for the load free operation. It shows that AE indicator increases with speed, showing the strong relation with friction process. Comparing the indicators between the two types of oils, the AE indicator for 20W50 oil is higher for most speeds. Especially for the speeds of 1200 and 1400rpm, the difference in AE indicators is very clear for all stokes and it is definite to make difference between the two oils. However, the difference for other speed operations is not so clear because of high AE noise resulting from clearance induced instability.

When engine operates with the loads the clearance instability is smaller. The AE indicators from power and exhaust strokes can show clear differences between the two oils for all the speeds tested. Especially, the fraction induced AE in the exhaust stoke is much less influenced by other AE events of valve impacts and combustion progress. Therefore, the result in the exhaust stroke is reliable. On the other hand, the influence of valve impacts in the inlet and compressions strokes becomes higher under the high loads where the AE indicators cannot make good difference between the two oils. In addition, AE indicators for the high load operation is slightly higher than that of load-free operation, showing that the fraction induced AE is less connected to the engine load.

VI. Conclusions

The study shows that wavelets-based multiresolution analysis can highlight the local nonstationary contents in engine AE signals for effective suppression. In meantime, it is also efficient for implementation further analysis as the discrete wavelets coefficient signal is much smaller and hence easier to be processed.

Based on the effective analysis, it is obtained that the fraction induced AE content can be extracted from the AE signals which contaminated by strong AE events including valve impacts, combustion progress and fuel injection excitation. The results show that the AE envelope indicator can reflect the connections between AE and engine friction under different speeds and loads. Especially, they can make good difference between two types of engine oils even they have little difference affecting engine performance. This shows that AE has higher performances in diagnosing engine lubrication conditions. Nevertheless, the research needs to be advanced more in optimizing WMRA symmetrically in order to find a better AE indicator.

References

[1] S. C. Tung and M. L. McMillan, “Automotive tribology overview of current advances and challenges for the future,” Tribol. Int., vol. 37, no. 7, pp. 517–536, 2004.

[2] G. Smedley, “Piston ring design for reduced friction in modern internal combustion engines,” PhD Thesis, Massachusetts Institute of Technology, 2004.

[3] J. A. Steel and R. L. Reuben, “Recent developments in monitoring of engines using acoustic emission,” J. Strain Anal. Eng. Des., vol. 40, no. 1, pp. 45–57, Jan. 2005.

[4] F. Elamin, Y. Fan, F. Gu, and A. Ball, “Diesel Engine Valve Clearance Detection Using Acoustic Emission,” Adv. Mech. Eng., vol. 2010, Jun. 2010.

[5] T. L. Fog, L. K. Hansen, J. Larsen, H. S. Hansen, L. B. Madsen, P. Sorensen, E. R. Hansen, and P. S. Pedersen, “On condition monitoring of exhaust valves in marine diesel engines,” Proceedings of the 1999 IEEE Signal Processing Society Workshop., 1999, pp. 554–563.

[6] A. J. C. Sharkey, G. O. Chandroth, and N. E. Sharkey, “Acoustic emission, cylinder pressure and vibration: a multisensor approach to robust fault diagnosis,” presented at the IJCNN 2000, Proceedings of the IEEE-INNS-ENNS International Joint Conference on Neural Networks, 2000, 2000, vol. 6, pp. 223–228 vol.6.

[7] R. M. Douglas, J. A. Steel, and R. L. Reuben, “A study of the tribological behaviour of piston ring/cylinder liner interaction in diesel engines using acoustic emission,” Tribol. Int., vol. 39, no. 12, pp. 1634–1642, 2006.

[8] P. C. Mishra, H. Rahnejat, and P. D. King, “Tribology of the ring—bore conjunction subject to a mixed regime of lubrication,” Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci., vol. 223, no. 4, pp. 987–998, Apr. 2009.

[9] H. S. Benabdallah and D. A. Aguilar, “Acoustic Emission and Its Relationship with Friction and Wear for Sliding Contact,” Tribol. Trans., vol. 51, no. 6, pp. 738–747, 2008.

[10] M. Shuster, D. Combs, K. Karrip, and D. Burke, “Piston Ring Cylinder Liner Scuffing Phenomenon Studies Using Acoustic Emission Technique,” SAE International, Warrendale, PA, SAE Technical Paper 2000-01-1782, Jun. 2000.

[11] M. El-Ghamry, J. A. Steel, R. L. Reuben, and T. L. Fog, “Indirect measurement of cylinder pressure from diesel engines using acoustic emission,” Mech. Syst. Signal Process., vol. 19, no. 4, pp. 751–765, Jul. 2005.

[12] F. Elamin, Y. Fan, F. Gu, and A. Ball, “Detection of diesel engine valve clearance by acoustic emission.,” in Proceedings of Computing and Engineering Annual Researchers’ Conference 2009: CEARC’09, G. Lucas and Z. Xu, Eds. Huddersfield: University of Huddersfield, 2009, pp. 7–13.

[13] F. Elamin, Y. Fan, F. Gu, and A. Ball, “Detection of Diesel Engine Injector Faults Using Acoustic Emissions,” presented at the COMADEM 2010: Advances in Maintenance and Condition Diagnosis Technologies towards Sustainable Society, Nara, Japan, Jun-2010.

[14] A. Albarbar, F. Gu, and A. D. Ball, “Diesel engine fuel injection monitoring using acoustic measurements and independent component analysis,” Measurement, vol. 43, no. 10, pp. 1376–1386, 2010.

[15] I. Daubechies, “The wavelet transform, time-frequency localization and signal analysis,” IEEE Trans. Inf. Theory, vol. 36, no. 5, pp. 961–1005, Sep. 1990.

[16] J.-D. Wu and C.-H. Liu, “Investigation of engine fault diagnosis using discrete wavelet transform and neural network,” Expert Syst. Appl., vol. 35, no. 3, pp. 1200–1213, Oct. 2008.

[17] S. Seker and E. Ayaz, “Feature extraction related to bearing damage in electric motors by wavelet analysis,” J. Frankl. Inst., vol. 340, no. 2, pp. 125–134, Mar. 2003.

[18] R. Rubini and U. Meneghetti, “Application of the Envelope and Wavelet Transform Analyses for the Diagnosis of Incipient Faults in Ball Bearings,” Mech. Syst. Signal Process., vol. 15, no. 2, pp. 287–302, 2001.

[19] C. Kar and A. R. Mohanty, “Monitoring gear vibrations through motor current signature analysis and wavelet transform,” Mech. Syst. Signal Process., vol. 20, no. 1, pp. 158–187, Jan. 2006.

[20] W. J. Staszewski and G. R. Tomlinson, “Application of the wavelet transform to fault detection in a spur gear,” Mech. Syst. Signal Process., vol. 8, no. 3, pp. 289–307, 1994.

[21] N. Baydar and A. Ball, “Detection of Gear Failures via Vibration and Acoustic Signals using Wavelet Transform,” Mech. Syst. Signal Process., vol. 17, no. 4, pp. 787–804, 2003.

[22] T.-Y. Yang and L. Leu, “Study of transition velocities from bubbling to turbulent fluidization by statistic and wavelet multi-resolution analysis on absolute pressure fluctuations,” Chem. Eng. Sci., vol. 63, no. 7, pp. 1950–1970, Apr. 2008.

[23] A. Datta, C. Mavroidis, J. Krishnasamy, and M. Hosek, “Neural Netowrk Based Fault Diagnostics of Industrial Robots using Wavelt Multi-Resolution Analysis,” in American Control Conference, 2007. ACC ’07, 2007, pp. 1858–1863.

[24] S. G. Mallat, “A theory for multiresolution signal decomposition: the wavelet representation,” IEEE Trans. Pattern Anal. Mach. Intell., vol. 11, no. 7, pp. 674–693, Jul. 1989.

[25] A. M. Gaouda, E. F. El-Saadany, M. M. A. Salama, V. K. Sood, and A. Y. Chikhani, “Monitoring HVDC systems using wavelet multi-resolution analysis,” IEEE Trans. Power Syst., vol. 16, no. 4, pp. 662–670, Nov. 2001.