Acoustic Measurements for the Combustion Diagnosis of Diesel Engines Fuelled with Biodiesels

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Abstract

In this paper, an experimental investigation was carried out on the combustion process of a compression ignition (CI) engine running with biodiesel blends under steady state operating conditions. The effects of biodiesel on the combustion process and engine dynamics were analysed for non-intrusive combustion diagnosis based on a four-cylinder, four-stroke, direct injection and turbocharged diesel engine. The signals of vibration, acoustic and in-cylinder pressure were measured simultaneously to find their inter-connection for diagnostic feature extraction. It was found that the sound energy level increases with the increase of engine load and speed, and the sound characteristics are closely correlated to the variation of in-cylinder pressure and combustion process. The continuous wavelet transform (CWT) was employed to analyse the non-stationary nature of engine noise in a higher frequency range. Before the wavelet analysis, time synchronous average (TSA) was used to enhance the signal-to-noise ratio (SNR) of acoustic signal by suppressing the components which are asynchronous. Based on the root mean square (RMS) values of CWT coefficients, the effects of biodiesel fractions and operating conditions (speed and load) on combustion process and engine dynamics were investigated. The result leads to the potential of airborne acoustic measurements and analysis for engine condition monitoring and fuel quality evaluation.

Key words: Airborne acoustic; CI Engine; Combustion diagnosis; CWT;

1. Introduction

The demand for petroleum-based fuel has risen recently, whilst resources of petroleum-based fuel have declined. Consequently, efforts to develop alternative fuels which are cheaper and environmentally acceptable have been considered to reduce the dependency on fossil fuels [1]. Previous research [2-4], has shown that biodiesel is one of the most promising renewable, alternatives and environmentally fuels. Biodiesel is composed of fatty acid methyl or ethyl esters from vegetable oils or animal fats and its properties are similar to petroleum-based fuel [5]. It is renewable, biodegradable, oxygenated and can be used in diesel engine without any modification [11]. However, as diesel engines are not specifically manufactured for biodiesel fuel, the impact of biodiesel on the performance and condition of diesel engine needs to be analysed.

Numerous studies [2-12] have been conducted to research performance, especially the combustion and emission characteristics of diesel engines fuelled with biodiesel compared with petroleum-based diesel. Dorado et al. [7] studied the effect of waste olive oil methyl ester on exhaust emissions using a DI diesel Perkins engine. They concluded that lower emissions of CO, CO_2, NO and SO_2 can be obtained by using biodiesel, but emissions of NO_2 increased. Tashtoush et al. [8] tested the combustion performance and emission of a water-cooled furnace with diesel fuel and ethyl ester of a waste vegetable oil. Their results demonstrated that biodiesel burned more efficiently with higher combustion efficiency and exhaust temperature at the condition of lower energy rate used. While at higher energy input conditions, biodiesel combustion performance deteriorated and was inferior to diesel fuel as a result of the high viscosity, density and low volatility. Gumus [25] investigated the combustion and heat release rate characteristics of a direct-injection compression ignition engine fuelled with biodiesel. He concluded that the engine running with biodiesel did not show obvious deviation from the engine fuelled with diesel in parameters characterising combustion.

However, most of researchers have used destructive test methods for investigation of combustion characteristics which are inconvenient and/or costly in real application. For instance, it has to fix a pressure sensor on the cylinder head of a test engine for in-cylinder pressure measurement. Hence, airborne acoustic and/or vibration measurement has a potential to be used for engine condition monitoring and combustion diagnosis [13-16]. As airborne acoustic sensor is not only easy to install in real application but also measured with more comprehensive information in a remote way. Various acoustic-based engine monitoring studies have been reported in recent decades. For example, S. H. Cho *et al*. [13] presented an analytical model which can predict the impact forces and vibratory response of an engine block surface induced by the piston slap of an internal combustion engine. The equivalent parameters such as mass, spring constant and damping constant of the piston and cylinder inner wall were estimated by using measured point mobility. The results were compared with experimental results to verify the model and to reach the conclusion that prediction of overall vibration level showed a similar tendency to the measured noise level close to the surface of engine block. Shu and Liang [14] analyzed the complex engine noises using coherent power spectrum analysis. They found that the main sources of the engine noise are combustion and machinery. They concluded that the noise of the low-frequency band is mainly the machinery noise, while the noise of high-frequency band is mainly combustion. Most engine noise is produced by the combustion process and slight portion of noise is contributed by the injector, the intake and exhaust valves [15].

The combustion induced noise occurred towards the end of the compression stroke and subsequent expansion stroke. The change of in-cylinder pressure causes the vibration of the engine components such as the cylinder head, pistons, connecting rods and engine body, hence produces airborne noise accordingly. All the vibration induced noises contribute to the overall engine noise level [16]. The vibration and noise of engine are generated due to the in-cylinder pressure variation which is related to the engine combustion process. Therefore, the combustion process could be diagnosed and monitored through analysing the vibration and noise of the engine. Actually, the unpleasant noise signature of diesel engines is due to the harsh irregular self-ignition of the fuel [17]. So the fuels can also be evaluated by analysing the combustion induced noise and relate the noise quality back to the combustion characteristics.

Vibration and acoustic signals from an engine are usually noisy and non-stationary. It is essential to develop an appropriate analysis tool in order to extract accurate features from the non-stationary signals. Time-frequency analysis has been developed as a more reliable and effective method for machinery condition monitoring. Wavelet transform is a typical and powerful time-frequency tool and being widely used in machinery condition monitoring and diagnostics. It is capable of revealing the time-frequency characteristics of a signal, in particular, it is more efficient to disclose small transients and enhance the spikes in signals.

In this paper, the characteristics of the engine noise were investigated in relation to the variation of in-cylinder pressure during the combustion process. The objective of the paper is to determine the relationship between the acoustic characteristics and combustion process of a CI engine running with biodiesel and its blends with normal diesel. And then the acoustic characteristics were used to diagnosis the combustion process and to monitor the fuel quality. Thus, the paper is organised as follows, section 2 presents the diesel engine combustion process characteristics, combustion vibration and noise generation. Section 3 reviews the basic theory of the continuous wavelet transforms and its properties. Section 4 introduced the experimental facilities and testing procedures. The analysis results and discussion are detailed in section 5. Finally, the conclusions are drawn.

2. CI engine Combustion Characteristics

2.1 Combustion process

Engine combustion is a complex process due to the combustion mechanism. The main parameters used for analysing the characteristics of the combustion process are cylinder pressure, ignition time delay, combustion duration and heat release rate (HRR) [1]. All these parameters are based on the variations of in-cylinder pressure. Hence the combustion parameters can be calculated based on the in-cylinder pressure data. Other important combustion parameters, such as combustion duration and intensity, can be estimated from the variation of HRR over an engine cycle. In addition, the HRR can be used for identifying the start of combustion, indicating the ignition delay for different fuels, showing the fraction of fuel burned in the premixed mode and recognizing differences in combustion rates of fuels [10]. The HRR can be calculated from a simplified approach derived from the first law of thermodynamics [18] as expressed in Equation (1).

$$\frac{dQ}{d\theta} = \frac{1}{\gamma - 1}\left(\gamma P \frac{dV}{d\theta} + V \frac{dP}{d\theta}\right) \tag{1}$$

where, $dQ/d\theta$ is the heat release rate across the system boundary into the system (kJ/deg), P is the in-cylinder pressure (Pa), V is the in-cylinder volume (m^3), γ is the ratio of specific heats with an appropriate range from 1.3 to 1.35, and θ is the crank angle (deg). Moreover, $P(dV/d\theta)$ is the rate of work transfer done by the system due to system boundary displacement [18]. Furthermore, the accumulative heat release rate Q_c can be obtained from the heat release rate in Equation (2). The accumulative heat release is the gross heat release due to combustion.

$$Q_c = \int \frac{dQ}{d\theta} d\theta \tag{2}$$

Ignition delay is also an important parameter for analysing the combustion process of an engine. It is defined as the time interval between the start of fuel injection into the combustion chamber and the start of combustion [1]. The ignition delay corresponds to the period between the beginning of fuel injection until the cylinder pressure rises and can be obtained by calculating the HRR of the engine combustion process. Theoretically, a longer ignition delay means more fuel is available for the ignition and resulting in more energy release during the premixed combustion stage. However, the cumulated fuel with longer ignition delay has the risk to lead to poor air-fuel mixing and result in incomplete combustion [5]. Therefore, under the condition of using the fuels with the same properties, reduction in ignition delay may result in earlier complete combustion and lead to slightly higher peak pressure while the increase in delay period results in poor combustion and may lead to lower peak pressure [18]. Figure 1 shows the cylinder pressure and HRR of a diesel engine. It can be seen that the combustion process can be divided into three distinguishable stages [18]. The first stage is the premixed period, where the rate of burning is very high and the combustion time is short (for only a few crank angle degrees) as well as the cylinder pressure rises rapidly. The second stage is the mixing controlled period and is the main heat release period corresponding to a period of gradually decreasing HRR and lasting about 30 crank degrees. The third stage is the late combustion period which corresponds to the tail of the heat release diagram in which a small but distinguishable HRR occurs throughout much of the expansion stroke.

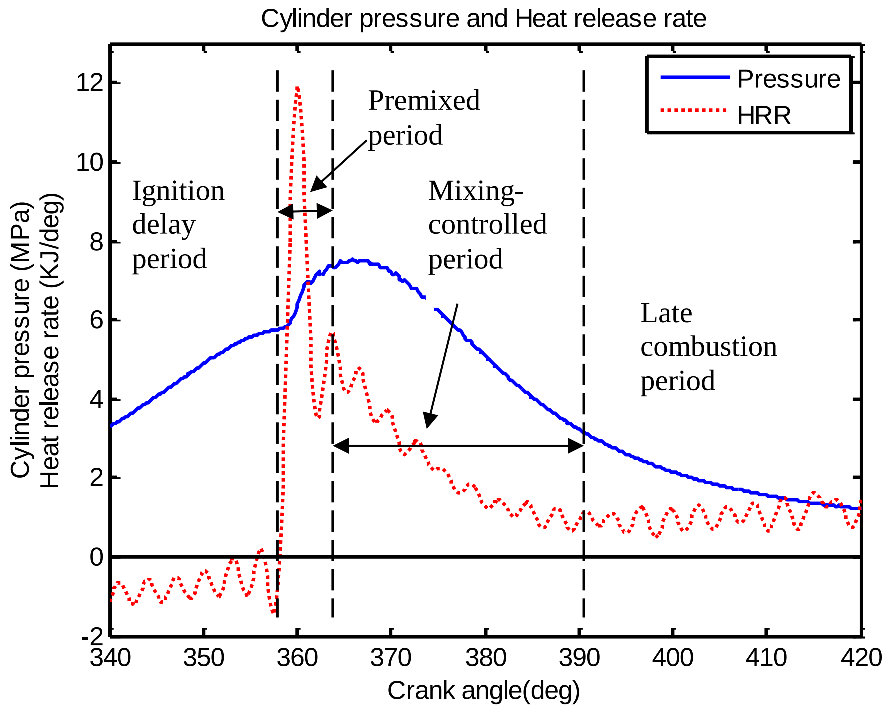

Figure 1 Cylinder pressure, heat release rate for diesel engine

2.2 Combustion vibration and Noise

Combustion noise is a complex phenomenon whose level and sound quality are strongly dependant on the fuel combustion and it is one of the main engine noise sources [17]. It occurs towards the end of the compression stroke and subsequent expansion stroke. And the pressure variation in the engine cylinder plays a significant role in the analysis of the combustion characteristics, combustion induced noise. The noise quality can be related to the in-cylinder pressure variation [17]. On the other hand, the combustion process and engine fuels could be monitored through analysing the characteristics of engine combustion noise.

Figure 2 shows the engine acoustic signals monitored in relation to vibration and in-cylinder pressure. It indicates that corresponding to the higher cylinder pressure; the combustion process produces higher engine vibration and subsequently higher level acoustic signals contributing knocking noise. It also shows that the peak of vibration signal happens slightly later than the peak of in-cylinder pressure. And the peak of acoustic signals occurred slightly later than the peak vibration signals due to sound transmission from the vibration sound source to the noise receiver.

There are three main paths for the vibration and noise transmission based on their generation mechanism and the engine structures [19]. The first path is from the cylinder head to the cylinder block and then directly into the air. The second path is the gas explosion directly exciting the cylinder block through which the noise is transmitted. The third path begins from the piston to the connecting rod and then transmitted to cylinder block through the crankshaft which can be considered as mechanically induced noise. All the combustion induced noise is radiated to the air through the external surfaces of the engine, and contributes to the overall engine noise level.

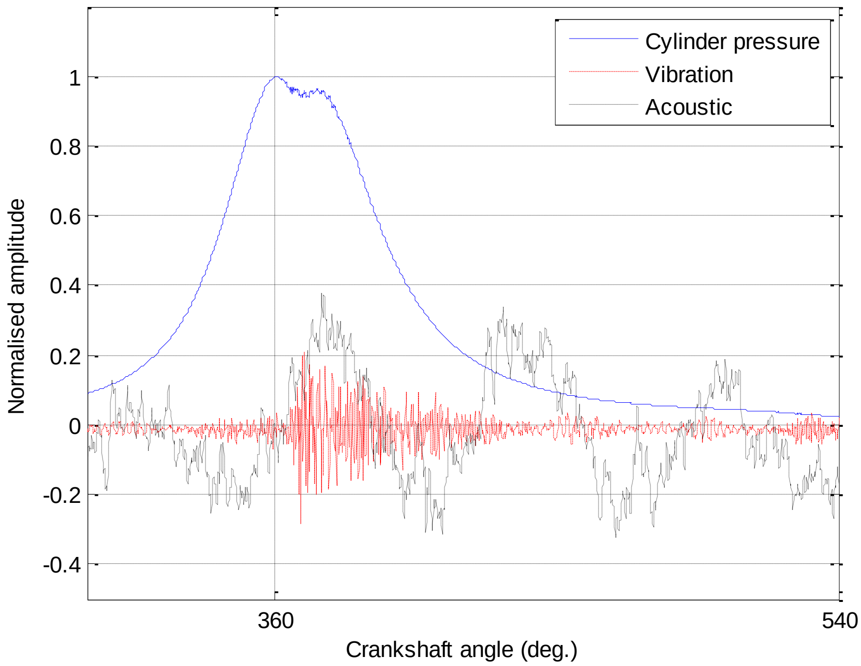

Figure 2 Normalised cylinder pressure, engine vibration and acoustic [28]

3. Continuous Wavelet Transform

In the field of machinery condition monitoring, CWT is recognized as a powerful and effective tool for feature extraction from a non-stationary signal. The theory of CWT used in this study can be detailed as follows [20].

$\psi(t) \in L^2(R)$ and its Fourier transform $\psi(f)$ which should be subjected to the admissibility condition in equation (3),

$$C_\psi = \int_{-\infty}^{\infty} \frac{|\hat{\psi}(\omega)|^2}{|\omega|} d\omega < \infty \tag{3}$$

where $\psi(t)$ denotes a mother wavelet function, ω is the angular frequency and $L^2(R)$ is the space of the square integral complex functions. The corresponding family of a wavelet consists of daughter wavelets as shown in Equation (4).

$$\psi_{a,b}(t) = |a|^{-1/2}\psi\left(\frac{t-b}{a}\right) \tag{4}$$

where a is scale factor and b is time location factor, $|a|^{-1/2}$ is used to ensure energy preservation. The daughter wavelets are the translated and scaled versions of the mother wavelet with the factors a and b vary continuously.

The CWT of a signal $x(t)$ is defined as the inner products between signal $x(t)$ and the wavelet family. They are derived from the wavelet function by dilation and translation through adjustment of the parameters a and b.

$$WT_x(a,b) =< \psi_{a,b}(t), x(t) >= |a|^{-1/2} \int x(t)\psi^*_{a,b}(t)dt \tag{5}$$

where $WT_x(a,b)$ denotes the wavelet transform coefficient, $\psi^*_{a,b}(t)$ represents the complex conjugate of the wavelet function. a is known as a dilation parameter and b gives the location of the wavelet and is known as a translation parameter.

For a discrete sequence x_m, let $a = m\delta t$ and $b = n\delta t$, where $m, n = 0, 1, 2, \dots \dots, N-1$, N is the sampling point number and δt is the sampling interval. The CWT of x_m can be defined as:

$$WT_n(a_j) = \sum_{m=0}^{N-1} x_m \psi^* \left[\frac{(m-n)\delta t}{a_j}\right] \quad (6)$$

The amplitude of the feature corresponding to the scale and how this amplitude varies with time can be presented through variation of the index j and n corresponding to the scale factor a and time location b, respectively.

Wavelet coefficients obtained from the wavelet transform can be used to measure the similarity between the interesting signal and daughter wavelets. It is noted that the more similar the daughter wavelet is to the feature component the more interesting the signal; the corresponding wavelet coefficients are consistent [21]. Moreover, the wavelet has oscillating wave-like characteristics and allows simultaneous analysis in the time and frequency domains with the flexible wavelet functions. In the CWT the wavelet has finite energy concentrated around a limited time interval [22]. In addition, it can also represent a sharp feature in the signal and hence the original signal can be completely reconstructed or recomposed.

4. Experimental Facilities and Testing Procedure

To investigate characteristics of vibro-acoustics from an engine fuelled with biodiesels, an experimental study was conducted on a test rig which consists of diesel engine, charge amplifier (for vibration signal), filter and amplifier (for acoustic signal), cylinder pressure sensor and Analogue-to-Digital Converter (ADC). The diesel engine is a four-cylinder, four-stroke, turbocharged, intercooled and direct injection engine. It is a typical engine and widely used in the industry application. The load to the engine is provided by a 200 kW AC dynamometer with 4 quadrant regenerative drive with monitoring and absorbing capability for both steady and transient conditions. The schematic diagram of test rig and engine specifications is shown in figure 2 and table 1, respectively.

Table 1 Specifications of the test engine

Type of engine	Turbocharged diesel engine
Number of cylinders	4
Bore	103mm
Stroke	132mm
Compression ratio	18.3:1
Number of valves	16
Injection system	Direct injection
Displacement	4.399 litre
Cooling system	Water
Maximum power	74.2 kW @ 2200 rpm

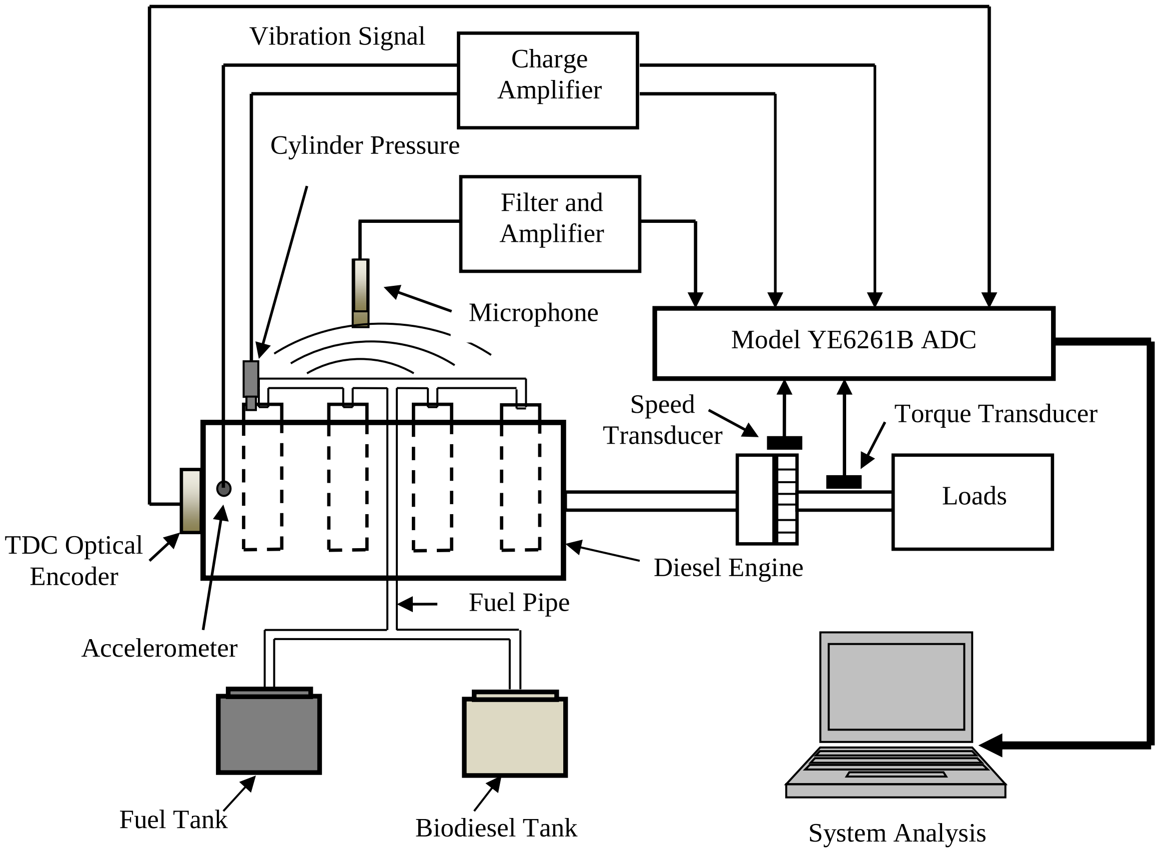

Figure 3 Schematic diagram of engine test system

In the experiment, the engine was tested with range of fuels blends and operated at the constant speeds of 900rpm, 1100rpm and 1300rpm and loads from 105Nm to 420Nm with an interval of 105Nm at each constant speed. The details of the operating conditions are given in table 2.The test engine was fuelled with rapeseed oil (B50 and B100) as well as pure diesel. B50 represents the mixture of 50% rapeseed oil and 50% diesel by volume, whereas B100 is 100% rapeseed oil by volume. The rapeseed biodiesel is produced by a transesterification process from 'virgin' oil using methanol. The main physical properties such as the composition, density, measured heat value (MHV) and viscosity of pure biodiesel and diesel are presented in Table 3 and Table 4 [6, 24].

Table 2 Operating conditions

Fuel	**Speed (rpm)**	**Load (Nm)**
Pure Diesel	900 1100, 1300	105, 210, 315, 420
B50	900, 1100, 1300	105, 210, 315, 420
B100	900,1100, 1300	105, 210, 315, 420

During the test, the engine speed, cylinder pressure, crank angle position, engine vibration and acoustic signals were measured and recorded for analysis. Engine speed was measured by a Hengler RS58 speed sensor. The in-cylinder pressure in cylinder #1 was measured by Kistler 6125A11 model air-cooled Piezo-Quartz pressure sensor that was mounted on the cylinder head. The vibration of the engine body was measured using accelerometers with the sensitivity of 4.9 mV/ms^{-2}. The signals from the pressure sensor and accelerometer were passed through a B&K type 2635 charge amplifier before feeding them to the Analogue-to-Digital Converter (ADC). The charge amplifier was used to amplify the signals [23]. The engine acoustic signal was measured by using BAST's microphone system including electrets microphone CHZ-211 and preamplifier YG-201 with the sensitivity of 48.4mV/Pa and frequency response of 6.3-20 kHz. Moreover, Crankshaft position was obtained using a crankshaft angle sensor to determine cylinder pressure as a function of crank angle.

Table 3 Properties of biodiesel B100 [6]

Property	Units	Measured
Composition	% C	77
	% H	12
	% O	11
Density	Kg/m^3	879
MHV, KJ/Kg	MJ/Kg	38.5
Kinematic Viscosity	mm^2/s	4.9

All the signals collected from the test engine needed to be converted from the analog form to the digital form so that they were suitable for computer analysis. This can be achieved by a data acquisition system which is based on the hardware of Model YE6261B dynamic data acquisition instrument. The Model YE6261B consists of 32 channels with 16-bit resolution for each channel, synchronized acquisition at 100 kHz per channel and an IEEE 1394 interface selectable signal conditioners. This data acquisition system is adequate for monitoring vibration and acoustic signals.

Table 4 Properties of diesel [24]

Property	Units	Measured
Composition	% C	86.1
	% H	13.25
	% O	-
Density	Kg/m^3	837.8
MHV, KJ/Kg	MJ/Kg	45.85
Kinematic Viscosity	mm^2/s	3.275

5. Results and Discussion

During the test, all the signals were collected simultaneously by the data acquisition system at a sampling rate of 100 kHz. Each collection has 403456 data points which is more than 4 seconds in duration. This data length covers about 30 engine combustion cycles and is sufficient for random noise suppression in TSA process. Additionally, the high sampling rate allows a high accuracy in waveform parameter calculation.

5.1 Cylinder pressure variation

Cylinder pressure versus crank angle over the compression and expansion strokes of the engine running cycle can be used to obtain quantitative information on the progress of combustion [18]. Figure 4 shows the cylinder pressures versus crank angle for different fuel cases (Diesel, B50, and B100), engine loads (105Nm, 210Nm, 315Nm and 420Nm) and at a constant speed of 900rpm, while Figure 5 presents the cylinder pressure versus crank angle at a constant speed of 1100rpm. From both figures, it can be seen that the peak cylinder pressure is higher for rapeseed oil biodiesel at most of the tests. This is possible due to the high oxygen content of biodiesel which contributes to the combustion process [5] that result in the fuel is easier to achieve complete combustion and lead to a higher in-cylinder pressure. Moreover, the higher viscosity and density of biodiesel can also enhance fuel spray penetration through increased fuel injection pressure and thus improve air-fuel mixing [24]. This maybe another reason of biodiesels can generate higher peak in-cylinder pressures than that of pure diesel. On the other hand, a possible explanation for B100 has lower peak in-cylinder pressure than that of B50 in Figure 4 and Figure 5 might be the viscosity of B100 is higher than that of B50 because a higher viscosity of biodiesel can lead to bad fuel injection atomization that may affect the combustion efficiency [5].

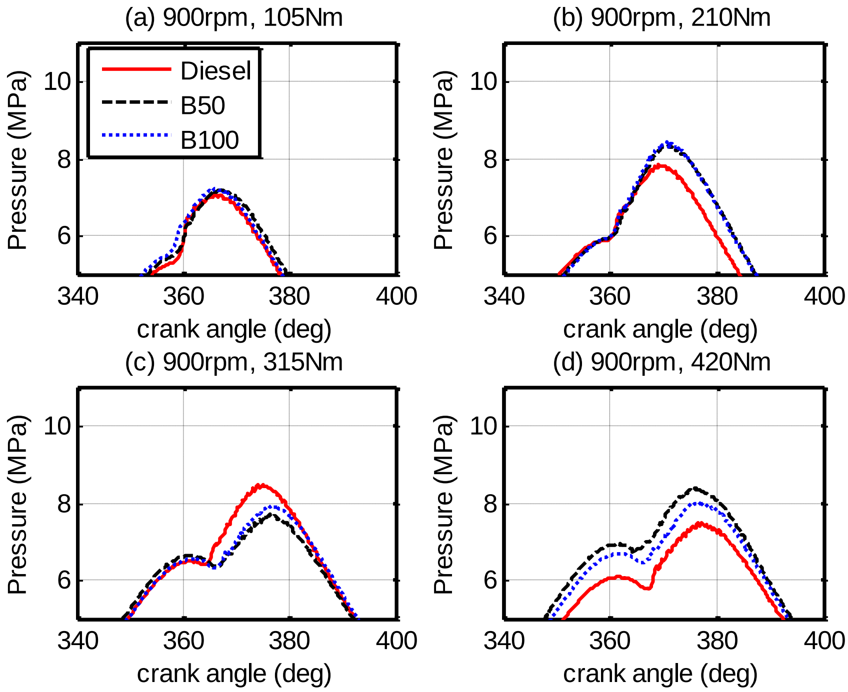

Figure 4 Cylinder pressure at speed of 900rpm

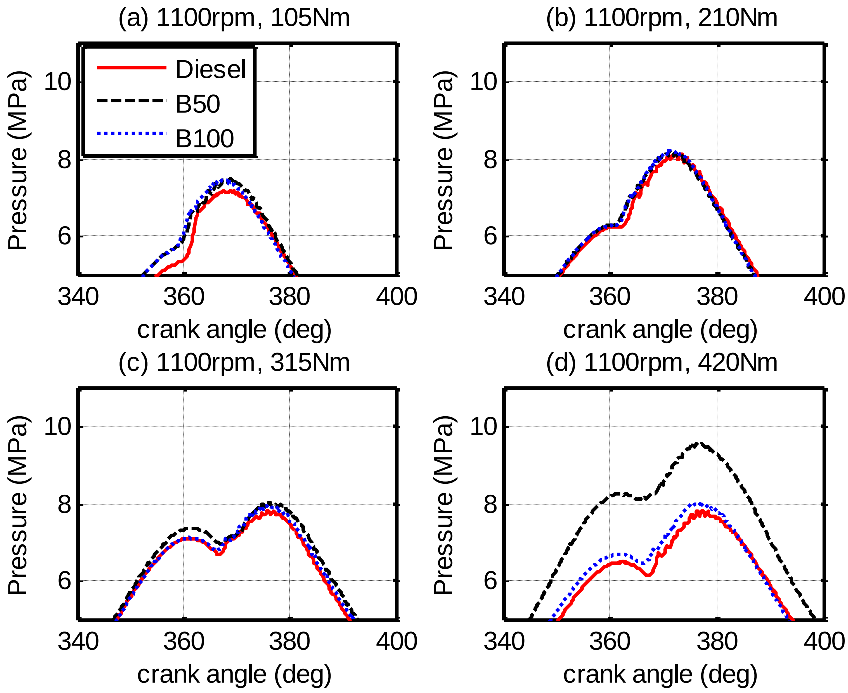

Figure 5 Cylinder pressure at speed of 1100rpm

From Figure 4 and 5, it can be see that the peak cylinder pressure for both diesel and biodiesel blends increased when the engine loads and speeds increased. This is natural and due to more fuel injected for higher loads and faster angular displacement for higher speed, which all lead to a longer ignition delay and results in more fuel available for ignition and more energy release during the premixed combustion stage combined with complete combustion [1].

To show further theses understandings, a heat release analysis is performed based on Equation (1) and its results are presented in Figure 6 and Figure 7. The HRR for diesel, biodiesel blends (B50 and B100) under a load of 210Nm with speeds of 900rpm, 1100rpm and 1300rpm are shown in Figure 6. It can be seen that the combustion starts earlier for reduced engine speeds. This means that a longer ignition delay is required at higher speeds for both diesel and biodiesel blends. Figure 7 shows the HRR of diesel, biodiesel and its blends at loads of 105Nm, 210Nm, 315Nm and 420Nm at a constant speed of 1100rpm. In general, it shows that ignition delay increases with the increase of engine load for all types of fuel. The slight advancement and gradual combustion under 420Nm for B50 may be due to a better fuel mixture preparation resulted from combined effects of higher injection pressure, compared with diesel, and lower viscosity, compared with B100. In addition, the maximum HRR increases with the rise of engine load due to the increase in the quantity of fuel injected into the cylinder [25].

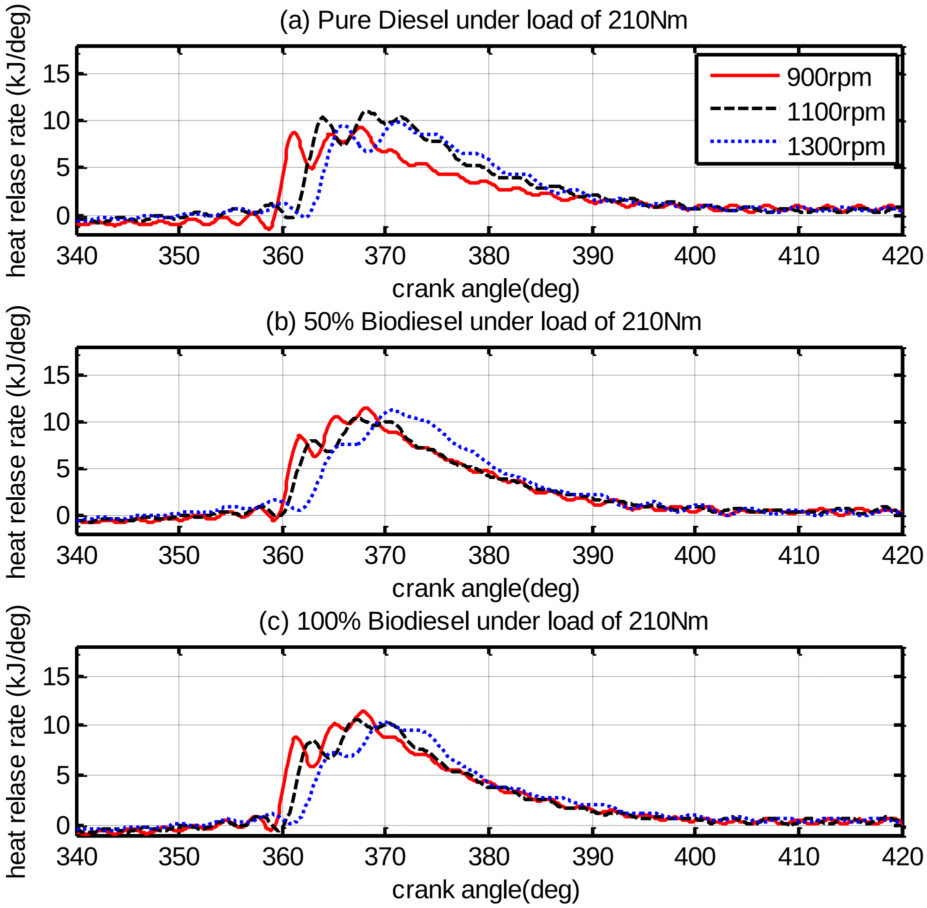

Figure 6 HRR under a load of 210 Nm and at varying speeds for different fuel cases

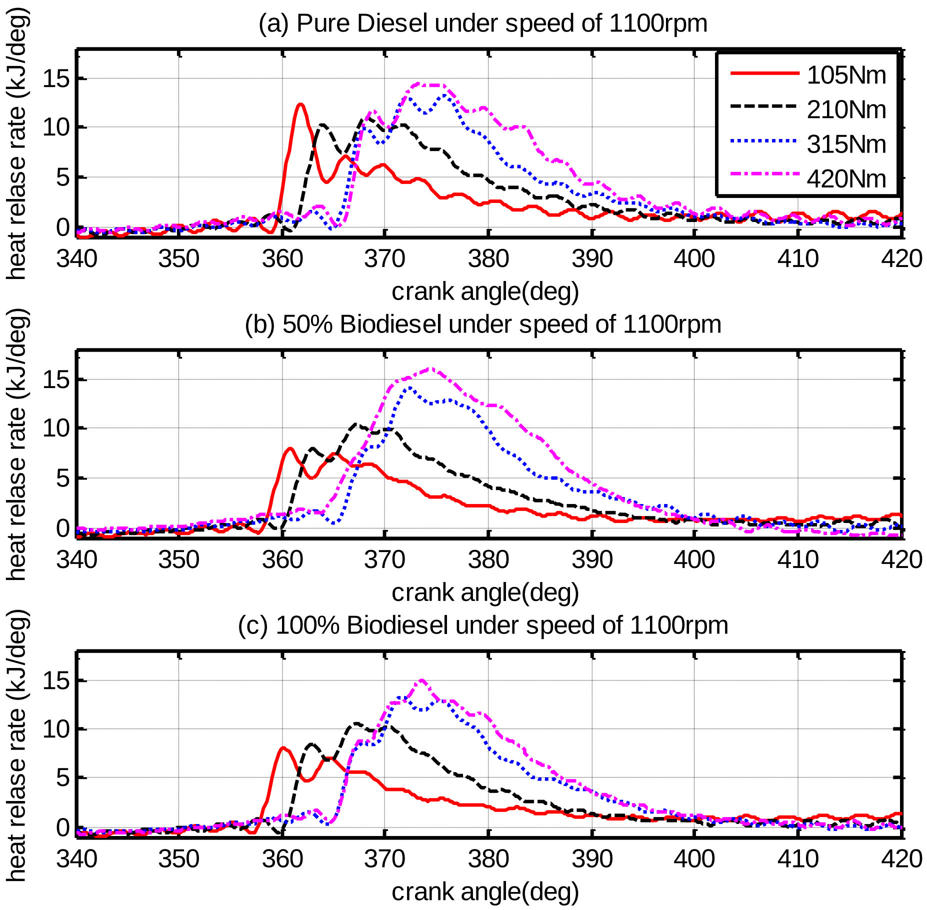

Figure 7 HRR at speed of 1100rpm and under varying loads for different fuel cases

5.2 Time synchronous average

In a real application, the vibration and acoustic signals collected are commonly contaminated by different noises such as those from the dynamotor and ventilation fan which will affect the accuracy of feature extraction for condition monitoring and combustion diagnosis. Figure 8 and 9 show the engine vibration and acoustic signals at a speed of 1300rpm and at different loads of 210Nm, 315Nm and 420Nm while the test engine is fuelled by different fuel of diesel, B50 and B100, respectively. The signal covers one complete combustion cycle (720 degree) which is a simple and fundamental way of presenting data in the angular domain. It can be seen that the amplitude of the acoustic signals increased alongside the increasing engine loads under all types of fuels, showing the signal related to engine process closely.

Moreover, it can be also seen from Figure 9 that the variations of acoustic signal corresponding to each cylinder in one complete combustion cycle is not as clear as that of vibration signal, especially under lower load conditions. The main reason for this is that the acoustic signal is much noisy because of various noise sources. In addition, acoustic signal is more correlated to the velocity of surface vibration which highlights more on low frequency vibrations such as that from engine mounting system. These indicate more careful analysis needs to be carried out for the acoustic signals to obtain useful information for diagnosis.

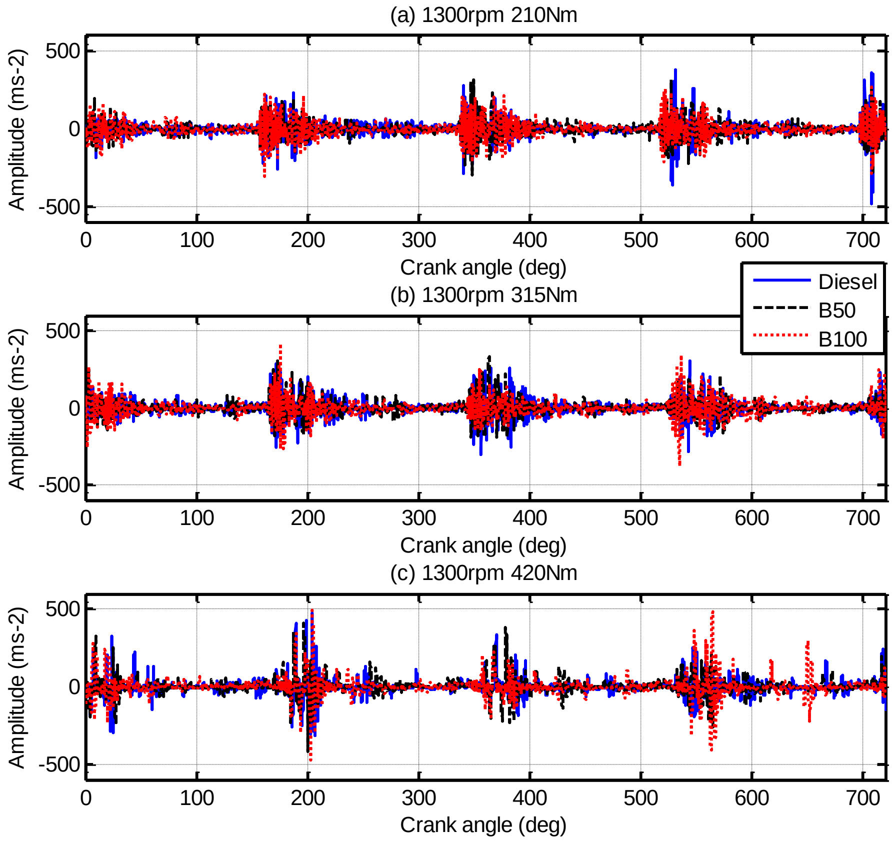

Figure 8 Vibration signals at speed of 1300rpm and under different loads

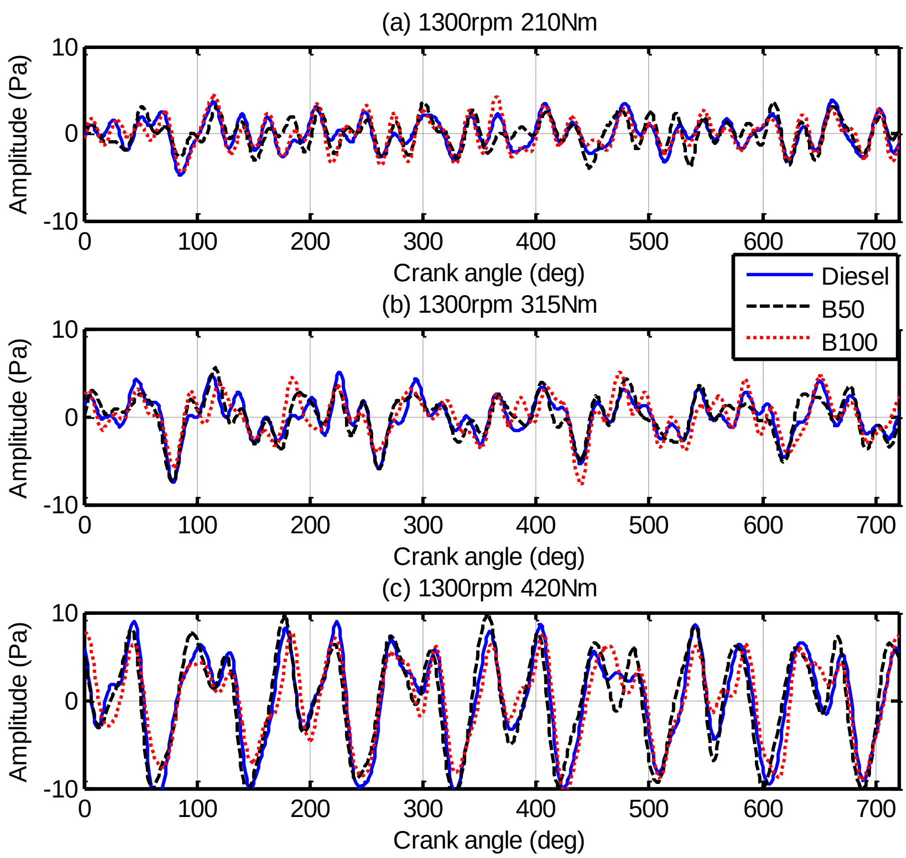

Figure 9 Acoustic signals at speed of 1300rpm and under different loads

TSA is an effective technique in the time domain to remove the noise in a repetitive signal and is widely used in vibration monitoring and fault diagnosis [26]. The SNR of an acoustic signal can be improved significantly by suppressing the components which are asynchronous with that of interest. TSA is based on the knowledge of the revolution specifications of the rotating part. Generally, this requirement is met by using an external trigger signal provided by a shaft encoder, and the revolution period of rotating machinery can then be obtained. In the present study, a Hengler RS58 speed sensor was used to collect the engine speed and provided revolution information for the test engine for TSA processing. The time interval of the pulses in the speed signal was not constant due to oscillation of the shaft speed. Based on this consideration, assuming the shaft speed is undergoing constant angular acceleration [27]. The angular acceleration was calculated using the arrival times of the three adjacent pulses obtained from the sampling of the speed signal. The correct placement of the resample on the time axis was then carried out based on constant angular acceleration. In this study, the time axis resampling was processed in sections with each section length having 1000 points and 5 lengths were selected. Once the resample times are calculated, the vibration signal was resampled according to the resampled time axis for synchronous average.

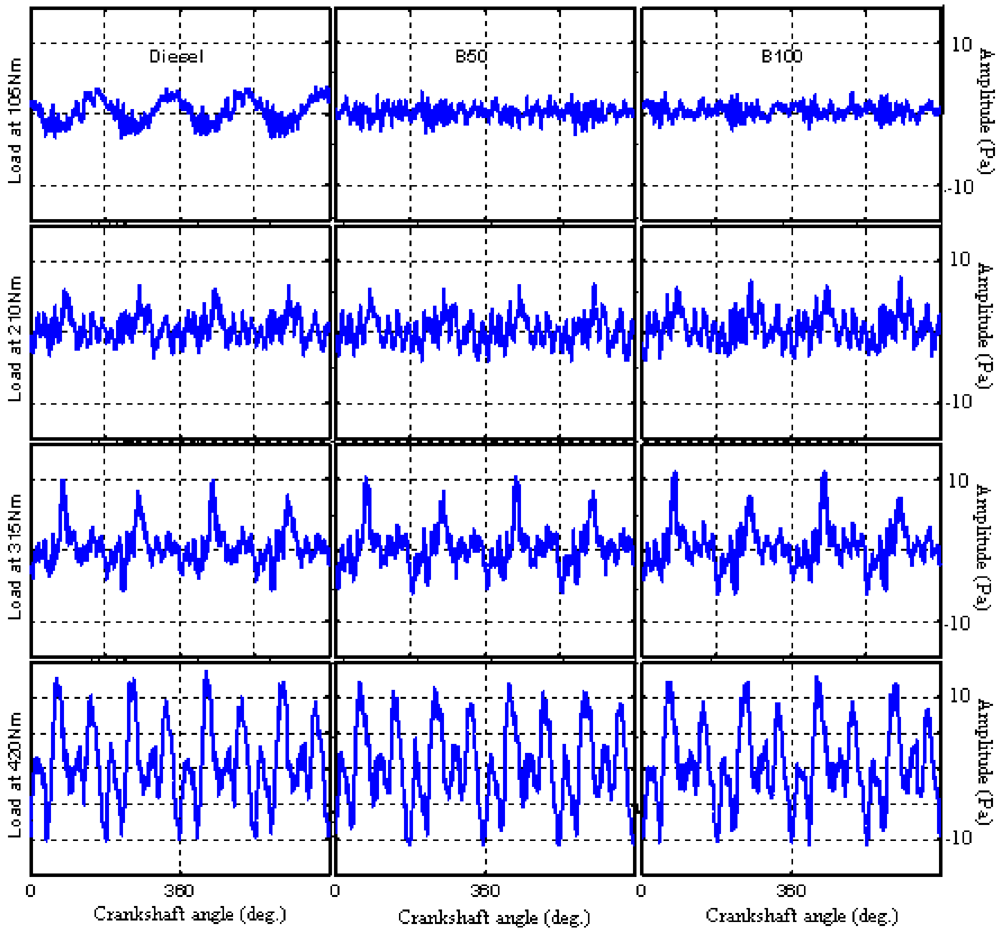

Figure 10 TSA acoustic signals under different operating conditions and fuel types

Figure 10 shows the averaged acoustic signals using TSA processing for one complete combustion cycle. The engine was operating under different loads and fuel types at speed of 1300rpm. It can be seen that the amplitude of the acoustic signals increases with increased load for all fuel types, and the periodic characteristic of the acoustic signals in Figure 10 is better understood compared with results in Figure 9.

For a detailed comparison, root mean square (RMS) values were calculated from the TSA acoustic signals as a feature parameter for comparative analysis. As shown in Figure 11, RMS values of TSA acoustic signals have presented similar trends for the three fuel causes over different loads. The RMS values increase with the increase of the engine loads and speeds. However, RMS values cannot separate the three fuel cases over different loads, especially under low loads such as 105Nm and 210Nm.

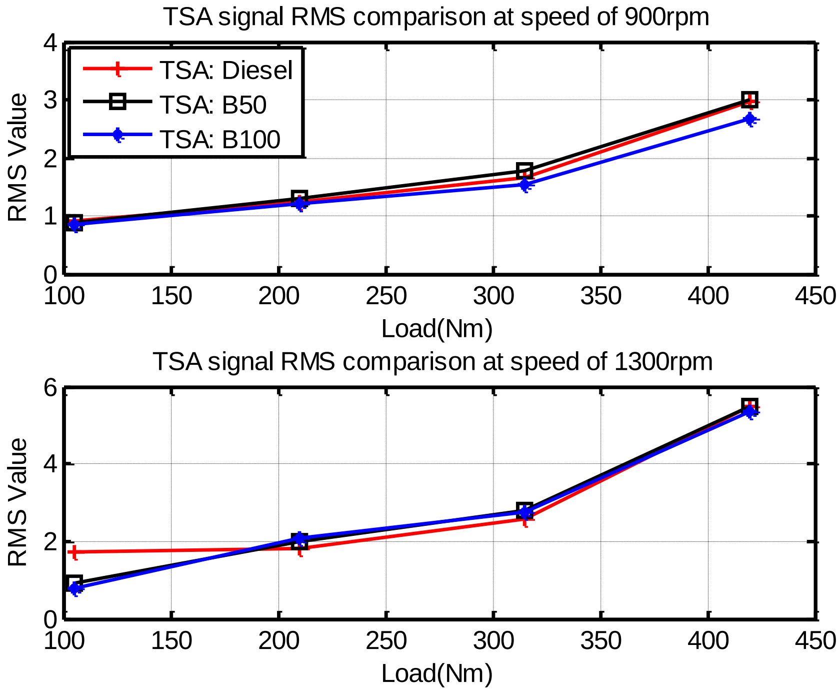

Figure 11 RMS values of TSA acoustic signals under different fuel types

5.3 Feature extraction based on CWT

To obtain more details of the combustion events for different fuel cases, the CWT is used to analyse the TSA acoustic signals collected under different fuel types of diesel, B50 and B100 in the higher frequency band (from 10 kHz to 40 kHz). The scales from 0.5 to 2 are selected for CWT analysis application in this study to investigate the time-frequency properties of the engine acoustic signals in high frequency range in which more content of direct sound radiation is included.

Figure 12 shows the contour plot of the CWT coefficients for the TSA acoustic signals at 900rpm with varying loads and different fuel types. It can be seen the contour shapes of the CWT in the high frequency band give a superior representation of the start, strength and duration of each combustion event. In addition, the contour distribution shows good uniformity among the four cylinders, giving an indication of the uniformity of combustions between different cylinders. These show that the CWT was very effective in extracting combustion related information from the acoustic signals.

Moreover, it has observed that the strength increases with loads for all three types. These characteristics may indicate that the strength of the combustion events can give sufficient information for differentiating fuel types.

To confirm this at different speed, the CWT coefficients at a higher speed (1300rpm) were also presented in Figure 13 for corresponding fuel types. It can be seen that the strength of combustion events was higher for higher speed and also increases with loads.

Therefore, a common feature parameter, RMS, is extracted from the CWT coefficients results for fuel types. This detection approach involves minimal computational effort, making it suitable for use as an on-line condition monitoring technique. As a measure of overall sound level intensity, the average RMS value of the multi-cycle acoustic signal is calculated over the four load settings and the three fuel types. Figure 14 presents a comparison of the RMS value of the CWT results under varying loads and different fuel types at the speeds of 900rpm and 1300rpm respectively.

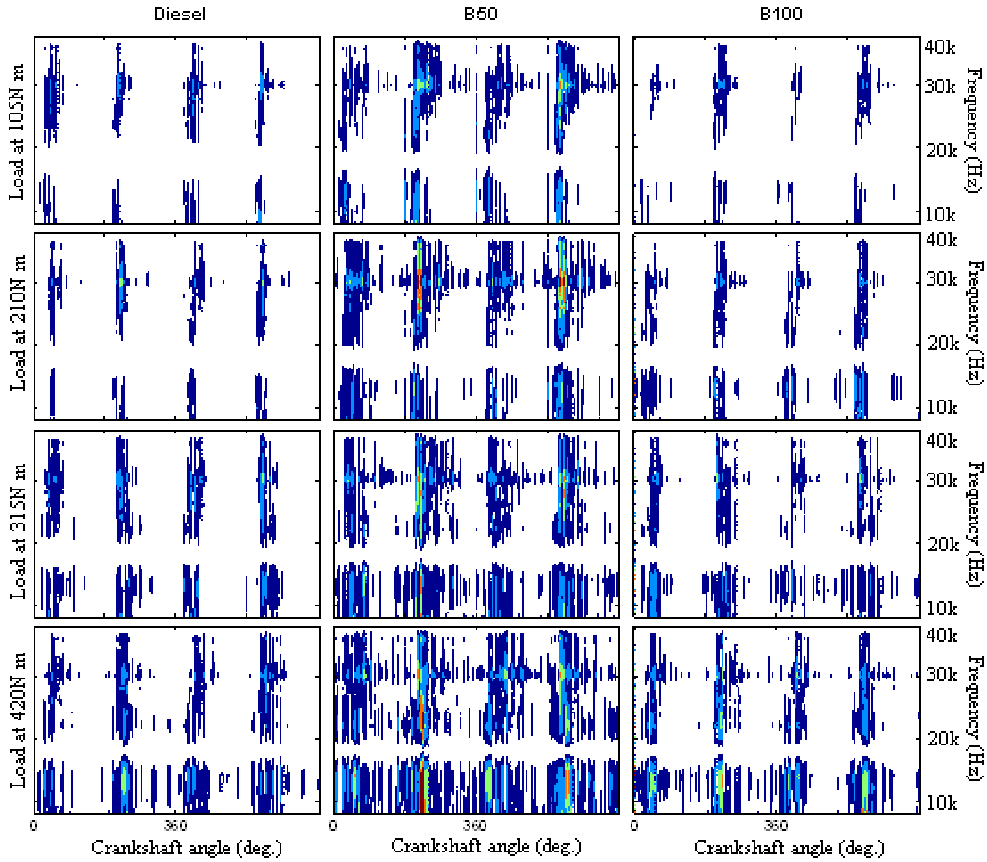

Figure 12 Contour plots of the CWT results for different fuel types at the speed of 900rpm

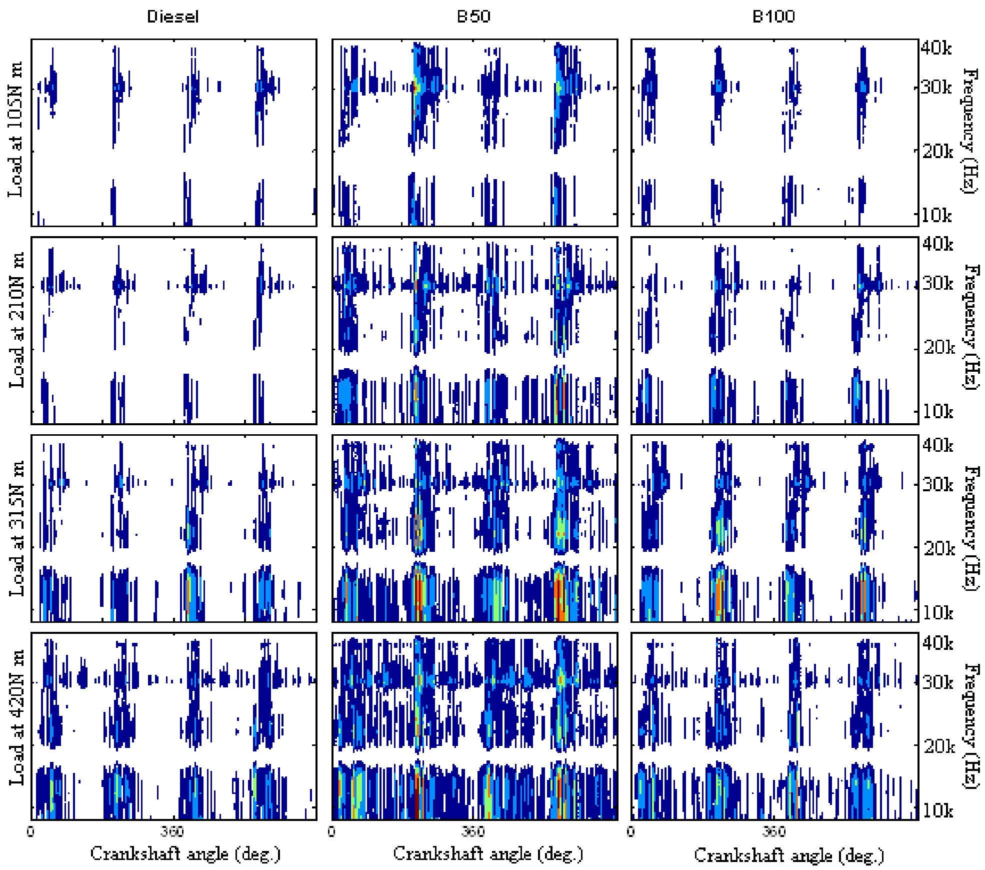

Figure 13 Contour plots of the CWT results for different fuel types at the speed of 1300rpm

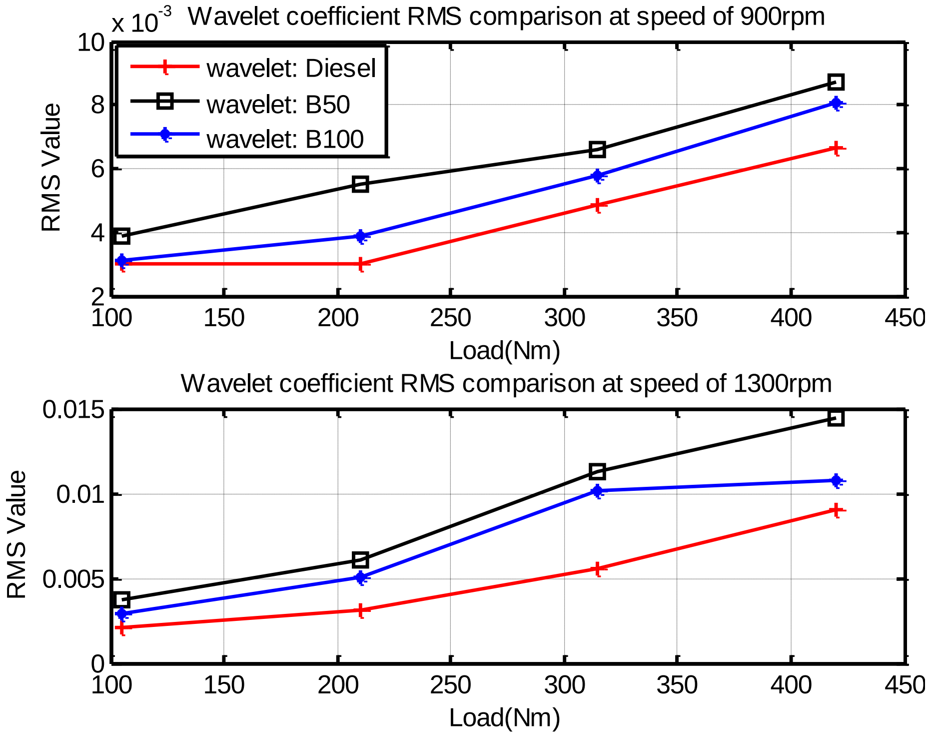

Figure 14 Comparison of RMS between different loads and fuel types

It can be seen from Figure 14 that the RMS values increase alongside engine loads and speeds. Moreover, the RMS values of the CWT coefficient results for biodiesel and its blends (B50 and B100) are slightly higher than those for pure diesel. Focusing on the fuel cases of B50 and B100, it shows that the RMS values for B50 are slightly higher than those of B100 in all test conditions. These behaviours correspond to the variation of the in-cylinder pressure, which indicates that the peak cylinder pressure for B50 is the highest and the peak cylinder pressure for diesel is the lowest over almost all the test conditions in accordance with discussion in Section 5.1. The trends were confirmed to the vibration and noise generation mechanism [19] that higher peak in-cylinder pressure combined with higher rate of pressure rise should produce higher vibration and acoustic.

6. Conclusions

In the present study, an experimental investigation of the combustion process and noise characteristics was carried out on a diesel engine operating with rapeseed biodiesel and its blends under steady state operating conditions. Based on the experimental study, the main results are summarized as follows:

- The peak cylinder pressure is higher when the engine runs with rapeseed oil biodiesel in comparison with pure diesel over almost all tests. The possible reasons for this may be the high oxygen content and higher viscosity of biodiesel which help the combustion in the premixed stage.
- The sound in the higher frequency band is less influenced by the measurement environment than the sound in the low frequency equivalent. These high frequency components can represent the CWT coefficients, allowing the determination of the start, duration and strength of combustion in each cylinder.
- The RMS values of the CWT coefficients of the engine acoustic signal correspond to the variation of the in-cylinder pressure, while the changes of the in-cylinder pressure depend on the properties of the fuels.
- The effects of fuels types on combustion can be extracted from the CWT contour plots and the RMS values of the CWT coefficients.

According to the study in this paper, it found that the characteristics of engine acoustic signal are potential to indicate the variation of in-cylinder pressure and diagnose the engine combustion process. And the RMS values of CWT coefficients of engine acoustic signals can be used to distinguish the differences of fuel types under different engine operating conditions. It is capable of evaluating the fuel qualities in diesel engines.

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