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An investigation of the acoustic characteristics of a compression ignition engine operating with biodiesel blends

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Abstract. In this paper, an experimental investigation has been carried out on the acoustic characteristics of a compression ignition (CI) engine running with biodiesel blends under steady state operating conditions. The experiment was conducted on a four-cylinder, four-stroke, direct injection and turbocharged diesel engine which runs with biodiesel (B50 and B100) and pure diesel. The signals of acoustic, vibration and in-cylinder pressure were measured during the experiment. To correlate the combustion process and the acoustic characteristics, both phenomena have been investigated. The acoustic analysis resulted in the sound level being increased with increasing of engine loads and speeds as well as the sound characteristics being closely correlated to the combustion process. However, acoustic signals are highly sensitive to the ambient conditions and intrusive background noise. Therefore, the spectral subtraction was employed to minimize the effects of background noise in order to enhance the signal to noise ratio. In addition, the acoustic characteristics of CI engine running with different fuels (biodiesel blends and diesel) was analysed for comparison. The results show that the sound energy level of acoustic signals is slightly higher when the engine fuelled by biodiesel and its blends than that of fuelled by normal diesel. Hence, the acoustic characteristics of the CI engine will have useful information for engine condition monitoring and fuel content estimation.

Key word: Acoustic Characteristics; CI Engine; Biodiesel Blends

1. Introduction

Combustion induced noise is the main noise source of engines operating under different conditions. The combustion characteristics can be monitored through analysing the combustion noise due to the engine combustion process [1] and the features of combustion noise can be extracted for analysing the performance of combustion process. Generally, the sound and vibration are often linked, where the generation of sound or noise is usually attributed to the vibration of solid objects and can be explained as vibration of the air and considered as airborne noise [2]. Another airborne engine noise is the machinery noise generated by mechanisms travels through several transmission paths. Beside the airborne noise, the structure noise refers to the noise generated by vibration induced in the structure, which also can contribute to the total level of engine noise.

Many researchers have attempted to predict the noise level of engine during recent decades. Fujimoto[3] investigated the effect of the oil film on the piston slap induced noise, and found that the oil film formed between the piston skirt and the cylinder reduced the clearance and acted as a damper, thus reducing the piston slap force to some extent. Periede et al [1] also carried out similar investigation and they concluded that the piston slap noise was also proportional to the cylinder bore dimension. An analytical model, which can predict the impact forces and vibratory response of engine block surface induced by the piston slap of an internal combustion engine, was developed by S. H. Cho et al. [4]. The equivalent parameters such as mass, spring constant and damping constant of piston and cylinder inner-wall were estimated by using measured point mobility. The simulation results were compared with experimental results to validate the model and reached the conclusion that prediction of overall vibration level shows a similar tendency with measured noise level close to engine block surface. Shu and Liang [5] analyzed the complex engine noises using coherent power spectrum analysis, and concluded that the noise of low-frequency belt is mainly machinery noise, while the noise of high-frequency belt is mainly combustion noise. Even though most of the engine noise sources are produced by the combustion process, additional noise [1], such as the injection, inlet and exhaust noise, the intake and exhaust valves all made up a fraction of the overall noise.

In the combustion process, the in-cylinder pressure is varied during the compression and expansion procedures. The change of the in-cylinder pressure causes the vibration of the engine components such as the cylinder head, pistons, connecting rods and engine body [6] which result in noise radiation from the engine surface. Therefore, the combustion noise occurs towards the end of the compression stroke and subsequent expansion stroke which is related to the engine combustion process. Hence, the combustion process should be diagnosed and monitored through analysing the vibration or combustion noise of the engine. Generally, the unpleasant noise signature of diesel engines is due to the harsh irregular self-ignition of the fuel [7], and this may lead to the changes of the combustion parameters such as in-cylinder pressure, heat release rate (HRR) and ignition delay. Moreover, the fuels can also be monitored by analysing the combustion induced noise and relate the noise quality back to the combustion characteristics.

In this paper, the combustion noise level and characteristics are investigated according to the combustion parameters variation during the combustion process. This paper is organized as follows: section 2 presents the combustion process, noise generation and transmission path; section 3 describes the experimental facilities and test procedures; section 4 set the analysis results and discussions and section 5 summarize the conclusions.

2. Combustion process and noise generation

The combustion of fuel in the engine is a complex process due to the sophisticated combustion mechanism. According to the variation of in-cylinder pressure and HRR, the combustion process can be divided into three distinguishable stages as shown in Figure 1. The first stage is the premixed period, where the rate of burning is very high, the combustion time is short (for only a few crank angle degrees) and the cylinder pressure rises rapidly. The second stage is the main heat release period corresponding to a period of gradually decreasing HRR and last for about 30 crank degrees with a named mixing controlled period. The third stage is the late combustion period which corresponds to the tail of heat release diagram in which a small but distinguishable HRR throughout much of the expansion stroke.

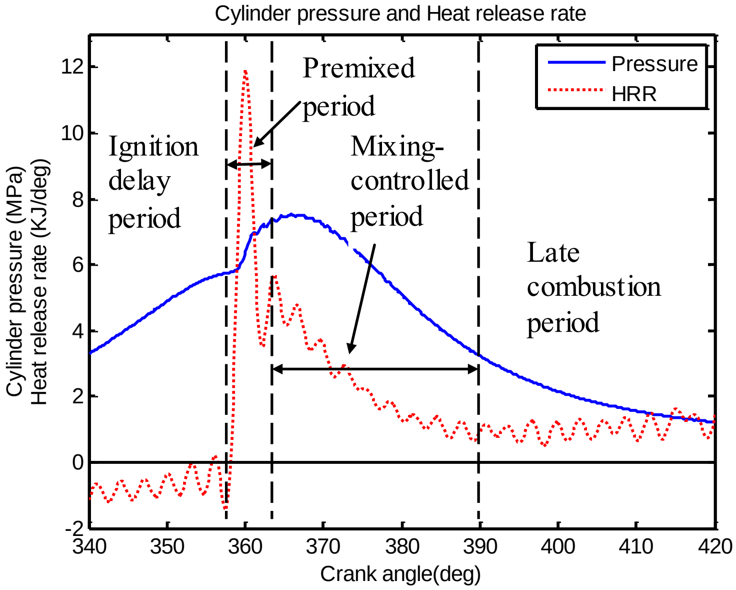


Figure 1. Combustion process of a diesel engine [17].

The main parameters used for analysing the characteristics of the combustion process are the in-cylinder pressure, heat release rate and the ignition delay [8]. All these parameters can be calculated based on the in-cylinder pressure which is considered as the basic parameter of the combustion process and can be measured by a pressure sensor. The HRR can be used to identify the start of combustion, indicates the ignition delay for different fuels and operating conditions [9], and it can be calculated from a simplified approach which was derived from the first law of thermodynamics [16].

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

where, $dQ/d\theta$ is the heat release rate across the system boundary into the system, P is the in-cylinder pressure, V is the in-cylinder volume, γ is the ratio of specific heats and an appropriate range for γ for heat release analysis is from 1.3 to 1.35. θ denotes the crank angle.

Ignition delay is defined as the time interval between the start of fuel injection into the combustion chamber and the start of combustion [15]. It determines the quantity of premixed flame forming the rate of pressure increase and its maximum value [8], and ignition delay corresponds to the beginning of the fuel injection until the cylinder rise in pressure. Theoretically, a longer ignition delay means more fuel available for the ignition and more energy released during the premixed combustion stage. Otherwise, the reduction in ignition delay may result in earlier combustion leading to slightly higher peak pressures, and the increase in delay period may result in poor combustion and may lead to lower peak pressure [10].

Combustion noise is a complex noise whose level and quality both depend on the fuel combustion and the variation of in-cylinder pressure. The rapid pressure changes due to the fuel combustion results in vibration transmitted through engine structures and forms a part of the airborne noise and contributes to the entire engine noise level. Based on their generation mechanism and the engine structures, there are mainly three paths for the vibration and noise transmission [11] which are cylinder head, gas excitation inside cylinder and mechanical parts as shown in Figure 2.

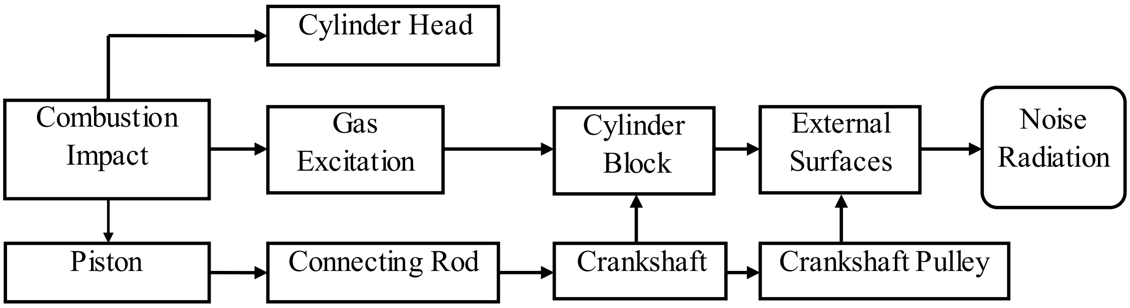


Figure 2. the combustion noise generation diagram [11].

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 is 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.

3. Experimental procedure

The experiments were conducted on a four cylinders, four-stroke, turbocharged, water-cooled and direct injection diesel engine. The experimental set-up is shown schematically in Figure 3, and the engine specifications are presented in Table 1. The test engine with a bore of 103mm, a stroke of 132mm, a displacement of 4.4 liter and a compression ratio of 18.3 is used. The load to the engine was provided by a 200 kW AC dynamometer with 4 quadrant regenerative drive with monitoring and absorbing capability for both steady and transient conditions.

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
Number of valves	16
Injection system	Direct injection
Displacement	4.399 litre
Cooling system	Water
Recommended speed	850 rpm
Maximum power	74.2 kW @ 2200 rpm

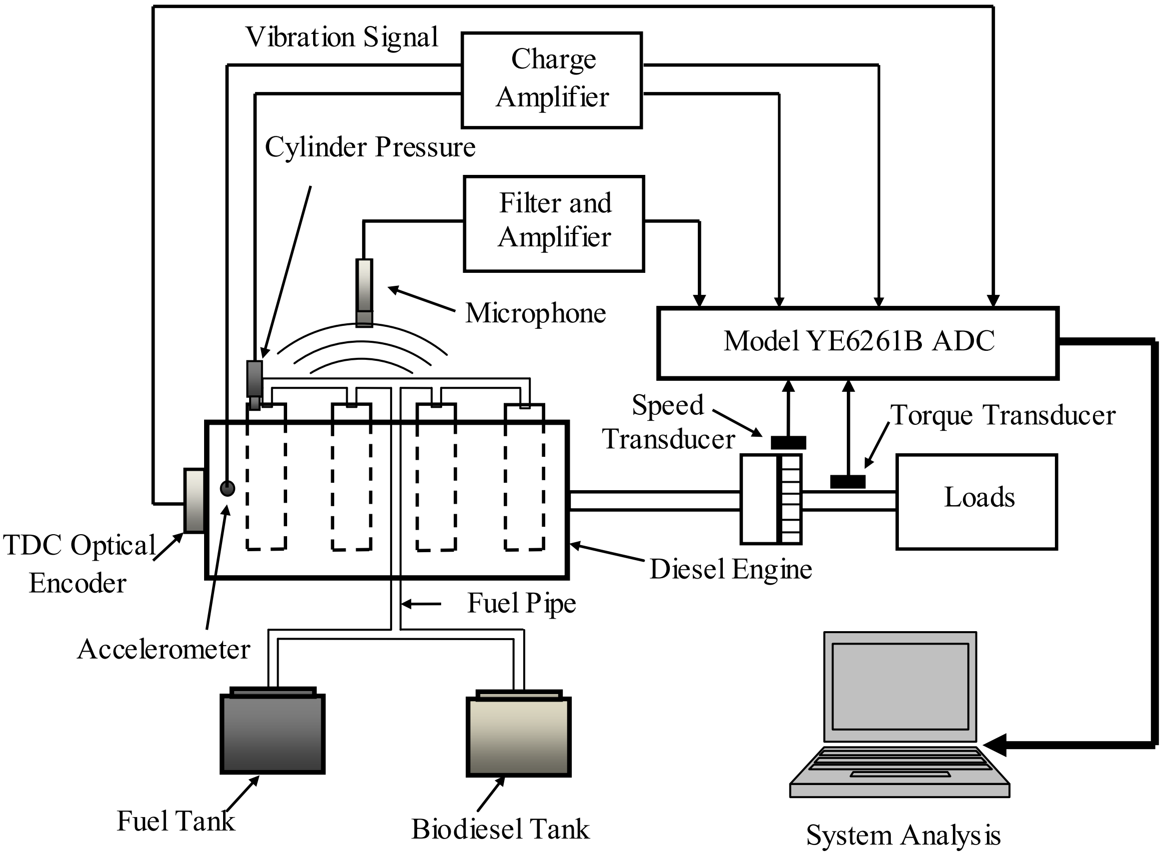


Figure 3. Schematic diagram of engine test system.

In the test, the engine was fuelled with rapeseed oil blends and pure diesel at the speeds of 900rpm, 1100rpm and 1300rpm. The loads were varied from 0 to 420Nm with an interval of 105Nm at each constant speed. In other words, the test engine was operated at different speeds and loads when different fuels were tested. The details of the operating conditions are given in Table 2. Where, B50 is 50% rapeseed oil and 50% diesel, B100 is 100% rapeseed oil.

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, vibration and acoustic were measured and recorded. Engine speed was measured by a Hengler RS58 speed sensor. The cylinder pressure 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 pressure and accelerometer signals were passed through the B&K type 2635 charge amplifier before feeding them to the Analogue-to-Digital Converter (ADC). The charge amplifier was used to amplify the signal and filter out unwanted signal components. The acoustic signal produced by the test engine was measured by using BAST's microphone system composed of electrets microphone CHZ-211 and preamplifier YG-201 with the sensitivity of 48.4mV/Pa and frequency response of 6.3-20 kHz. The background noise of the test conditions was recorded when the test engine was off, and then the spectral subtraction was employed to improve the effect on the acoustic signals by subtracting the background noise. Moreover, crankshaft position was obtained using a crankshaft angle sensor to determine in-cylinder pressure as a function of crank angle.

4. Results and discussion

The signals of acoustic, vibration and in-cylinder pressure were measured for CI engine running with diesel and biodiesel blends under a range of operating conditions. In this section the data were analyzed and detail discussion is carried out. The vibration and acoustic signals of the test engine were related to the combustion process due to the variation of in-cylinder pressure. Figure 4 shows the normalized amplitude of cylinder pressure, body vibration and acoustic signal. It can be seen that higher cylinder pressure, which results from the combustion process produces higher engine vibration and hence leads to higher acoustic signals. The vibration occurs in the mixing controlled period according to the combustion process stages in Figure 1. It demonstrates that the peak of vibration signal occurred slightly later than that of peak pressure, and the peak acoustic signals occurred later than peak vibration due to the sound transmission from the vibration sound source to the position of the microphone. It means that the variation of vibration and acoustic signals are referred to the changes of in-cylinder pressure, and hence the combustion parameters such as HRR, ignition delay are varied accordingly.

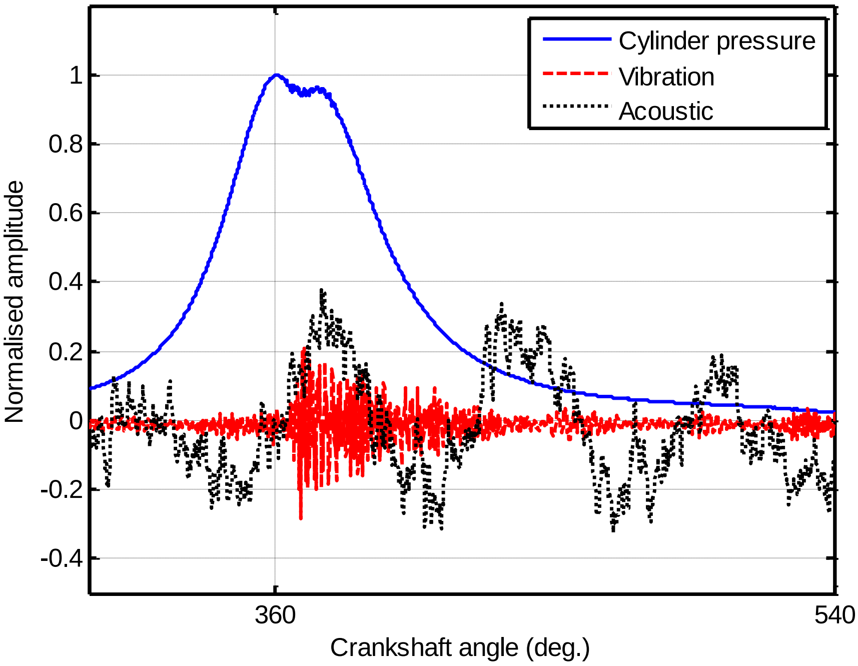


Figure 4. Normalized cylinder pressure, body vibration and engine acoustic.

Figure 5 shows the cylinder pressures versus crank angle for different fuels (Diesel, B50, and B100), different engine loads (105Nm, 210Nm, 315Nm and 420Nm) and at a constant engine speed of 1100rpm. Figure 6 presents the cylinder pressure versus crank angle for different fuels (Diesel, B50, and B100), different engine speeds (900rpm, 1100rpm and 1300rpm) and under a constant engine load of 420Nm. From the two figures it can be seen that the peak cylinder pressure is higher for rapeseed oil biodiesel at all tests. This is due to the high oxygen content of biodiesel which contributes to the combustion process [12, 15], and the fuels achieve complete combustion so that it results in a higher in-cylinder pressure. Moreover, the higher viscosity of biodiesel can enhance fuel spray penetration thereby improving air-fuel mixing [13], but a higher viscosity of biodiesel can also lead to bad fuel injection atomization. The peak cylinder pressure of B50 is slightly higher than that of B100, especially in high load. This may be because of the higher viscosity of B100. The viscosity of the biodiesel is increased with the increase of biodiesel percentage in the blends, and higher viscosity decreases combustion efficiency due to the bad fuel injection atomization [14].

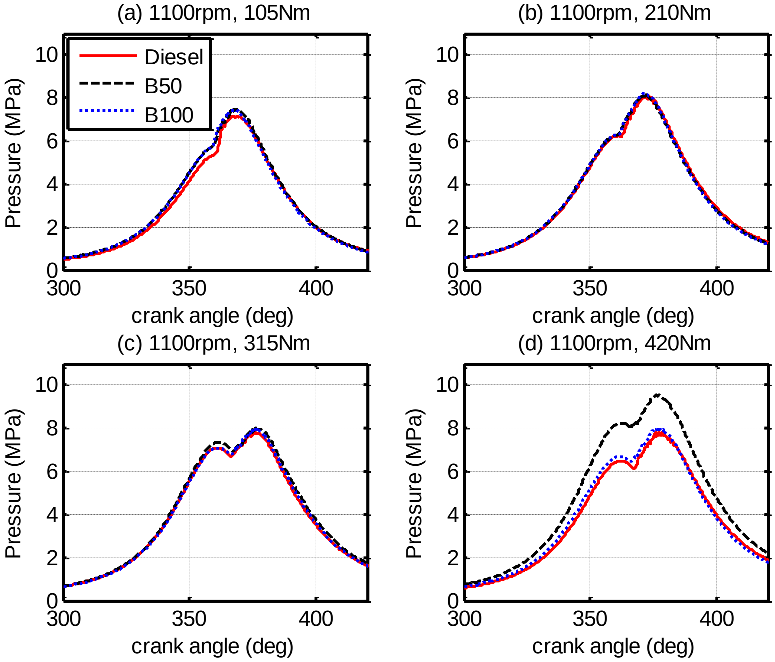


Figure 5. Cylinder pressure at speed of 1100rpm and under different loads.

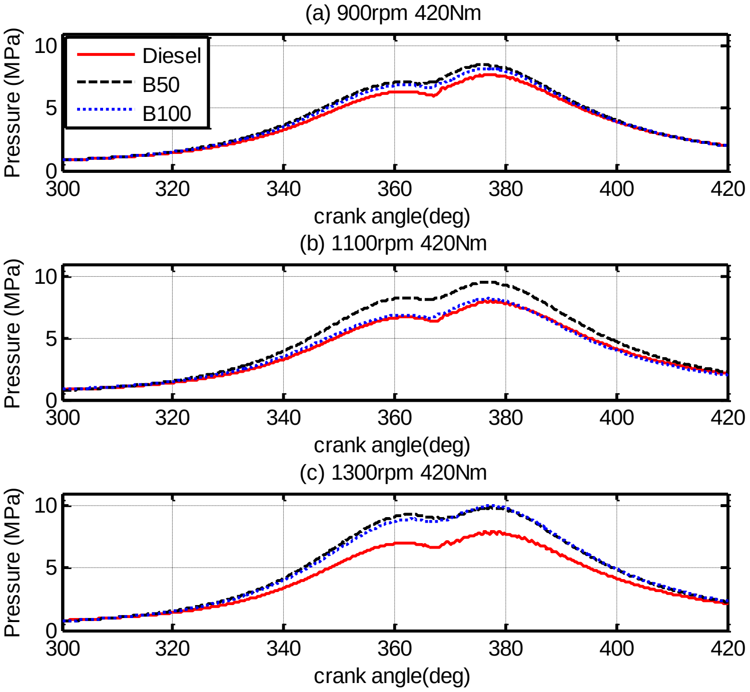


Figure 6. Cylinder pressure at load of 420Nm and under different speeds.

The HRR for diesel, biodiesel and its blends (B50 and B100) at speed of 1100rpm with different loads were illustrated in Figure 7. It can be seen that combustion starts earlier for biodiesel and its blends, and the start point of combustion crank angle decreases with increases in the percentage of biodiesel under all engine operating conditions. From Figure 7 it can be seen that the combustion start angles for pure diesel, B50 and B100 are 358.8°, 357.6° and 357° respectively at the speed of 1100rpm and load of 105Nm. Figure 7 also demonstrates that at lower loads of 105Nm and 210Nm, the premixed combustion HRR is higher for diesel because of the longer ignition delay of diesel which leads to more fuel accumulation in the combustion chamber at the time of the premixed combustion stage, hence lead to higher HRR. However, the HRR of biodiesel was higher under higher loads of 315Nm and 420Nm even with shorter ignition delay. The reasons for this behavior are probably the increased oxygen concentration which provides more oxygen for combustion and the higher viscosity of biodiesel which improves air-fuel mixing and higher quantity of fuel injected for higher premixed burning.

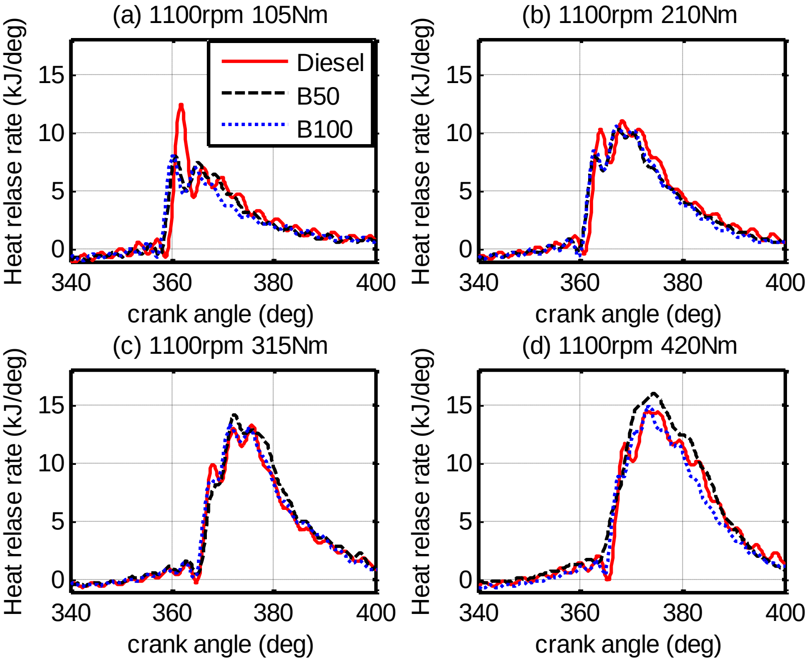


Figure 7. HRR at speed of 1100rpm and under different loads.

Figure 8 demonstrates the acoustic signals at the speed of 1300rpm and different loads of 210Nm, 315Nm and 420Nm fuelled by diesel, B50 and B100. It has been presented based on one complete combustion cycle (720 degree) which is a simple and fundamental way of data presentation in angular domain. It can be seen that the amplitude of the acoustic signals increases with increased engine loads for all types of fuels.

However, it is difficult to see any features between different fuels clearly from Figure 8. This is due to the complex engine noise sources, background noise and their multiplying interference during the engine operating. The main engine noises are the machinery noise and the combustion noise. The engine noise of low-frequency belt is mainly the machinery noise of the oil pump, gear and valve mechanism which radiate from the thin-walled area such as gear cover and valve cover [5]. The combustion noise is located in the high-frequency band of engine noise which radiates from the combustion process referred to in Shu G's analysis of engine noise using coherent power spectrum analysis in [5].

Figure 9 shows the spectrum of acoustic signals after processing by the spectrum subtraction using background noise in a low operating condition with speed of 900rpm and load of 105Nm, and at high operating condition with speed of 1300rpm and load of 420Nm respectively. It presents the amplitudes of acoustic signals increasing with the increasing of the loads and speeds. The main frequency components of the machinery noise in the low-frequency band are related to the firing frequencies and their harmonics according to the engine speeds. Moreover, the amplitudes in the low-frequency band are higher than that in high-frequency band. This is possible due to the resonance of the engine room modes excited by the test engine noise [11].

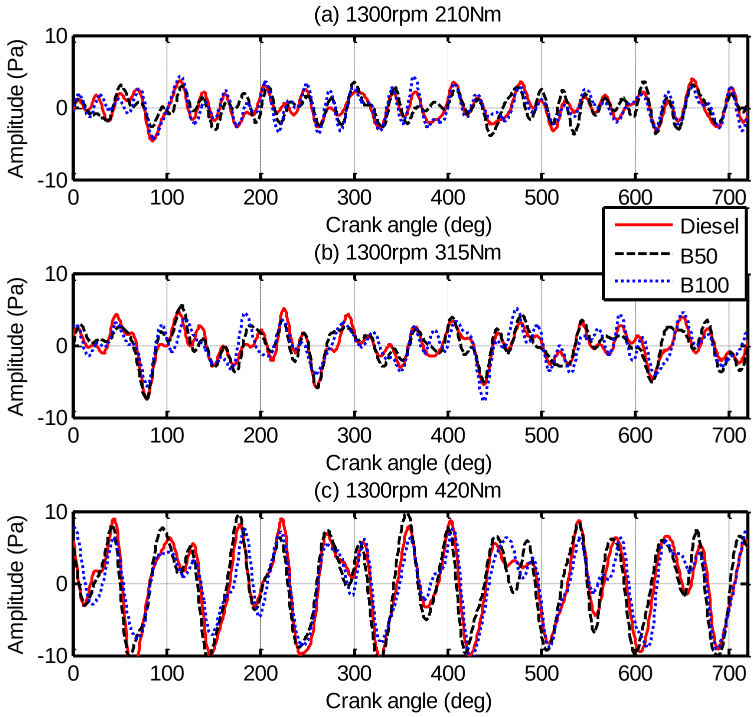


Figure 8. Acoustic signals at speed of 1300rpm and under different loads.

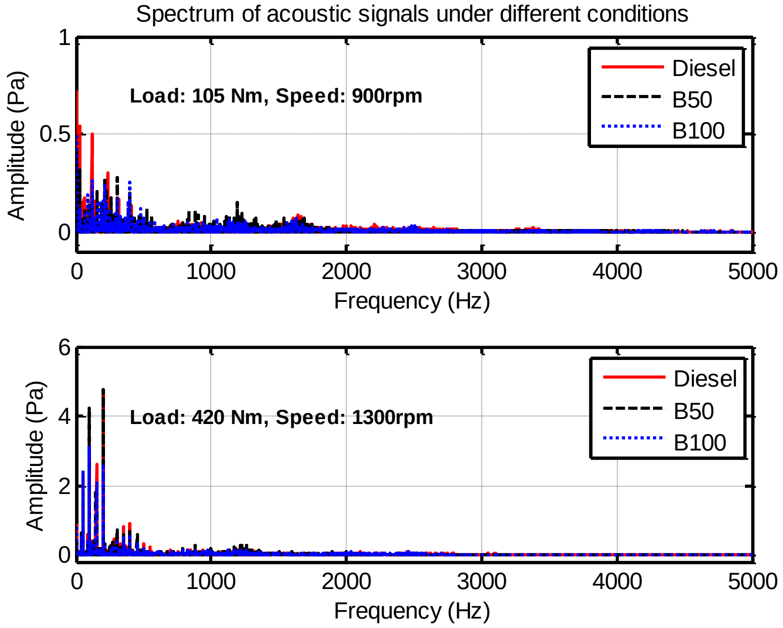
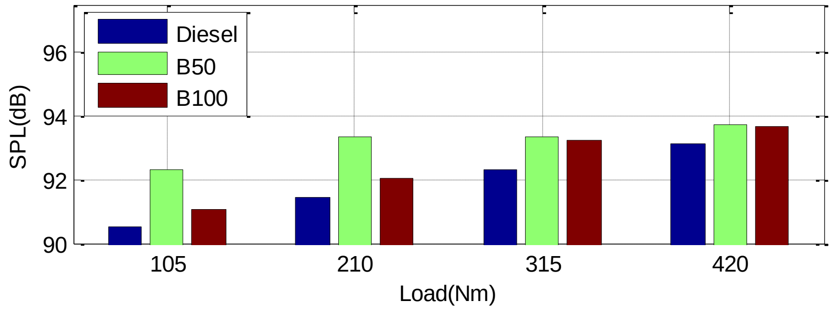


Figure 9. Spectrum of acoustic signals under different conditions.

Figure 10 shows the variations of sound pressure level (SPL) processed by a high-pass filter with the cut-off frequency of 1 kHz under different fuels of diesel, B50 and B100 at different speeds of 900rpm and 1300rpm and loads of 210Nm, 315Nm and 420Nm. It can be seen that the SPL rises with the increase of speeds and loads under all engine fuelled conditions. Moreover, the SPL of engine fuelled by biodiesel and its blends (B50 and B100) were slightly higher than that fuelled by diesel.

However, the SPL of engine fuelled by B50 is higher than that fuelled by B100 under all test engine conditions. This is because of higher peak pressures and heat release rate obtained during the combustion process when the engine was fuelled by B50 according to the combustion parameters analysis. Therefore, it can be concluded that higher pressure produces higher engine vibration and noise.

(a) Variations of SPL at speed of 900rpm



(b) Variations of SPL at speed of 1300rpm

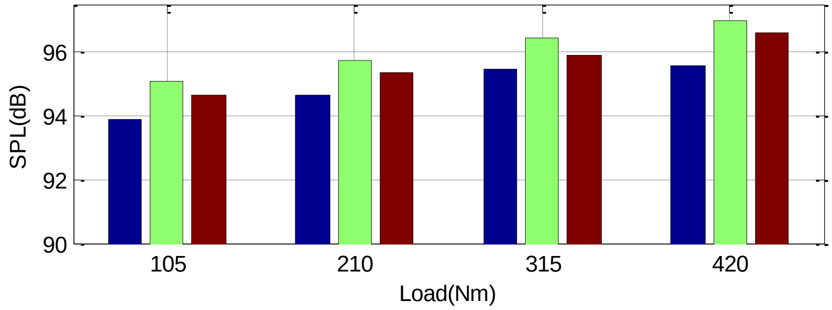


Figure 10. Variations of SPL for different fuels.

5. Conclusion

In this study, an experimental investigation was carried out on the combustion process, vibration and acoustics of a CI engine operating with rapeseed biodiesel and its blends under steady state operating conditions. From the experimental results, it has been observed that the peak cylinder pressure is higher for rapeseed oil biodiesel than that of diesel at all tests due to the higher oxygen content of biodiesel. The peak cylinder pressures for both diesel and biodiesel blends were slightly increased when the engine loads and speeds increased because of longer ignition delay resulting in more fuel available for ignition and more energy released during the premixed combustion stage. The HRR of biodiesel was higher even with shorter ignition delay at higher loads due to the increased oxygen concentration which provided more oxygen for complete combustion.

The amplitude of the engine acoustic signals increased with the increase of engine loads and speeds due to higher engine vibration. The SPL of engine fuelled by biodiesel and its blends were slightly higher than that fuelled by diesel due to higher peak pressures and heat release rate were obtained during the combustion process. Higher in-cylinder pressure and heat release rate produced by combustion process lead to higher noise level accordingly. Hence, the acoustic characteristics of the CI engine will have significant features for engine condition monitoring and supply fuels monitoring.

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