Combustion Diagnostics of a Diesel Engine with Biodiesel Fuels based on Vibro-acoustics and In-Cylinder Pressure Measurements

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ABSTRACT

Biodiesel is one of the alternative fuels which is renewable, environmentally and can be used in diesel engines without modifications. For non-intrusive diagnosis, this study investigates the characteristics of combustion induced vibration and noise in a diesel engine fuelled with biodiesel blends under different operating conditions. The relationship between the engine vibro-acoustics and in-cylinder pressure was investigated based on the analysis of the measured cylinder head vibration, engine acoustics and in-cylinder pressure (peak pressure, pressure rise, and pressure rise rate). It has found that the biodiesel blends result in a slight increase of peak value of in-cylinder pressure when increasing the percentage of biodiesel. The engine running with biodiesel blends has slightly higher vibration, which is more related to the maximum rate of pressure rise which is closely related to the combustion process. In addition, the time domain RMS values of vibration is relating to the maximum rate of pressure rise whereas the RMS of acoustics signals is more relating to peak pressure. These show that vibro-acoustics include good information about combustion. However, more advanced analysis is needed to suppress noise influences for accurately representation of combustions due to different types of fuels.

Keywords- Combustion Process, Diesel Engine, Vibro-Acoustic, In-Cylinder Pressure

Introduction

Considering the significant increase of oil imports and high crude oil prices in recent years, as well as the increasing concerns regarding stable, safe and environmentally friendly energy sources, the promotion of biodiesel used in the transport sector represents a priority on the world political agenda [1]. The in-cylinder pressure measurement is considered to be a very valuable source of information during the development and calibration stages of the engine[2]. The in-cylinder pressure signal can provide vital information, such as peak pressure, pressure rise, pressure rise rate, combustion duration, ignition delay and so on for detecting the combustion processing of diesel engines. Tesfa, B. et al [3], Agudelo, J. et al. [4],Sahoo, P.K. et al. [5], investigated the combustion process for diesel engines fuelled with biodiesel and diesel using the in-cylinder pressure measurement, they found that, the biodiesel blends is alternative diesel engine fuels, without any modifications the biodiesel produced a slightly higher in-cylinder pressure and peak heat release rate than the engine running on normal diesel under all operating conditions. Vibration and acoustic analysis based on vibro-acoustic measurement using accelerometers and microphone is also widely used for diesel engine condition monitoring and combustion diagnosis since accelerometers and microphones are not only easy to install in real applications with non-destructive but also contains more comprehensive information [6]. Engine combustion process with different fuels is one of the most important processes which affect the vibration and noise characteristics as well as the engine durability, there are many different excitation sources of vibration during the internal combustion process in a four-stroke diesel engine. Due to the excitation sources characteristics, the important source is the internal combustion process, which is due to the high combustion pressure of the gas and the reversible forces of the crank mechanism [7].

Many experiments have been performed on investigating the characteristics of vibration and acoustics of diesel engines and combustion process. Ahmad, et al.[8], Jindal. et al.[9], Zhen, D. et al. [10], carried out a study on the combustion process, vibration, and noise analysis of a CI engine operating with biodiesel blends under different operating conditions, the experimental results clearly showed the engine fuelled by biodiesel blends produced slightly higher vibration than those fuelled by diesel fuel. Cheng, Y. et al. [11] investigated the relationship between the cylinder head vibration and the combustion timing. The vibration has a similar trend to the in-cylinder pressure before the peak pressure. The diesel engine experiment results verify the feasibility of the method for identification of the combustion timing based on the vibration acceleration. W. LI. et al. [12] studied the independent component analysis (ICA) applied to engine acoustic signals to identify the engine noise sources, demonstrated that the ICA is powerful in the retrieval of engine noise sources such as combustion and valve operations. Nonetheless, it is obvious from the discussions in his paper that the application of the ICA to other mechanical signals is limited due to its non-Gaussian restriction on the sources.

This study was conducted to investigate the vibro-acoustic measurements for combustion process diagnostics of diesel engines running with diesel and biodiesel blends. Based on a typical diesel engine, it examines the characteristics of vibro-acoustics measured non-intrusively from combustion different biodiesel blends along with corresponding in-cylinder pressures. The relationship between vibro-acoustics and cylinder pressure is then determined for non-intrusive and efficient combustion diagnosis

Engine Combustion Noise and Vibration

The noise of combustion excitation is caused by the pressure of the gas mixture and the combustion process [15, 16]. There are many different excitation sources of vibration during the internal combustion process in a four-stroke diesel engine. These can be divided into two basic types: the first one is due to ignition and the second one is due to mechanical impacts. For diesel engines with low cyclic torque fuel systems, combustion is the main contributor to vibration [11]. The internal combustion engine noise is two parts. The first part is a low-frequency belt is mainly machinery noise from the oil pump, gear and valve mechanism; the second part is a high-frequency belt mainly from the ignited combustion fuel. Diesel engines produce a complex noise, the level and sound quality of which both strongly depend on a particular source: the fuel combustion, which produces the so-called combustion noise. The unpleasant sound signature of diesel engines is actually due to the harsh and irregular self-ignition of the fuel. Therefore, being able to extract combustion noise from the overall noise would be of prime interest. This would allow engineers to relate the sound quality back to the combustion measurement [14, 15]. Moreover, it will allow the diagnosis of combustion to be carried out based on non-intrusive vibro-acoustics measurements.

Experimental Facilities and Test Procedures

To investigate the characteristics of vibro-acoustics of diesel engines fuelled with biodiesels, JCB diesel engine with a four-cylinder, four-stroke, turbocharged, and direct injection engine was used in the test as shown in Figure 1. And its specification of the diesel engine was shown in Table 1. An encoder has been used to measure crankshaft angle and velocity. It was using to calculate the engine speed and record crankshaft angles for converting the measurement of vibro-acoustic and in-cylinder pressure into angular domain.

A charge amplifier was used to conditioning the output of piezo-electric pressure sensor for cylinder pressure measurement. A power CED1401 data acquisition instrument is used to record the cylinder pressure and angular signals whereas a Model YE6261B data acquisition system is used for both CED1401 and YE621B is synchronised by the pulse signals from the encoder vibration and acoustic signals.

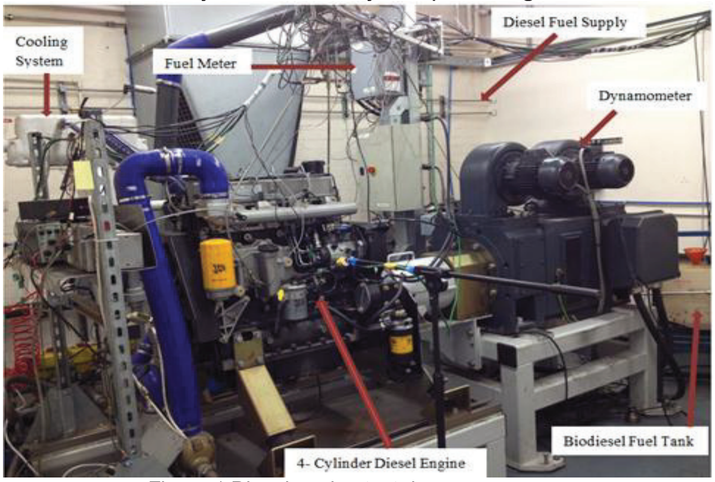

Figure 1 Diesel engine test rig

Table.1. Specification of test rig (Diesel Engine)

Engine Type JCB 444 TCA 74KW	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 torque	425 Nm @ 1300 rpm
Maximum Power	74.2 Kw @ 2200 rpm

During the experiments, the engine was tested with a range of fuel blends and operated at the constant speeds of 1000, 1300 and 1600 rpm and under loads from 100 to 400Nm with an interval of load at each constant speed. The details of the operating conditions are given in Table 2. These conditions will allow the vibro-acoustics to be studied in the full operating conditions. The test engine was fuelled with rapeseed oil (biodiesel, biodiesel blends, and petro-diesel). The details of the operating conditions of fuels are given in Table 3. The temperature was kept constant at 90℃ for all the tests.

Table 2 Engine operation condition

Fuel	Speed	Load. Nm
Pure Diesel	1000,1300 and 1600 rpm	100, 200, 300 and 400 Nm
Biodiesel (B20, B40 and B100)	1000,1300 and 1600 rpm	100, 200, 300 and 400 Nm

Table 3 Percentage of biodiesel blends

Fuel	Diesel	Biodiesel
Biodiesel 20	80 %	20%
Biodiesel 40	60%	40%
Biodiesel 100	0%	100%
Diesel	100%	0%

Waste vegetable oil (biodiesel) and red diesel have been used in this study, while the red diesel is exactly the same as regular diesel in its combustion, performance and emission behaviour, was used in all the tests, it is produced by adding colour additives to normal diesel, the red diesel was selected due to its low fuel tax for off-road engines.

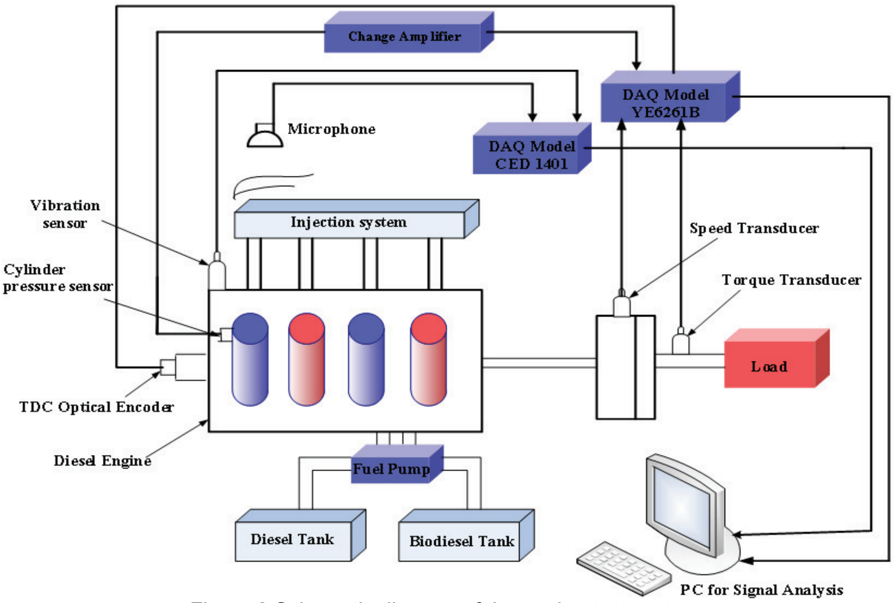

Figure 2 Schematic diagram of the engine test system.

Results and Discussion

In-Cylinder Pressure Measurement

The cylinder pressure profile is most commonly used to study the combustion process [3]. The function of cylinder pressure is related to crank angle for four strokes of the diesel engine cycle, and it has been used to obtain quantitative information about the combustion process. In addition, the peak pressure and maximum rate of pressure rise from cylinder pressure are common indicators of the timing and quality of the combustion.

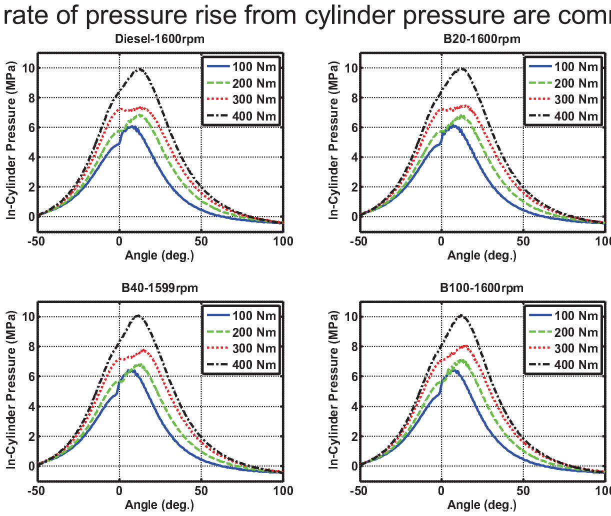

Figure 3 Cylinder pressure signal

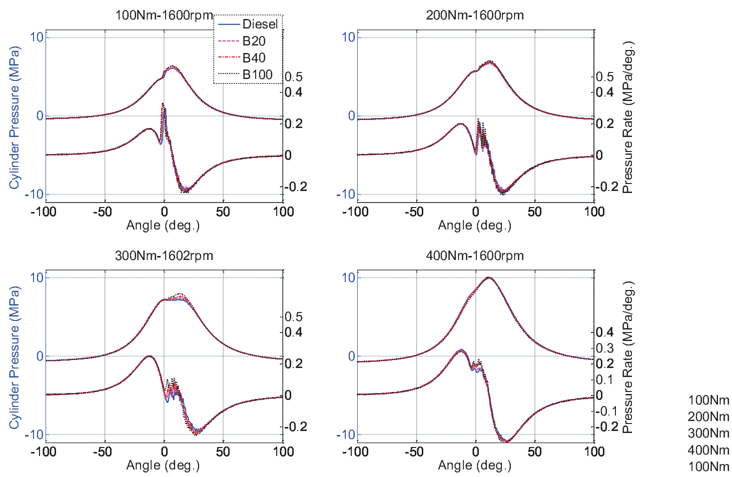

Figure 4 Cylinder pressure signal with pressure rate signal

Figure 3 shows the in-cylinder pressure around TDC of combustion when the engine is tested at speed of 1600rpm and under different loads which is (100, 200,300 and 400Nm) with fuelled diesel, biodiesel and biodiesel blends which is (B20, and B40). It can be seen that, the peak values of the in-cylinder pressures increased alongside the increasing of engine loads for all types of fuels. For more information about the combustion process, the higher peak pressure is observed for biodiesel and biodiesel blends as compared to diesel. This may be due to more advanced fuel injection which results in more initiation of combustion before TDC and the pressure rises quickly.

On the other hand, while running with diesel, due to shorter ignition delay, the combustion starts earlier for diesel compared to biodiesel and biodiesel blends fuel, which is lower peak cylinder pressure in diesel fuel as shown in the Figures 3 and 4. It is observed that, ignition delay is longer for biodiesel (B100) and biodiesel blends (B20, B40) as compared to diesel. Due to longer ignition delay of biodiesel and biodiesel blends compared to diesel, since more fuel is accumulated in the combustion chamber which leads to higher peak pressure at the time of premixed combustion stage.

From Figures 5, it can be seen that, the peak cylinder pressure for diesel, biodiesel and biodiesel blends increased when the engine loads and speeds increased. The maximum peak pressure and maximum pressure rate can be calculated according to the measured in-cylinder pressure under different fuels, loads and speeds as shown in the Figures 5 and 6. It can be that the pressure rise rates decreased with the increasing of engine loads, and increased with the increasing of engine speeds. Moreover, the reason of why biodiesels can generate higher peak in-cylinder pressures than that of pure diesel.

However, a possible explanation for B100 has lower peak in-cylinder pressure than that of B40 in Figures 5 and 6 might be the viscosity of B100 is higher than that of B40 because a higher viscosity of biodiesel can lead to bad fuel injection atomization that may affect the combustion efficiency.

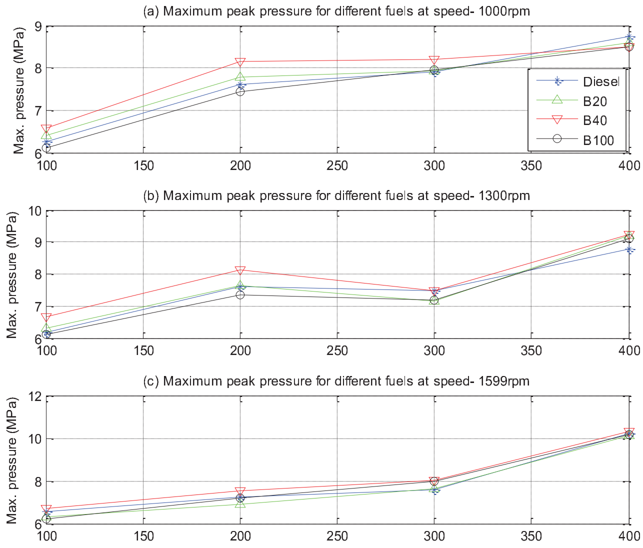

Figure 5 Peak pressure signal

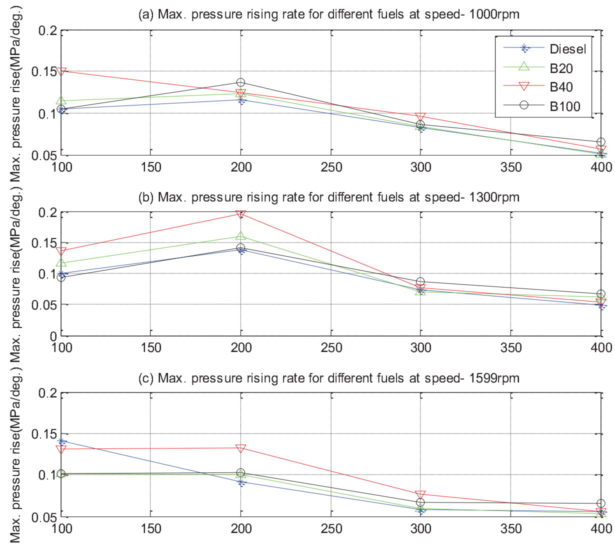

Figure 6 Maximum rate of pressure rising

Vibration and Acoustics Analysis

To study the vibration signal related to the engine combustion process, the cylinder head vibration signals are presented in the crank angular domain as shown in Figure 7, for different operating and fuel conditions. The vibration signal is related to combustion process at speed of 1600rpm and under different loads. The result observed that the amplitude of vibration is decreased with increasing of the loads for all types of fuels. The RMS values of vibration signals are calculated from raw vibrations signals. Figure 8 shows the RMS values with load variation at different speed, the amplitude of RMS cylinder head vibration decreased alongside the increasing of engine loads. This indicated the same trend results with the cylinder pressure rise rate as shown in the Figure 6.

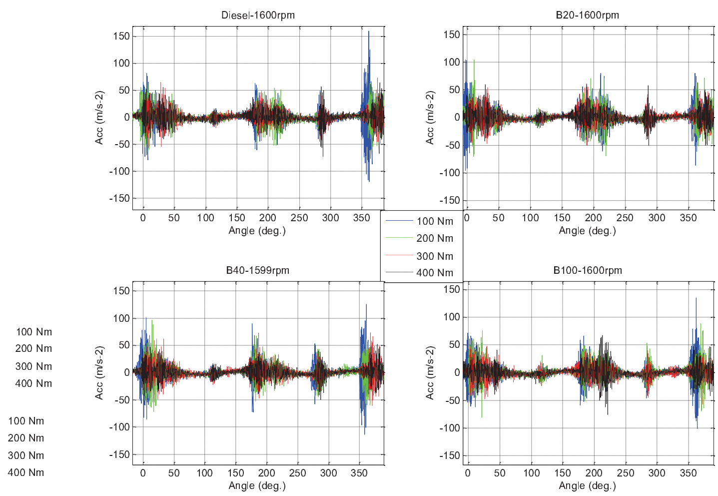

Figure 7 Cylinder head vibration signals

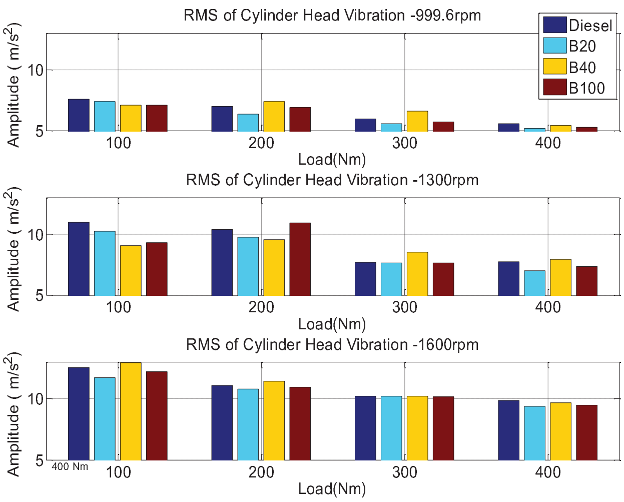

Figure 8 RMS of cylinder head vibration signal

The methods are applied to investigate the characteristics of engine noise aimed to extract useful features for combustion diagnostics. The acoustic signal was also obtained during the tests for combustion diagnostics of diesel engines; the acoustic technique is useful in understanding the combustion noise [12].

From the Figure 9, it can be seen that the amplitude of the acoustic signals increase with the increasing engine loads under all types of fuels. To see more details of the amplitude variation, the root mean square RMS is calculated from acoustics signals for a quantitative representation of the time domain signals. Figure 10 which revealed that the amplitude of noise increases alongside increasing speeds and loads for all fuel types. This indicated the same trend results with the variation peak pressure as shown in the Figure 5, that's signal related to engine process closely.

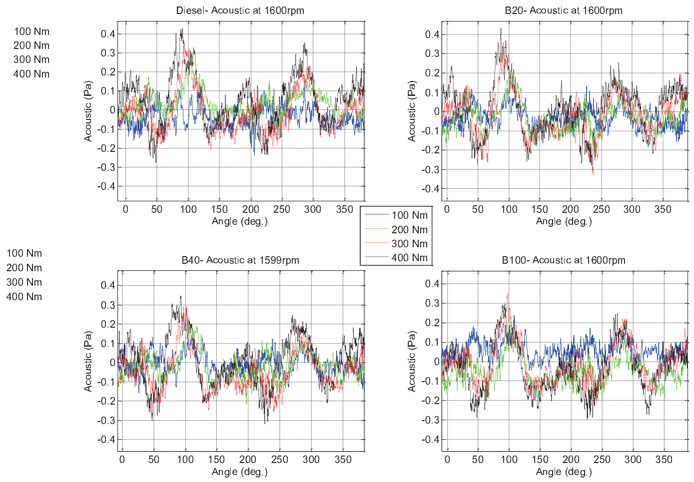

Figure 9 Acoustic signal

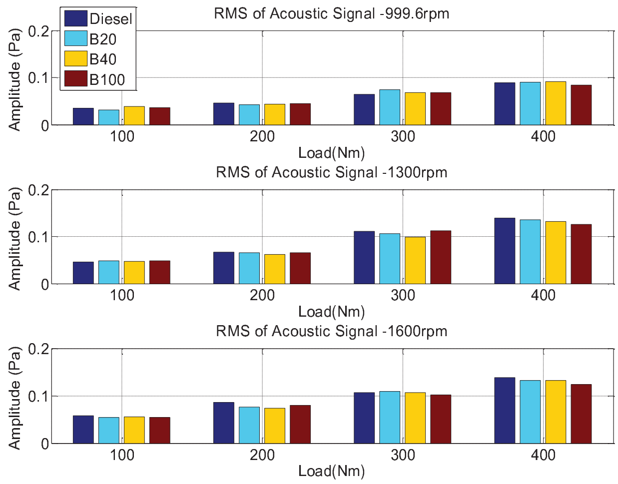

Figure 10 RMS of acoustic signal

Experimental result proved that, when the speed of the engine increases, the amplitude increases dramatically for vibro-acoustic signals, and RMS of acoustics for all fuel types used in the engine tests. From the previous study it can be noted that the relationship between these variables are proportional. However, the maximum rate of pressure rise, RMS of vibration signal and vibration signal, all have inversely proportional relationships with acoustics and cylinder pressure, when the load is increased in all engine tests.

The reason for this observation is that the vibration of cylinder head is related to the magnitude of the changing rate of cylinder pressure, and the changing rate of in-cylinder pressure was decreased alongside the increase of the load. Whereas the acoustic measurement observed that, it is not only containing the combustion reduced noise. Consequently the acoustic includes the noise from engine exhaust, engine intake and outlet valves and injection system. Therefore, the measured engine acoustic signal was not only related to the cylinder head vibration and combustion process due to the effects of other noise sources. It's related to the variation peak pressure.

As the result shown that, the engine noise and vibration levels slight increases with the addition of bio-diesel compared with diesel fuel, the reason for this increase might be the engine miss-firing and knocking at higher bio-diesel portions. This may have occurred because of some deposits on the fuel injector. If these deposits are drawn into the engine it is too viscous to pass through the engine's fuel.

Conclusions

This study was carried out for measurements of surface vibration, airborne acoustics and in-cylinder pressure of diesel engines operating under different operating conditions and fuels. The main purpose was to investigate effective measurement method for combustion diagnostics through analysing the interaction between the in-cylinder pressure and engine vibration and acoustic based on the experimental study. The main results are summarized as follows:

- The peak pressure increases marginally when increasing the percentage of biodiesel.
- The peak values of in-cylinder pressure increases with the increasing engine loads and speeds for all types fuel using in the test (Diesel, Biodiesel, B20 and B40).
- The RMS values of engine vibration decreased with the increasing of engine loads due to the maximum rate of pressure rise decreased with the increased engine loads. So the engine vibration is more relating to the maximum rate of pressure rise.
- Acoustic signals in the time domain and RMS values relates more to the peak pressure signal, Because both of them increases with load and speeds.

- Effective methods need to be developed to extract the combustion reduced noise and vibration from the measured engine acoustic signals for more detailed combustion diagnostics.

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