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Data-driven Approach for Condition Assessment of a Diesel Engine Powered with Various Biodiesels

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Abstract

In recent years, various biodiesels have been developed to decrease pollutant emissions from compression ignition engine. However, the current research focuses on reducing the pollutant components without considering the mechanical vibration that occurred due to the changes in fuel properties such as viscosity, calorific values, density, and bulk modulus. It is important to explore the relationships between fuel properties and engine vibration. Mechanical vibration could cause power loss and affect the lifetime of the engine. In this investigation, a lister-pitter 3-cylinder diesel engine was used to analyse the mechanical vibration of three different fuels including diesel, waste cooking oil biodiesel (WCOB), and lamb fat biodiesel (LFB). The high-frequency vibration sensors were mounted on the cylinder head to monitor and assess the vibration performance. The vibration data were collected under various operating conditions including varying engine speed from 1500 to 2000 rpm and varying engine loads ranging from 20% to 100%. Three practical assessment features of vibration signals were investigated to evaluate the vibration characteristics. The experimental results clearly demonstrate the relative relations between vibration, and fuel properties of the tested fuels, used in the diesel engine. Compared with fossil diesel fuel, the total vibration level decreased by 17% and 23% for WCOB and LFB fuels, respectively. The engine performance powered with LFB and WCOB are better than diesel's effect on both vibration and friction power (FP) perspective. Superior lubricity and viscosity of WCOB and LFB is the main reason causing good vibration performance.

Introduction

The internal combustion (IC) engine has been widely used in many engineering applications, including automotive, railways, power stations, etc. As carbon neutral raised up in recent years, one of the directions is to design more environmentally friendly machines and systems. However, for the current widely on service machines, such as diesel engines, it is urgent to reduce the pollutant without redesigning, refurbishment or remanufacturing them. Instead of improving the engine structure, developing alternative fuels would be a more reasonable way [1].

Biodiesel has been proposed as an alternative fuel for diesel engines, which are generally made from vegetable oils or animal fats [2]. It is an environmentally friendly fuel because of the high oxygen content and few aromatic compounds and sulfur [3, 4, 5]. This kind of sustainable renewable fuel plays an important role in the world's carbon neutrality by significantly reducing exhaust emissions including particulate matter, hydrocarbons and carbon monoxide [6]. However, it should also be necessary to consider its effect on the lifecycle of the diesel engine. It is not a sustainable option to sacrifice the service life of the mechanical machine by changing to biofuel. The reason is disposing of the end-of-life diesel engine will cause more complicated pollutants which is absolutely not cost-efficiency [7]. Therefore, it is expected that the engine with biofuel could work as long as the engine with diesel, or even has a longer lifetime.

As one of the most effective data-driven approaches to condition monitoring and assessment, vibration measurement and analysis have been proposed and verified as the most effective way to evaluate the lifetime of mechanical components of diesel engines [8, 9]. Vibration signal has been collected and stored for many industrial applications through the IoTs equipment and industrial network [10, 11, 12]. Since the requirement of high-frequency sampling for the vibration, there will be massive original vibration data for the engine's condition monitoring and assessment system. Since the requirement of high-frequency sampling for the vibration, there will be massive original vibration data for the engine's condition monitoring and assessment system. It is not possible to store all the original signals in the industrial system throughout the life cycle of the machine. Therefore, investigating and extracting the effective features which could represent the engine operating condition is a reasonable way for solving this problem [13]. There is no way to avoid vibration in an IC engine because the vibration is mainly caused by the cyclic nature of the combustion process. As the heart of the mechanical machine, abnormal or excessive vibrations will not only damage the engine but also be harmful to human health [14]. Meanwhile, the engine knock may decrease the thermal efficiency, thus declining the good enduring characteristics of an efficient biofuel [15]. Therefore, the effects of vibration on the IC engine working on various biofuels have obtained an increasing interest to be investigated by many researchers around the world.

Li et al. [16] built a simulation model based on the finite element modelling (FEM) method to study the vibration response of an IC engine fueled with biodiesel. Grajales et al. [17] proposed a fault diagnosis method for engines running with different fuel blends by using the spike energy spectrum to analyse the vibration signal. Uludamar et al. [18] used an artificial neural network to evaluate the engine vibration level of a hydroxyl gas generator which is derived by a diesel engine under various biodiesel fuel conditions. Satsangi et al. [19] conducted a comprehensive investigation of different diesel/n-butanol blends. The experiments have measured the noise of combustion, exhaust, and the whole engine, the vibration of the engine, emissions, engine pressure, and fuel consumption. Yang et al. [20] studied the general vibration characteristics of blended petro-diesel and Fischer-Tropsch diesel fuel on a compression ignition engine. Mirnezami et al. [21] applied biodiesel fuel on a riding two-wheel power tiller and studied the effects on the vibration envelop curves. Jaikumar et al. [22] investigated the combustion and vibration characteristics of a diesel engine with biodiesel and alcohol blends under variable compression ratio situations. Wrobel et al. [23] compared the vibroacoustic properties of diesel and biofuel under varying speeds and loads. From the above literature, it is concluding that most of the research was conducted on diesel/biodiesel blends, biodiesel/alcohols blends to analyses the relationship between fuel properties and engine vibration. When biodiesel was blended with diesel or alcohols, the viscosity and density were reduced, results lower vibration. The novelty of the current research article is to analysed the effect of 100% biodiesels with different fuel properties on engine vibration, which has not been investigated yet. Meanwhile, the RMS has been applied to evaluate vibration performance of biofuels in the most of current studies. There is very limited research work investigate and exploring other effective features.

To fulfil these research gap, we proposed an effective feature selection method for two new 100% biodiesels, including waste cooking oil biodiesel (WCOB) and lamb fat biodiesel (LFB). The vibration collected from the diesel engine is powered by the diesel, WCOB, and LFB. The engine was operated under various loads and speeds condition. Comprehensive vibration comparisons have been carried out for all the collected vibration signals. Frictional losses were also calculated and compared with the fuel types and vibration characteristics.

Materials and methods

Material

Based on their availability on the local market, two alternative oil feedstocks, such as waste cooking oil (WCO) and lamb fat (LF) were selected. While lamb fat was obtained from a local butcher's, WCO was obtained from Aston University cafeteria. The components required to make biodiesel, such as sulfuric acid (H_2SO_4), potassium hydroxide (KOH), and methanol (CH_3OH, 98% purity), were purchased from Sigma-Aldrich UK.

Biodiesel production and characterization

The large lamb skin was divided into smaller pieces and baked for one hour at 100°C. Later, the separated lamb fat (PF) was put into a jar for storage. Before the process, the WCO was filtered through a sock filter to get rid of sediments. Both feedstocks underwent transesterification to become biodiesel fuels [24]. The base catalyst, potassium hydroxide (KOH), is utilized with a 4:1 molar ratio of methanol to oil [24]. A mechanical stirrer was used to add the KOH-methanol combination to the heated oil at 60°C and agitate it for an hour. Following the procedure, the liquid was transferred to a separating device to separate the biodiesel and glycerol. In a procedure known as "biodiesel washing," dissolved catalyst and soap produced during the chemical reaction were removed using hot distilled water (80°C). The biodiesel fuel sample was then left overnight to allow the water drops to condense [24]. The sample was heated at a constant temperature of 100 °C for an hour to remove the moisture content [24]. In the fuel characterization laboratory at Aston University UK, prepared biodiesel fuel was characterized. Table 1 displays the tools and benchmarks used for fuel characterization. facilities. The fuel qualities that were measured were compared to the biodiesel standards listed in Table 2.

Table 1. List of the instruments used for characterization.

Fuel Properties	Name of the Instrument	Standards
Density	Pycnometer	ASTM D4892-14
Kinematic viscosity	Cannon-Fenske viscometer	ASTM D4603-18
Calorific Value	Bomb Calorimeter	ASTM D240-19
Acid value	Titration method	EN 14214
Flash Point	Closed cup	EN 3679

Table 2. Physical characteristics of the tested fuels.

Fuel Properties	Acid value (mgKOH/g)	Density (kg/m3)	Calorific value (MJ/kg)	Viscosity (cSt)	flash point (℃)
Diesel	0.02	835	45.312	2.65	65
LFB	0.3	887	39.621	3.45	135
WCOB	0.45	882	38.821	4.16	165
ASTM D6751	>0.5	800-950		1.9-6.0	min 93
EU 14214	>0.5	860-900		3.5-5	min 101

Engine experimental test rig

The Lister Petter Alpha series water-cooled, three-cylinder indirect injection (IDI) diesel engine was used (Figure 1). Table 3 shows the test engine's specifications. While the torque changed, the engine was controlled to keep its speed at 1500 rpm. For this investigation, six engine speeds were used: 1500, 1600, 1700, 1800, 1900, and 2000 RPM. To apply the load on the engine, a Froude Hofmann AG80HS eddy current dynameter was employed.

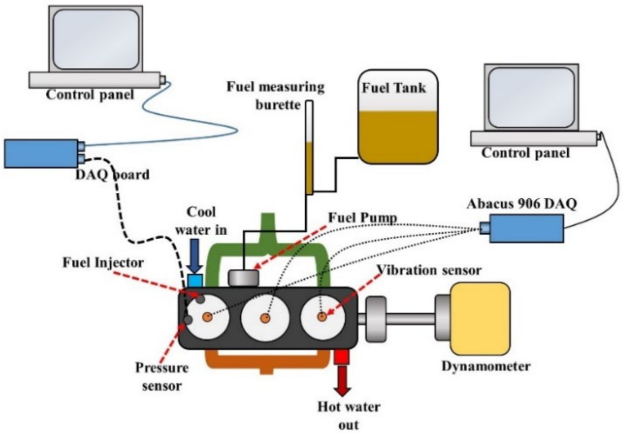

Figure 1. The overall system of test diesel engine.

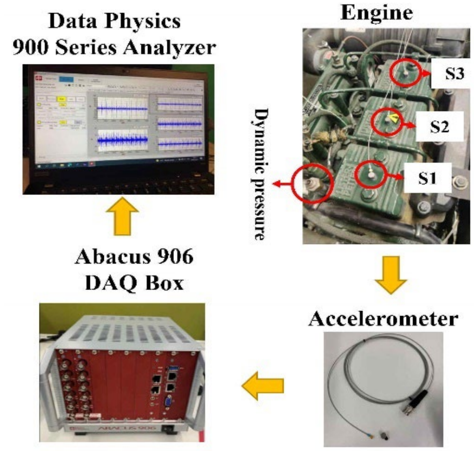

Figure 2. The vibration measurement system for engine.

Table 3. Engine specifications.

Specification	
Engine model & manufacture	LPWS Bio3, Lister Petter, UK
Number of cylinders	3
Bore/stroke	86x88 mm
Cylinder volume	1.395 litres
Rated speed	1500 rpm
Engine power	9.9 kW
Fuel injection timing	20 deg. bTDC
Compression ratio	22

Vibration Measurement System

The setup of the vibration measurement system is shown in Figure 2, which consists of an engine, accelerometer, Data Acquisition (DAQ) box, and SignalCalc 900 Series software. The technical specifications of the DAQ box and Accelerometers used in this work are shown in Table 4. In this work, we installed 3 piezoelectric accelerometers on the head of the 3 cylinders. The vibration signals are collected by the DAQ box, then the SignalCalc 900 software would record and show the original waves. In the engine, a dynamic pressure sensor was installed inside the first cylinder. Therefore, its vibration performance should be different from the other 2 cylinders. The detailed comparison results and analysis can be found in the experimental section.

Table 4. Technical specifications of DAQ Hardware and Piezoelectric accelerometer.

Specification	
DAQ Hardware	Abacus 900 Series hardware platform: Up to 216 k Samples/s for 80 kHz of alias-free bandwidth. 24-bit analog-to-digital conversion with up to 150 dB dynamic range. Channel-to-channel phase accuracy of better than 0.5 deg at 40 kHz.
Piezoelectric accelerometer	A/124/E Miniature Piezo-Tronic IEPE Accelerometer: Voltage Sensitivity ±10%: 100mV/g Frequency Response (±5%): 1Hz – 11kHz Cross Axis error: ⩽5% Temperature Range: -55/+125°C Saturation limit g: 50g Broadband resolution grms: 0.002 Base Strain Sensitivity: ⩽0.001g/μ strain

Data Acquisition Procedure

The accelerometers 1, 2, and 3 were located on the different cylinder heads to measure vibration in the vertical direction. The sampling frequency is set to 25.6 kHz and the data collection duration for each sample is 1 second. For each fuel type, the vibration signals are collected with different loads and speeds. The detailed testing conditions are shown in Table 5.

Table 5. Detailed testing conditions.

No.	Load	Speed	Abbreviation
WC 1	20%	1500 RPM	S15, L0.2
WC 2	40%	1500 RPM	S15, L0.4
WC 3	60%	1500 RPM	S15, L0.6
WC 4	80%	1500 RPM	S15, L0.8
WC 5	100%	1500 RPM	S15, L1.0
WC 6	100%	1600 RPM	S16, L1.0
WC 7	100%	1700 RPM	S17, L1.0
WC 8	100%	1800 RPM	S18, L1.0
WC 9	100%	1900 RPM	S19, L1.0
WC 10	100%	2000 RPM	S20, L1.0

Effective Features Selection

The experimental design for measurement of vibration was considered as 3 types of fuel (diesel, WCOB, LFB) under 10 different working conditions. Following the previous research [25], we initially selected ten features, which are shown in Table 6, using identifying the difference in response to vibration signals of different fuel types and operating conditions. However, not all the features are highly related to the change in working conditions. Therefore, the main goal of feature selection is to discard irrelevant and redundant features which didn't present the response of signal significantly. The good feature should be monotonically correlated with the working condition changes. In this work, we follow the literature [26] to use correlation and monotonicity indicators to determine the top 3 sensitive features.

The correlation indictor is calculated as follows:

$$Corr = \frac{\left|\sum_{t=1}^{T}(F_t-\overline{F})(l_t-\overline{l})\right|}{\sqrt{\sum_{t=1}^{T}(F_t-\overline{F})^2\sum_{t=1}^{T}(l_t-\overline{l})^2}} \tag{1}$$

where F_t and l_t are the feature and time values of the t-th observation sample. T is the length of the samples during the lifetime.

The monotonicity indictor is calculated as follows:

$$\mathrm{Mon} = \left|\frac{dF>0}{T-1} - \frac{dF<0}{T-1}\right| \tag{2}$$

Where dF is the differential of feature time sequence, T is the length of the feature.

Then, these two indictors can be combination as the criteria indictor for selecting the features, which are defined as follows:

$$Cri = \frac{Corr + Mon}{2} \tag{3}$$

Table 6. Definition of statistical features.

	Method	Equation
F1	Mean	$\frac{1}{n}\sum_{i=1}^{n} x_i$
F2	RMS	$\sqrt{\frac{1}{n}\sum_{i=1}^{n} {x_i}^2}$
F3	Skewness	$\frac{\frac{1}{n}\sum_{i=1}^{n}(x_i-\bar{x})^3}{[\frac{1}{n}\sum_{i=1}^{n}(x_i-\bar{x})^2\,]^{3/2}}$
F4	Peak to Peak	Max(x) – Min(x)
F5	Variance	$\frac{1}{n}\sum_{i=1}^{n}(x_i-\bar{x})^2$
F6	Entropy	$-\sum_{i=1}^{n} P(x_i)\, log_2[P(x_i)]$
F7	Crest factor	$\frac{\mathrm{Max}(\lvert x_i\rvert)}{\sqrt{\frac{1}{n}\sum_{i=1}^{n} {x_i}^2}}$
F8	Wave factor	$\frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}\lvert x_i\rvert^2}}{\frac{1}{n}\sum_{i=1}^{n}\lvert x_i\rvert}$
F9	Impulse factor	$\frac{Max\lvert x_i\rvert}{\frac{1}{n}\sum_{i=1}^{n}\lvert x_i\rvert}$
F10	Margin factor	$\frac{Max\lvert x_i\rvert}{(\frac{1}{n}\sum_{i=1}^{n}\sqrt{\lvert x_i\rvert}\,)^2}$

Results and Discussion

In this work, we selected two accelerometers (S1 and S2) to conduct the analysis of engine vibration of various biofuels, which are installed on cylinders 1 and 2 as shown in Figure 2. This is because the installation of a dynamic pressure sensor in cylinder 1 will make a hole in the cylinder head which make the structure of cylinder 1 different to others. We believe this will affect the vibration. Therefore, we take cylinder 2 as a benchmark for comparison. In the following section, we first carry out the general vibration analysis of diesel fuel in different working conditions. Based on these vibration signals, we determine the effective features based on the criteria indicator Cri. Then, the effects of diesel, WCOB and LFB under varying loads and speeds have been analyzed. Finally, comprehensive vibration comparisons with the engine PF have been conducted.

Original Vibration Signal Analysis

Figure 3 shows the vibration signal of diesel fuel under varying loads and speeds. We plot one vibration sample (1s) at each working condition, and the y-axis labels are the amplitude (m/s^2). It is obviously found that there are many strikes which are exactly caused by engine combustion. The amplitude of these strikes has been increased with the speed increase, while the load has a limited effect on the strike amplitude. Then, we use Fast Fourier Transform (FFT) technique to transfer the original time domain vibration to the frequency domain signal, which is shown in Figure 4. The results show that the strike energy is focused around 4200 Hz and 5600 Hz. This is because the amplitude of the vibration spectrum around these two frequencies significantly changes with the working speed increase. After the general vibration analysis, we could find that the vibration level of the engine is mainly influenced by engine combustion. From the original time domain vibration signal and frequency domain spectrum, it is not easy to evaluate the vibration performance using the general analysis method. Therefore, the quantitative assessment is necessary for in-deep comparison and analysis.

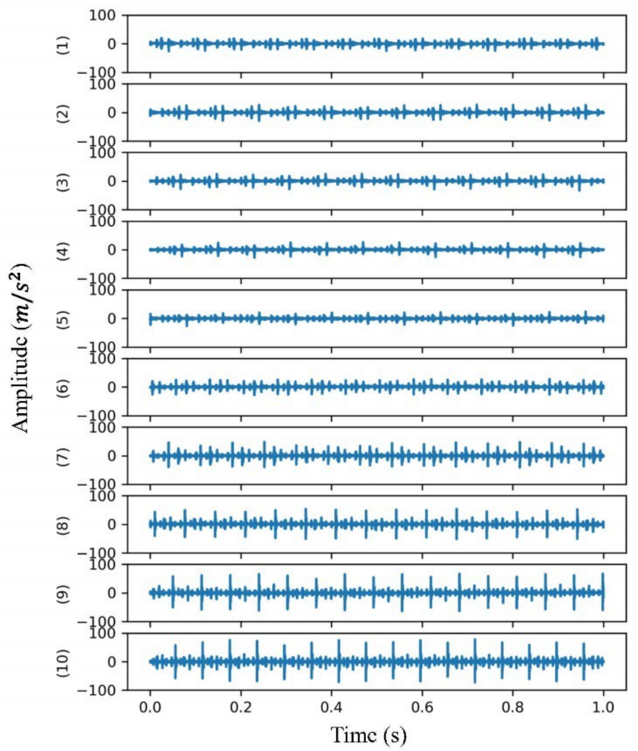

Figure 3. Vibration signal of diesel at different condition, (1) S15, L0.2; (2) S15, L0.4; (3) S15, L0.6; (4) S15, L0.8; (5) S15, L1.0; (6) S16, L1.0; (7) S17, L1.0; (8) S18, L1.0; (9) S19, L1.0; (10) S20, L1.0.

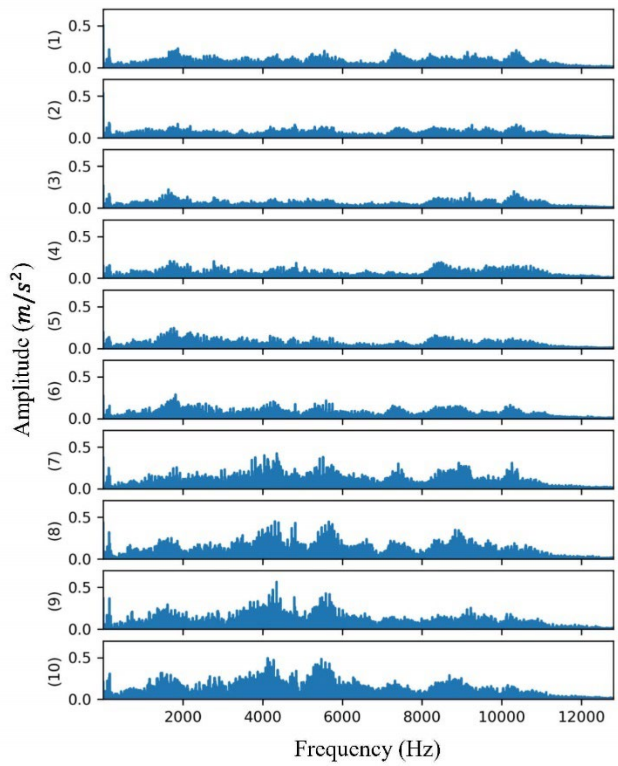

Figure 4. FFT of diesel vibration signal at different condition, (1) S15, L0.2; (2) S15, L0.4; (3) S15, L0.6; (4) S15, L0.8; (5) S15, L1.0; (6) S16, L1.0; (7) S17, L1.0; (8) S18, L1.0; (9) S19, L1.0; (10) S20, L1.0.

Effective Features Selection

In order to implement quantitative assessment, we need to study and determine which kind of features are suitable for this research. Therefore, we take the diesel fuel vibration signal as an example to select the effective features. We collect one sample with 30 s intervals, 10 samples have been recorded for each working condition. Figure 5 shows the vibration signal of diesel fuel with varying working conditions. The amplitude changes a little when the speed keeps 1500 RPM and the load increase from 20% to 100%. However, it will significantly increase with the speed running up. As shown in Table 6, ten statistical features have been calculated at different working conditions. The Results are shown in Figure 6. The x-axes range from 1 to 100 seconds because there are 10 samples in each working condition and the testing has been conducted at 10 working conditions.

It is obvious that three features including F2: RMS, F4: Peak to Peak, and F5: Variance are highly related to the varying trend of the original vibration. Based on the proposed effective feature selection method, the criteria indicators Cri of ten features have been calculated in Figure 7. The quantitative results verified that F2, F4 and F5 are the top 3 effective features which mean they are highly related to the varying working conditions and have good monotonicity. The F2 (RMS) has been used in many related research works [12-19] as the only measurement metric. However, we find that F4(Peak to Peak) and F5 (Variance) are also effective to reflect the vibration characteristics. Intuitively, the F2 (RMS) represents the overall vibration energy, F4 (Peak to Peak) represents the peak amplitude of every strike in the cylinder, and the F5 (Variance) represents the degree of difference between the strike and other vibrations. We could only identify the change of the whole vibration signal while combining with the F4 (Peak to Peak) and F5 (Variance) we could distinguish where the change comes from.

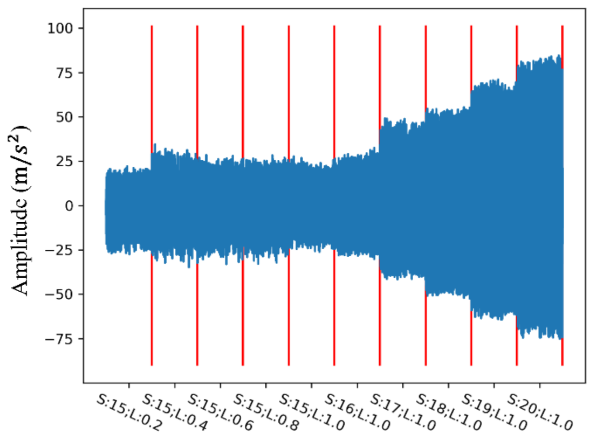

Figure 5. Original vibration of diesel fuel at different condition.

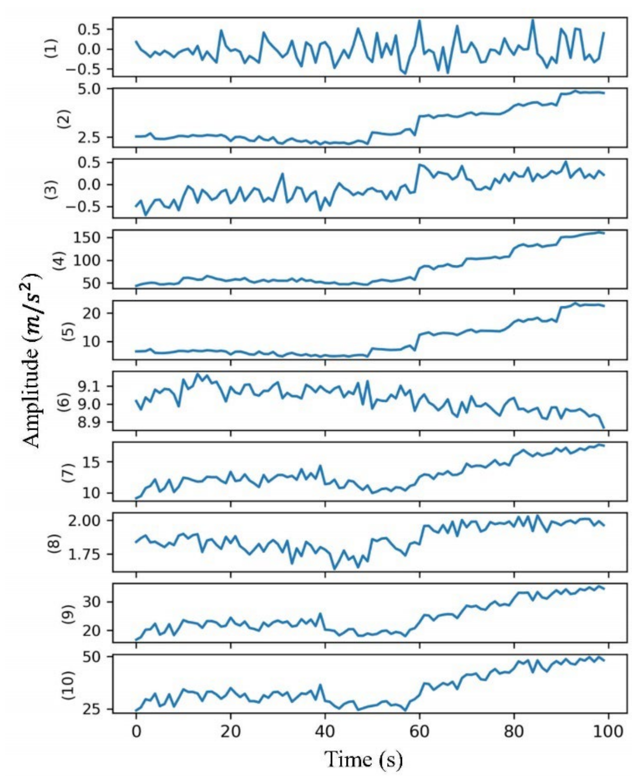

Figure 6. Features extracted from original vibration signal of diesel fuel, (1) F1: Mean; (2) F2: RMS; (3) F3: Skewness; (4) F4: Peak to Peak; (5) F5: Variance; (6) F6: Entropy; (7) F7: Crest factor; (8) F8: Wave factor; (9) F9: Impulse factor; (10) F10: Margin factor.

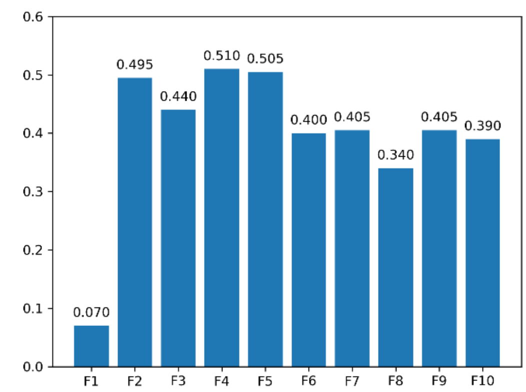

Figure 7. Cri of 10 features of diesel fuel.

Effects of Engine Load on Vibration

We analysed the effects of load on vibration for three types of fuel (Diesel, WCOB and LFB) using selected three features (RMS, Peak to Peak and Variance). The results of S1 and S2 are shown in Table 7 and Table 8, respectively. For cylinder 1, LFB obtains the best vibration performance on three features, WCOB takes second place, and diesel performs worst. The vibration performance acts worst under a load of 40% and best under a load of 100%. A similar phenomenon could be found for WCOB and LFB of cylinder 2. For the diesel fuel of cylinder 2, the vibration level performs highest under a load of 20% and lowest under a load of 100%. The overall vibration level of cylinder 2 is higher than cylinder 1's for all three types of fuel and varying loads.

Table 7. Results of S1 (cylinder 1) with different loads.

	Fuel Type	Load				
		20%	40%	60%	80%	100%
RMS	Diesel	2.53± 0.08	2.58± 0.07	2.42± 0.12	2.27± 0.08	2.23± 0.06
	WCOB	2.22± 0.12	2.58± 0.07	2.46± 0.09	2.22± 0.07	2.02± 0.07
	LFB	1.97± 0.12	2.02± 0.06	2.09± 0.05	2.02± 0.04	1.89± 0.06
Peak to Peak	Diesel	49.77 ±3.14	60.42 ±3.28	55.52 ±3.03	55.48 ±1.70	47.83 ±3.18
	WCOB	39.87 ±2.62	55.33 ±3.71	53.06 ±2.92	45.32 ±2.24	38.91 ±2.18
	LFB	38.00 ±5.29	38.94 ±3.39	42.39 ±2.38	40.01 ±1.59	35.26 ±1.97
Variance	Diesel	6.31± 0.37	6.56± 0.30	5.75± 0.54	5.09± 0.32	4.87± 0.22
	WCOB	4.84± 0.50	6.60± 0.34	5.95± 0.42	4.82± 0.30	4.02± 0.25
	LFB	3.80± 0.46	3.99± 0.28	4.30± 0.20	4.02± 0.14	3.47± 0.18

Table 8. Results of S2 (cylinder 2) with different loads.

		Load				

	Fuel Type	20%	40%	60%	80%	100%
RMS	Diesel	2.98±0.09	2.81±0.09	2.58±0.12	2.41±0.05	2.24±0.06
	WCOB	2.33±0.14	2.86±0.11	2.43±0.09	2.19±0.04	2.00±0.06
	LFB	2.32±0.19	2.94±0.10	2.67±0.11	2.38±0.05	2.15±0.05
Peak to Peak	Diesel	72.49±3.37	61.98±2.29	54.72±3.51	47.65±1.51	39.15±1.89
	WCOB	47.24±4.00	61.24±2.68	48.42±3.18	40.07±1.58	33.70±1.91
	LFB	46.39±6.66	60.89±2.69	53.00±3.47	45.24±2.86	39.34±2.32
Variance	Diesel	8.82±0.52	7.84±0.48	6.65±0.61	5.75±0.25	4.97±0.25
	WCOB	5.43±0.67	8.18±0.61	5.90±0.46	4.79±0.19	3.97±0.25
	LFB	5.40±0.89	8.63±0.59	7.09±0.58	5.61±0.22	4.55±0.15

Effects of Engine Speed on Vibration

The effects of engine speed on vibration performance under different fuels of cylinders 1 and 2 have been shown in Table 9 and Table 10. The speed has significantly affected the vibration performance. It is obviously found that the vibration level increase with the speed going up. For cylinder 1, the LFB perform best, WCOB takes second place, and the diesel performs worst. On the contrary, the WCOB perform better than LFB while they all have better vibration performance than diesel in cylinder 2. In comparison with cylinder 1 and cylinder 2, the overall vibration performance of S1 is better than S2 which is opposite to results on different loads. Meanwhile, when the speed is over 1800 RPM, the feature values of Peak to Peak for cylinder 1 are around 2 or 3 times that of cylinder 2'. This means the strike on cylinder 1 would be heavy under high-speed conditions. We believe this is caused by the installation of a dynamic pressure sensor which makes a hole in the head of cylinder 1.

Table 9. Results of S1 (cylinder 1) with different speeds.

	Fuel Type	Speed					
		1500 RPM	1600 RPM	1700 RPM	1800 RPM	1900 RPM	2000 RPM
RMS	Diesel	2.23±0.06	2.74±0.20	3.59±0.03	3.75±0.06	4.19±0.03	4.75±0.06
	WCOB	2.02±0.07	2.22±0.05	2.92±0.05	2.92±0.05	3.37±0.07	4.00±0.17
	LFB	1.89±0.06	2.10±0.06	2.45±0.06	2.43±0.04	2.84±0.06	3.32±0.07
Peak to Peak	Diesel	47.83±3.18	56.51±2.82	87.19±1.67	105.48±1.70	132.14±0.97	153.65±3.45
	WCOB	38.91±2.18	41.09±2.29	59.98±1.53	78.00±1.78	99.00±3.70	129.64±6.20
	LFB	35.26±1.97	36.72±3.00	45.02±2.98	54.24±1.81	74.54±1.44	93.61±2.01
Variance	Diesel	4.87±0.22	7.41±0.53	12.85±0.24	13.91±0.46	17.50±0.23	22.52±0.55
	WCOB	4.02±0.25	4.89±0.20	8.42±0.26	8.43±0.28	11.28±0.49	15.88±1.36
	LFB	3.47±0.18	4.32±0.22	5.94±0.30	5.86±0.18	7.99±0.24	10.95±0.48

Table 10. Results of S2 (cylinder 2) with different speeds.

	Fuel Type	Speed					
		1500 RPM	1600 RPM	1700 RPM	1800 RPM	1900 RPM	2000 RPM
RMS	Diesel	2.24±0.06	2.38±0.10	2.99±0.05	2.79±0.03	3.22±0.10	4.25±0.28
	WCOB	2.00±0.06	1.96±0.04	2.47±0.06	2.42±0.04	2.86±0.08	3.59±0.06
	LFB	2.15±0.05	2.10±0.05	2.42±0.04	2.38±0.04	3.00±0.08	3.83±0.11
Peak to Peak	Diesel	39.15±1.89	44.19±0.64	51.89±1.37	42.58±1.48	45.83±2.97	80.22±4.00
	WCOB	33.70±1.91	35.16±1.15	43.76±2.20	35.90±1.35	44.00±2.73	61.13±1.19
	LFB	39.34±2.32	38.97±1.21	44.37±1.43	35.54±1.86	40.82±2.97	61.95±2.07
Variance	Diesel	4.97±0.25	5.61±0.48	8.89±0.30	7.75±0.19	10.37±0.64	18.08±2.46
	WCOB	3.97±0.25	3.80±0.14	6.05±0.31	5.81±0.17	8.13±0.44	12.84±0.41
	LFB	4.55±0.15	4.34±0.19	5.84±0.20	5.62±0.18	8.98±0.48	14.61±0.82

Comprehensive Comparison of Vibration Profiles

In order to further analyse the vibration performance between different types of fuel and different cylinders, we calculate the quantitative proportion for 3 different features to identify which kind of fuel has the best vibration performance. The results are shown in Figure 7 and Figure 8. As shown in Figure 8 (a), the WCOB declined 11.735%, 19.663% and 22.384% while LFB declined 23.628%, 35.145%, and 41.299% under features F2 (RMS), F4 (Peak to Peak), and F5 (Variance), respectively, comparing with diesel fuel. This case will be different shown in Figure 8 (b), the WCOB's decrement remains similar with cylinder 1', which is 12.069%, 16.091% and 22.213%, but the decrement of LFB is significantly shrunk which is 8.148%, 12.201%, and 14. 997%. On average, compared with diesel fuel, WCOB decreased by 17.326% and LFB decreased by 22.570%.

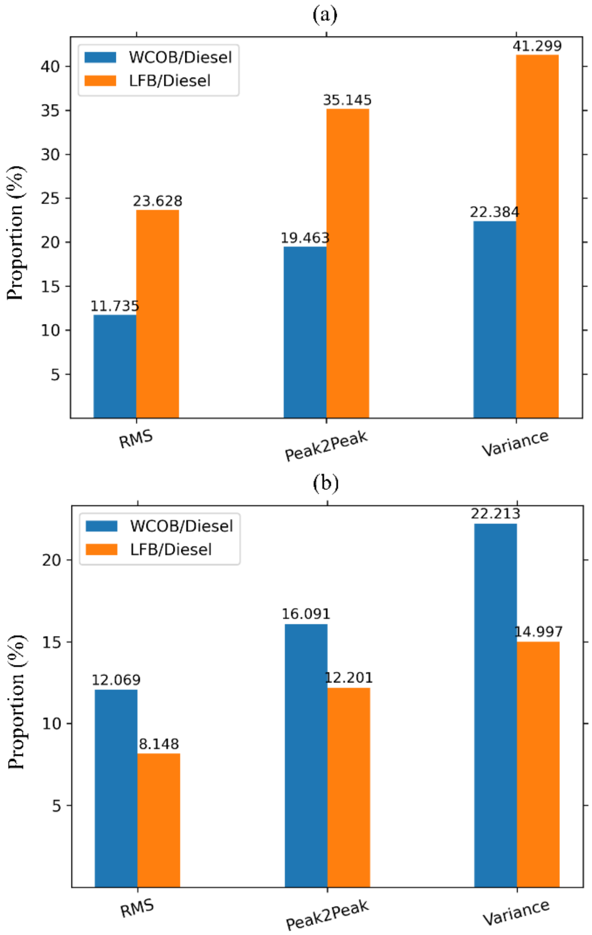

Figure 8. Results of comparison between different fuel, (a) Cylinder 1; (b) Cylinder 2.

Figure 9 shows the comparison results between the vibration level of cylinders 1 and 2 at three different features. We could easily find that the F2 (RMS), F4(Peak to Peak), and F5 (Variance) of cylinder 1 will be 8.377 %, 48.611% and 21.291% larger than cylinder 2 for diesel fuel, while a similar phenomenon can be found for WCOB which are 7.248%, 42.071%, and 15.763%. The vibration level of cylinder 1 is generally larger than cylinder 2's for both types of diesel fuel and WCOB. These results verify that the installation of dynamic pressure indeed increases the strikes and vibration energy. The high-level vibration and heavy strikes would decrease the lifetime of the mechanical component of the internal combustion engine [8]. However, the LFB fuel performs differently, the F2 (RMS) of cylinder 1 is 11.684% smaller than cylinder 2's, the F4 (Peak to Peak) of cylinder 1 is 6.907% larger than cylinder 2's, and the F5 (Variance) of cylinder 1 is 22.683% smaller than cylinder 2's. Combined with the results of LFB at different working conditions, it indicates that the LFB fuel could effectively relieve the influence caused by the dynamic pressure sensor installed on cylinder 1.

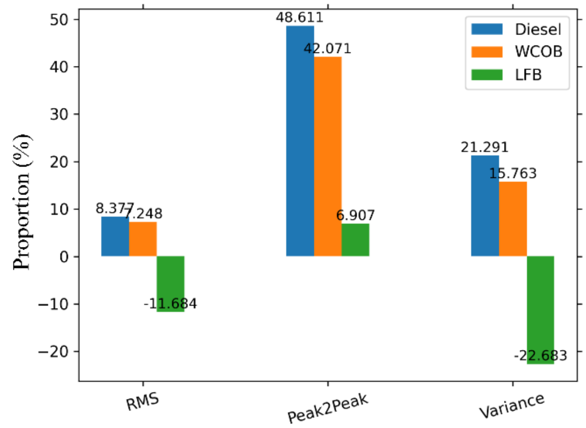

Figure 9. Results of comparison between cylinder 1 and cylinder 2.

Engine Friction Power Comparison

Forces acting between surfaces when they are in motion are commonly referred to as friction power (FP). The gap between stated horsepower and brake horsepower is known as total engine friction [27]. At both operating conditions with variable loads and speeds, it is seen that FP for the biodiesel fuel was found to be lower than the diesel fuel (Figure 10). It was also noted that under both working conditions, WCOB displays lower FP than LFB (Figure 10). It might be because WCOB has a higher viscosity, which also means that it has a higher degree of lubricity [27]. Due to its superior lubricity and viscosity, biodiesel fuel generally produced fewer friction losses when compared to fossil fuel [27]. As compared to diesel fuel, FP for LFB at variable load was found to be lower by 12-53% at engine loads of 20% to 60% and it raised by 5-9% at 80% and 100% (Figure 10(a)). Increases of FP for LFB at higher load could be due to lower viscosity which is closer to diesel fuel (Table 1) and this further decreased with increases in the in-cylinder temperature. LFB is a highly saturated fuel, containing a high percentage of a shorter chain of (C12-C14) which evaporate faster than a longer carbon chain [24]. Sharma et al [24] investigated the characterization of WCOB and animal fat (pig fat) and observed a high percentage of shorter carbon chain fatty acids present in animal fat. Furthermore, FP for WCOB was observed to be 4–36% lower than diesel fuel at engine loads from 20–100%. (Figure 10(a)). At variable speeds, however, it was discovered that the FP for both biodiesel fuels was lower than that of diesel fuel (Figure 10(b)). At variable speeds between 1500 and 2000 rpm, FP for LFB and WCOB were found to be decreased by 1-6% and 4-11%, respectively. In summary, the main reason of vibration level of the two types of biofuels is lower than diesel is because of the superior lubricity and viscosity. The results of FP have verified this conclusion. The low vibration level will extend the lifetime of the critical mechanical component of the IC engine, which means that the biofuels of WCOB and LFB are highly recommended as alternatives to diesel.

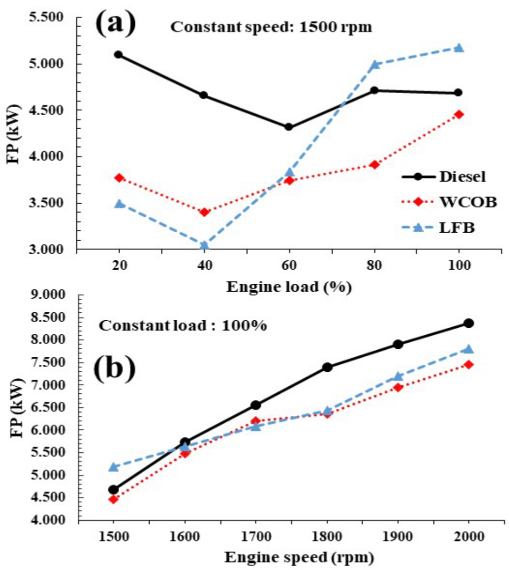

Figure 10. Variation in FP with engine loads and speeds.

Conclusions

This study has conducted vibration measurements on a diesel engine powered by various fuels including diesel, WCOB, and LFB. The vibrations were collected when the engine was operated at different loads and speeds. The vibration characteristics have been evaluated by the selected effective features including RMS, Peak to Peak, and Variance. The results demonstrate that the vibration level will significantly increase with working speed, while the loads have a limited impact on it. Overall, compared with diesel fuel, the WCOB could cut 17.326% vibration energy and LFB could reduce 22.570%. vibration energy. Through comparing with different cylinders, the results verified that installing the dynamic pressure sensor will greatly improve the vibration level. This effect is very noticeable when the engine was fueled with diesel and WCOB. The LFB fuel can alleviate this problem to a certain extent. Engine performance of FP with LFB and WCOB was found lower as compared to diesel fuel. Vibration analysis of different biodiesel on the real automotive engine could be the future scope of the work.

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Definitions/Abbreviations

WCOB	waste cooking oil biodiesel
LFB	lamb fat biodiesel
IC	internal combustion
RMS	root means square
DAQ	data acquisition
FFT	fast fourier transform
FP	friction power