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Research Article

Comparative study of vibration signatures by correlating them with engine oil degradation for diesel and blended fuel DBD20 in a CI engine

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Abstract
The use of biofuels as a sustainable alternative to fossil fuels has garnered significant attention. However, several factors, including oil degradation, can impact the effectiveness of biofuels. It is recommended to regularly change and maintain the oil to minimize the impact of oil degradation on biofuel performance. This can be achieved by monitoring the engine's vibration signature without draining any oil from the engine. This study aimed to investigate the correlation between engine vibration signatures and the degradation of lubricating oil. A 5 horse power (HP) compression ignition (CI) engine fuelled with a mixture of 80% diesel and 20% biodiesel, referred to as diesel biodiesel (DBD)20, was used for the study. The engine operated at a steady load, equivalent to 50% of its rated power at 1500 rpm. The vibration signatures, including amplitude and frequency of vibration in the longitudinal direction, were recorded at regular intervals of 2 hours using an accelerometer placed on top of the engine head. Samples of used lubricating oil were collected every 20 hours of operation, and properties such as viscosity, density, soot content, and moisture were measured and compared with the vibration signatures. The analysis revealed distinguishable differences in vibration signatures and lubricating oil properties between diesel and DBD fuelled engines. The findings indicated a significant decline in oil quality and corresponding vibration signatures after 80 hours of engine operation. Therefore, it is recommended to replace the engine oil every 80 hours of engine run for stationary field engines.

Keywords
Biofuel, CI engine, Degradation of engine oil, fast Fourier transform (FFT) analyzer, Vibration signature.

1.Introduction
Condition monitoring through vibration analysis has attracted the researchers at the beginning of 21st century. The technology updates and the invention of the new instrument have broadened the application of vibration analysis. This technology also has got its potential in analysing the condition of internal combustion (IC) engines fuelled with diesel and biodiesels. In recent years, biofuels are considered one of the best options for blending with diesel, which is capable of partially fulfilling the present energy requirement[1]. The maintenance of bio-fuelled-operated diesel engines is always a challenging task and has fascinated the researchers to establish the guidelines for the proper maintenance of the engines that ensures smooth operation[2].

Vibration signature analysis has arisen as an important tool for condition monitoring of the engine powered with biofuels. Many researchers applied the concept of vibration signature analysis to ensure the proper condition monitoring of diesel engines [3], gearboxes, and some biodiesel fuelled engines. Vibration analysis is widely used to identify a significant fault in machinery [4, 5]. Uneven combustion, knocking, bearing problems, failure of the piston crank mechanism, and any loose engine structural components are the main causes of vibrations in diesel engines [6]. The torsional vibration is most dangerous for the crank shaft of the engine [7]. The abnormal noise of the engine is usually generated by coupled mechanical systems [8]. Engine knock can be identified using a vibration signature [9]. The 50% of energy loss in IC engines is due to friction and wear between the piston ring and cylinder liner [10]. Degradation of the lubricant causes poor engine performance and reduces the life of the internal components [11]. The study of oil

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samples obtained from an engine indicates the oil's appropriateness for continuous usage and supplies significant information regarding the engine's wear state [12]. This helps in identifying the components in severe condition before the occurrence of catastrophic failure even without removing the engine lubricant. Baweja et al. [13] recently observed the vibration characteristics of a diesel engine fuelled with DBD20. According to the study the amplitude of vibration was found to be higher in comparison to pure diesel. This signifies that performance of the engine with DBD20 has been degraded.

However, substantial research work on correlating engine performance with vibration signature has been reported in the literature, but there is scarcity of research that addresses the issue of correlating engine oil degradation with vibration signature [14]. This becomes the motivation to conduct some experimental studies to get more insights into the various facets of engine performance by correlating the engine oil degradation with the vibration signatures.

The present work tries to explore the idea and intends to perform an experimental study to lay down some guidelines for engine oil monitoring and change of oil by merely observing the vibration signature. The objective of the current research is to set up the guidelines for engine health monitoring by establishing a correlation between the vibration signature and engine oil degradation of the diesel engine powered by biodiesel blends.

Experiments are performed on a single-cylinder, four-stroke compression ignition (CI) engine with a capacity of 5 horse power (HP) which runs at 1500 rpm and a constant load of 50% of rated power. The engine is powered by diesel (80%) and jatropha-biodiesel (20%) named DBD20. For every two hours, the vibration signatures in terms of amplitude and frequency are recorded by placing an accelerometer probe on top of the engine head. With this for every 20 hours of operation, samples of spent lubricating oil are taken, and its characteristics like viscosity, density, soot, and moisture, are measured and correlated with vibration signals.

It has been discovered that the vibration signatures and lubricating oil characteristics can be used to discriminate between the performance of diesel and DBD20-powered engines. According to the investigation, oil degradation and associated vibration signals become considerable after 80 hours of engine operation. Therefore, it is advised that in the case of stationary field engines, the engine oil be changed every 80 hours of engine operation.

The research paper is organized into several sections. Section 2 provides a summary of previous investigations conducted in the field, offering a background and context for the study. In Section 3, the research methods employed in this study are outlined. The experimental assessment results are presented in Section 4, offering a comprehensive overview of the findings obtained from the study. Section 5 delves into a detailed discussion of the findings, exploring their implications, interpretations, and significance. Finally, Section 6 serves as the conclusion of the paper, summarizing the key points of the study and suggesting potential avenues for future research.

2.Literature review

Biodiesel is biodegradable, has low environmental impact, and green fuel for engines [15]. Chemically, biodiesel is a free acid methyl ester obtained from the bio feedstock, such as edible and non-edible oil [16]. Because of the blow-by and reduced oxidation stability, biodiesel dilutes the engine oil [2].

Macian et al. [17] clarified that in low-viscosity oil, biodiesels perform better than conventional oil. But at the other end applications like compressed natural gas (CNG) engines, the oil degradation increases. Therefore, oil condition monitoring has become essential to get the optimum performance from the engine. The monitoring of the engine oil condition may provide very essential information about engine health. The monitoring of the CI engine may be done in many ways. Engine oil changes its property due to high temperature and pressure inside the cylinder of a diesel engine [18]. For example, an engine oil viscosity increase will generate engine vibration [19]. This brings the idea of correlating the engine oil degradation with vibration signature. However, some newer approaches like analyzing the indicator diagram by Fourier transform also have been tried but it is still done manually [20]. Some experimental works have been performed to capture the dynamics of engines with biofuels by knowing the facts that with the use of biodiesel fuel, the viscosity of lubricating oil samples increases [21, 22]. To decrease friction power loss and increase engine efficiency, the clearance in the piston is frequently filled with lubricant [23]. The engine oil condition monitoring is instrumental in explaining the lubricant's state of health [24, 25]. It is observed that the piston's lubrication will be more affected by the connecting rod's inertia when the engine is operating quickly [26]. By understanding these dynamics, it can be concluded that in the form of wear particles, chemical pollutants, and other information, the lubricant also transports information from the inside to the exterior of functioning. These signals from the engine can be captured by understanding the vibrational behaviour of engines [27]. Vibro-acoustic studies have proven their ability to measure the failure of components [27]. The engine response in terms of vibration provides much information concerning fault condition of individual components in an assembly. Thus, vibration analysis is one of the methods mostly used for condition-based monitoring. This method can provide precise results about the engine. The expertise is required in data acquisition and analysis. Fast fourier transform (FFT) analyzer has emerged as an important instrument in direct recording the real-time vibration signature. These signatures generated by this instrument are directly related to the actual values and the deviation of these signals from the initial ones indicate the fault and ground for corrective measures. There are some other methods to record the signatures. For example, Li et al. [28] recorded vibration in empirical mode by decomposition method. In studying the industrial mufflers, the vibration analysis is done and the results are verified by finite element method (FEM) software results. Geng and Chen have conducted experiments for the cause of piston slaps and formulated a model for root cause analysis. Another way of analysis is to record the vibration signature on a smaller scale model and then transport these results to understand its effect on a larger scale prototype [29]. Few of the examples are the condition monitoring of the bearings in IC engines [30] and the effect of vibration in changing lubricating oil conditions [31]. Liu et al. [32] proposed a system capable of monitoring engines online. This system measures the torque wear particle, rotation velocity, and lubricant quality assessment. They used the ferrography method to assess the condition of the engine. The study proposes the use of new approaches to overcome the problem of person-based analysis of indicator diagrams using Fourier transform [33].

From the literature analysis, the vibration signature analysis is a very good way to understand the oil condition. This is a better way than the use of an engine oil viscosity sensor in the form of a metal-core piezoelectric fiber/aluminum composite proposed by Yanaseko et al. [34]. The vibration signature analysis is done on other machine parts, but no evidential literature has been reported for engine oil degradation. For example, Albarbar et al. [35] have monitored the lubricating oil degradation of journal bearing through the vibration signature, Peng and Kessissoglou [36] have examined the fault and condition monitoring of gear through wear particle analysis in the engine oil and correlation with vibration signature. Jafarian et al. [37] have examined the misfire and valve clearance of diesel engines using vibration signatures. *Table 1* highlights some of the facets of vibration signature analysis of bio-fuelled engines.

Table 1 Facets of vibration signature analysis of bio-fuelled engines

References	**Method**	**Results**	**Advantages**	**Limitations**
[38]	Time–frequency Analysis of a single-cylinder, water-cooled, direct injection four-stroke diesel engine (ASHTAD DF120-RA70) is done. B10 refers to 10 % ester and 90 % diesel and so on.	The A-Weighted Sound pressure levels (SPL) of B10 is lowest and that of B30 is found to be highest.	The analysis is capable of reporting and identifying the major source of engine noise apart from combustion like piston slap and outlet valve closing.	Longer combustion times for higher percentage of blending of ester in diesel.
[39]	Vibration signatures have been recorded for blends of conventional diesel and Niger seed oil methyl ester (NSOME) at various engine running loads viz. 25%, 50%, 75%, and 100%.	Substantial vibration reduction in case of B20	The intensity of vibration signatures lowered down with Biodiesel blends.	Higher percentage of blending increases vibration.
[6]	Vibration analysis of	The DC-11 vibration	Application of	Vibrations are high

References	Method	Results	Advantages	Limitations
	naturally aspirated CI engine.	analyzer is a digital spectrum analyzer that gives the collected spectral data in FFT plots.	supercharged palm methyl ester (S-PME) can reduce the vibration and achieving smooth combustion.	with natural aspiration compared to supercharging.
[40]	vibrational characteristics of the compression engine along variable pressure rating (VPR) use nanoparticles added to macadamia biodiesel Macadamia biodiesel at 30 and 50 prepared.	Vibration acceleration and sound pressure level of diesel engines increased with the increase of engine load at compression ratios (CR) of 17:1, 18:1 and 19:1.	nanoparticle addition into macadamia biofuel decreased both vibration	Vibration increases with Higher compression ratio
[41]	Performance of Diesel engine (tractor) fuelled with methyl ester biodiesel is examined for vibration analysis.	The percentage reduction in vibration amplitude for B20 is 14.27 for no load and 9.46 reduction at full load.	blends Hybrid biofuel(P75SNB25) and Biodiesel blend (SNB20) had shown better results in terms of vibration.	Higher percentage of biodiesel produces more vibration.
[42]	To create a ternary fuel, conventional diesel was combined with biodiesel made from Kusum seed oil and isobutyl alcohol. The biodiesel-diesel blend (B20) was created in a volume ratio of 20% and 80%. Different CRs, including 16.5, 17.5, and 18.5, were used for the experiment.	As the amount of isobutyl alcohol increases, vibration declines until it reaches a minimum with B20+1% isobutyl alcohol.	The VPR diesel engine can be utilised with isobutyl alcohol and diesel- Kusum seed oil methyl ester (KSOME) mix without any modifications.	Higher missing of alcohol produces high vibrations.
[43]	a common rail diesel engine of capacity is 1248cc, was used.	Vibration accelerations were rising between 1800 and 2000 rpm.	Pure diesel has lesser vibration than that of pure biofuel	better measurement of pressures and vibration extensions, a pressure sensor should be placed inside the cylinder.
[44]	single cylinder, direct injection, fuelled with POME10+Bu10, and POME15+Bu10. Run with 25% and 50 % load condition with variable speed.	Better reduction in vibration with B10Bu10 blend. The reduction is observed to be up to 13.46% for 1800 RPM and 22.9% for the 2100 RPM.	Biodiesel blend with butanol improves reduces the vibration signature of the engine.	The vibration is likely to increase as there is more biodiesel in the mixture.

Many researchers have performed vibration analysis by condition monitor of an engine through FFT analyzer. The prediction study mainly includes vibration as an important factor even for new biodiesel blends [30]. The vibration signature of different components and the interlinked data with proper analysis will provide the condition details of the engine and its associated factors.

From the literature review, it can be concluded that however condition monitoring with the vibration signature analysis is carried out on engine performance parameters (*Table 1*), but no work is reported on correlating the degradation of engine oil with vibration signature. The present literature review fosters us to use the FFT analyzer and its ability to direct measure the vibration signature for monitoring the condition of lubricating oil. Which will be an extended application in other tribological fields of research.

The present study proposes a new approach to correlate the degradation of engine oil with variation in vibration signature and establishing guidelines for change of lubricating oil.

3.Methods

3.1Preparation of biodiesel

Jatropha seed is crushed and raw oil is subjected to transesterification process. In preparation of Jatropha biodiesel involves two steps transesterification process, the raw Jatropha oil is mixed with methanol and sulphuric acid for acid reaction. The process of stirring was compatible with the magnetic stirrer setup. Then, the mix is poured into the separator, and after separation, the soap is drained out. In continuation, the base reaction is performed by mixing methanol and potassium hydroxide catalysts. The separation processes result in biodiesel and ester. As the ester is drained out, the biodiesel is washed using hot water. Thus, the Jatropha biodiesel is prepared using a magnetic stirrer at constant temperature followed by separation and filtering washing. The yield was recorded as 92%. The test fuel is prepared with 20% of Jatropha biodiesel and 80% of diesel forms the DBD20 blend. *Table 2* displays the characteristics of diesel and blended fuel.

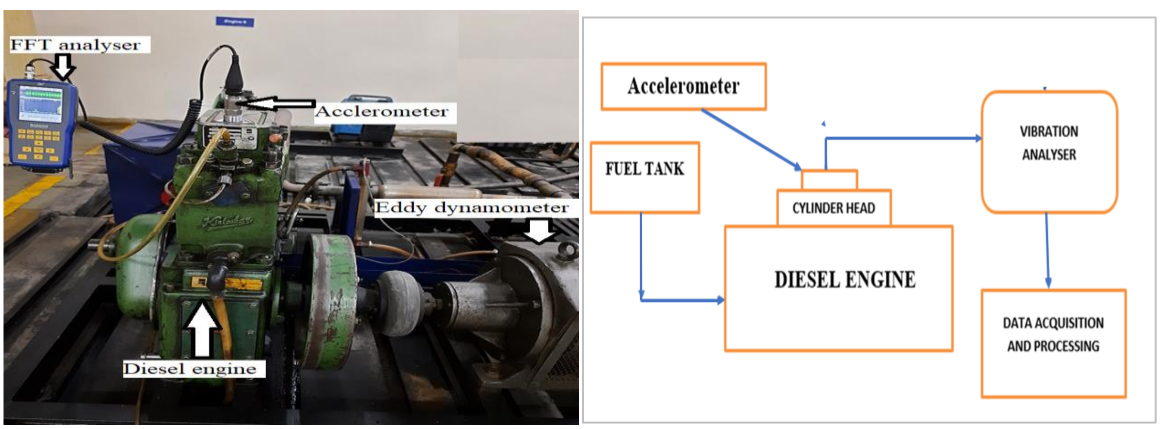
Table 2 Test fuel diesel and blend properties

Property	Diesel	DBD20
Viscosity in mm²/s	4.25	4.28
Density in g/cm³	0.8207	0.8332
Flash point in °C	54.6	46.8
Fire point in °C	82.6	79.5
Calorific value in kJ/kg	45000	42333

3.2Experimental set up and procedure

3.2.1Engine test rig

The CI engine used for the experiment is a 4-stroke single cylinder Kirloskar make diesel engine of 5 HP capacity with a water-cooling arrangement. The engine is mounted with air tank, fuel tank, and fuel-measuring burette. The load is exerted on the engine by using an eddy current dynamometer. The Fuel control valve and the load-varying regulator are mounted on a panel separately. The complete test setup is depicted in *Figure 1*. In *Table 3*, the specification is listed.



(a) (b)

Figure 1 (a) single cylinder four stroke diesel engine with FFT analyzer setup (b) a schematic diagram of the experimental setup

Table 3 Engine specifications

Features	Specifications
Manufacturer	Kirloskar (model AV1)
Power	5HP
Cycle	4 strokes
Speed	1500 rpm
Compression ratio	16:1
Cooling system	Water cooled
CC	0.661 litres
Fuel ignition	Diesel compression
Lubricating oil	20W40
Loading type	Eddy current dynamometer

3.2.2Test procedure

The DBD20 and diesel are used as test fuels. The test conditions have been maintained identically for both the test. The engine is run at a steady speed of 1500 rpm and the constant load of 50% of rated power, for every 2 hours of engine run for both fuels, the vibration signatures are recorded with the help of

FFT analyzer. The display of the FFT analyzer details the maximum amplitude of acceleration and corresponding frequency associated with the longitudinal direction. These signals are captured by putting the accelerometer probe on the cylinder head's top. Along with the capturing of vibration signatures for both the fuel engine run, the oil sample is also taken for observation after equal intervals.

For every 20 hours of run, the engine oil 20W40 is changed, and a sample of 100 ml is drawn after every 20 hrs of runs. The sample drawn is subjected to further oil analysis for oil properties such as standard test techniques provided by the American Society for Testing and Materials (ASTM) is used to determine physicochemical properties such as density, viscosity, moisture, and soot.

Fourier transform infrared (FTIR) spectroscopy is used to identify the metallic elements contained in the additive package. FTIR analysis is used to determine the amount of moisture. Rheometers are used to determine the viscosity of motor oil. The density is measured using a density meter.

3.3Measurement of properties

3.3.1 Vibration measurement

Three accelerometers with the connection technology center (CTC) AC102-1A specifications (sensitivity, 100 Mv/g, dynamic range, 50 g, source voltage, 18-24 volts) were utilized to collect engine vibration readings. The frequency range being measured by this highly accurate accelerometer is 0.5 to 15,000 Hz. The vibration produced as the result of combustion holds the maximum value compared with other sources of vibration in an engine. These vibration signatures are observed and recorded with minimum error by locating the accelerometer probe at the top of the cylinder head. The vibration signatures of the engine are recorded along the axis of the cylinder and termed longitudinal vibration in wavelet form. The FFT analyzer reveals the graph between linear frequency and magnitude of acceleration. The sample graphs by FFT analyzer is shown in *Figure 2.* The linear frequency is termed longitudinal frequency and the peak of acceleration is termed as longitudinal amplitude for further discussions.

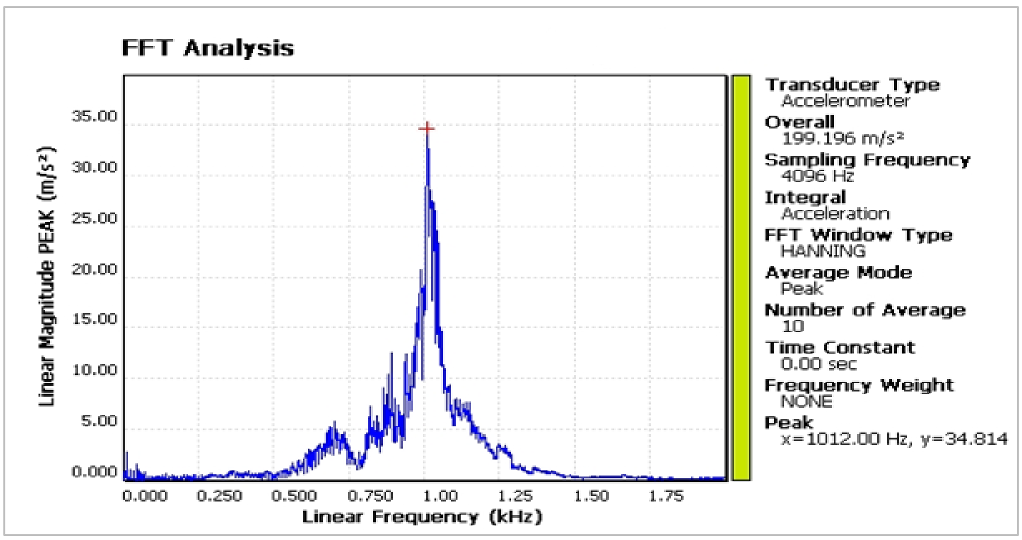


Figure 2 Sample vibration signature of longitudinal direction for DBD20 fuelled engine after 40 hrs of engine run

3.3.2 Viscosity measurement

The viscosity is measured with the help of a rheometer (Rheoplus/32.62 210007158- 33024) manufactured by Anton Paar, as per ASTM standards. The sample is stirred in a ceramic container at 40°C. The viscosity of the liquid is recorded in the system every 10 sec and 50 cycles.

3.3.3 Density measurement

The density of the oil is measured with the help of DM 300 Lemis Instruments MAC. The measurement is done every 20 hours of engine run at room temperature.

3.3.4 Moisture and soot measurement

Moisture and soot measurements are done with the help of FTIR graphical analysis which provides the change in property in terms of % transmittance (%T) or % absorption. *Figure 3* shows the FTIR curve for DBD20 fuelled engine oil at 80 hours of the run. The corresponding wavelengths for soot loading and moisture content in lubricating oil are 2000/cm and 3400/cm respectively.

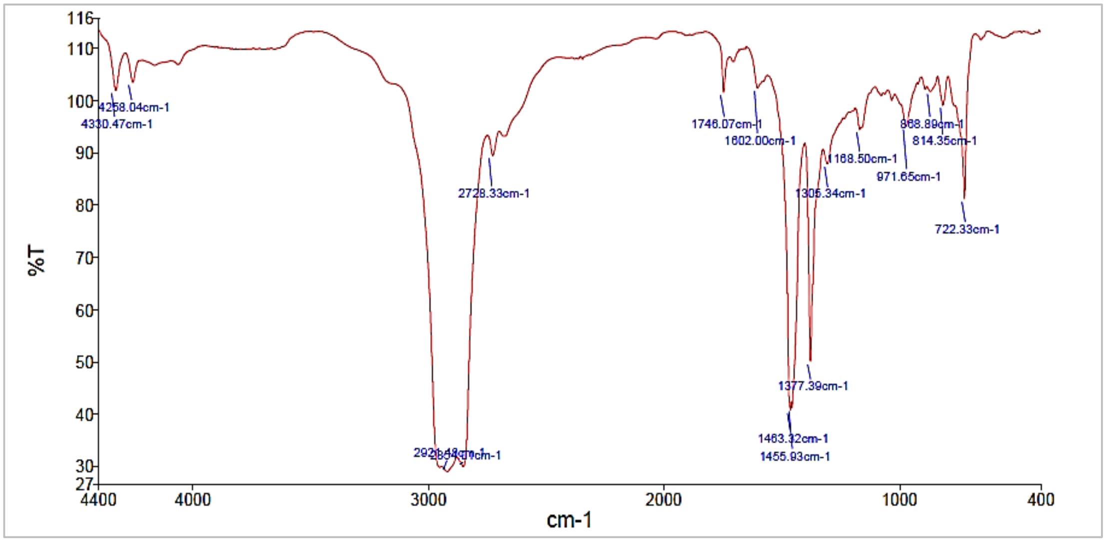


Figure 3 FTIR curve for DBD20 fuelled engine oil at 80 hours of run

4.Results

4.1Vibration signatures

The accelerometer of the FFT analyzer is placed over the cylinder head for 5 minutes. The accelerometer installed on the cylinder head's top measures the frequency and amplitude of the engine's vibration. For every 2 hours, the vibration signature is recorded. The engine oil is changed every 20 hours of operation for accurate results. The initial 20 hours of engine run, wherein maximum wear and tear of internal components takes place has been excluded from observations. The vibration signatures after 20 hrs of engine run were recorded after every 2 hours and the average values are plotted for 40, 60, 80, and 100 hours of engine run as shown in *Figure 4* and *Figure 5*.

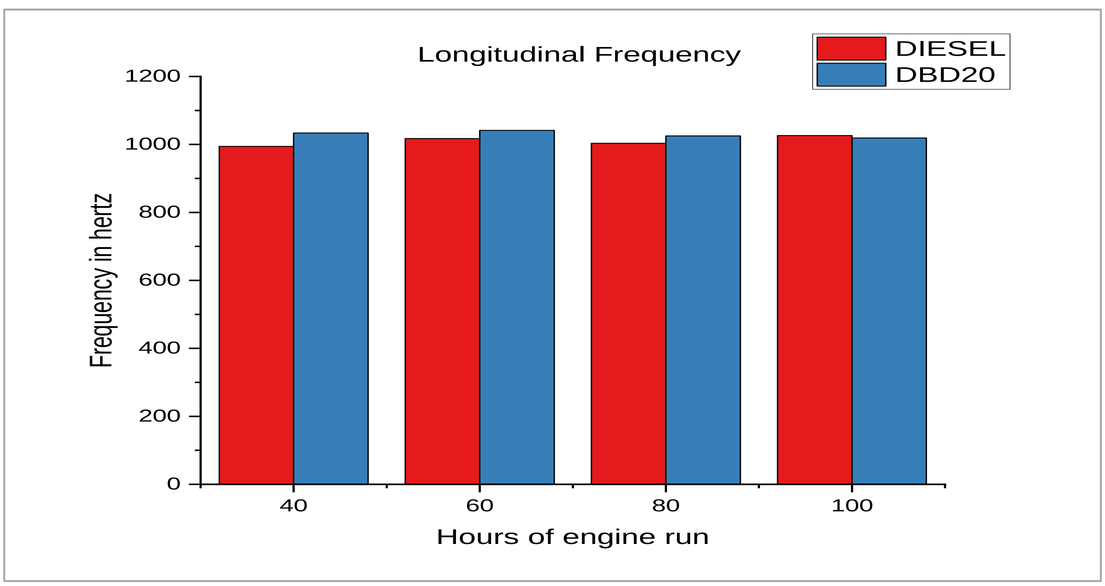


Figure 4 Longitudinal frequency v/s engine run period

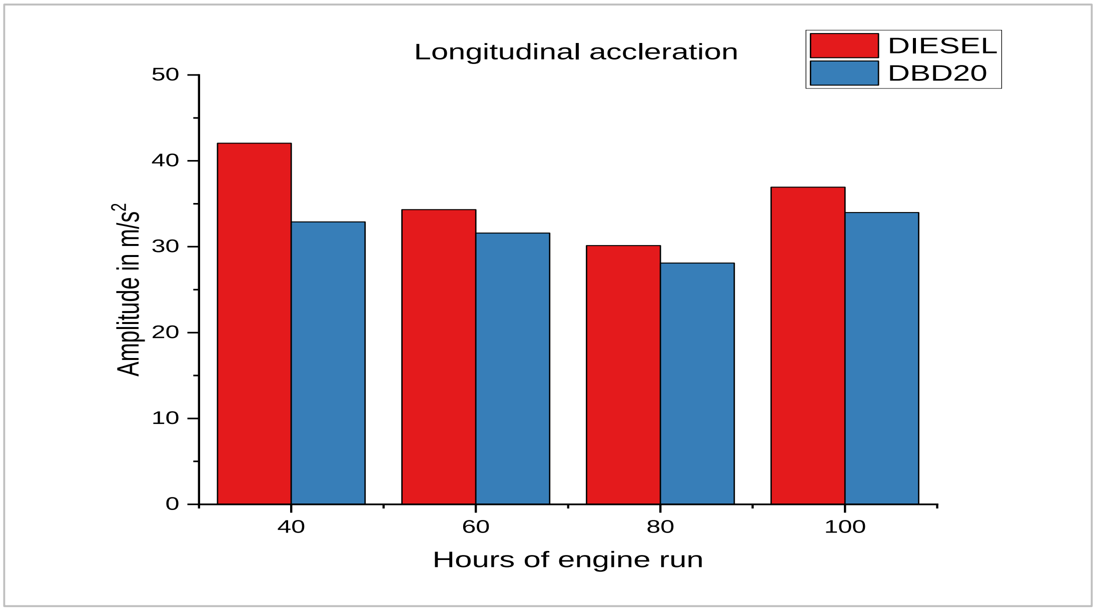


Figure 5 Longitudinal amplitude v/s engine run period

4.2Variation of density with vibration signature

The density of the oil is measured after every 20 hours at the time of the oil change. Engine performance is greatly influenced by engine oil density, which decreases as temperature rises. The variation of density of engine oil with engine run period is plotted and shown in *Figure 6.*

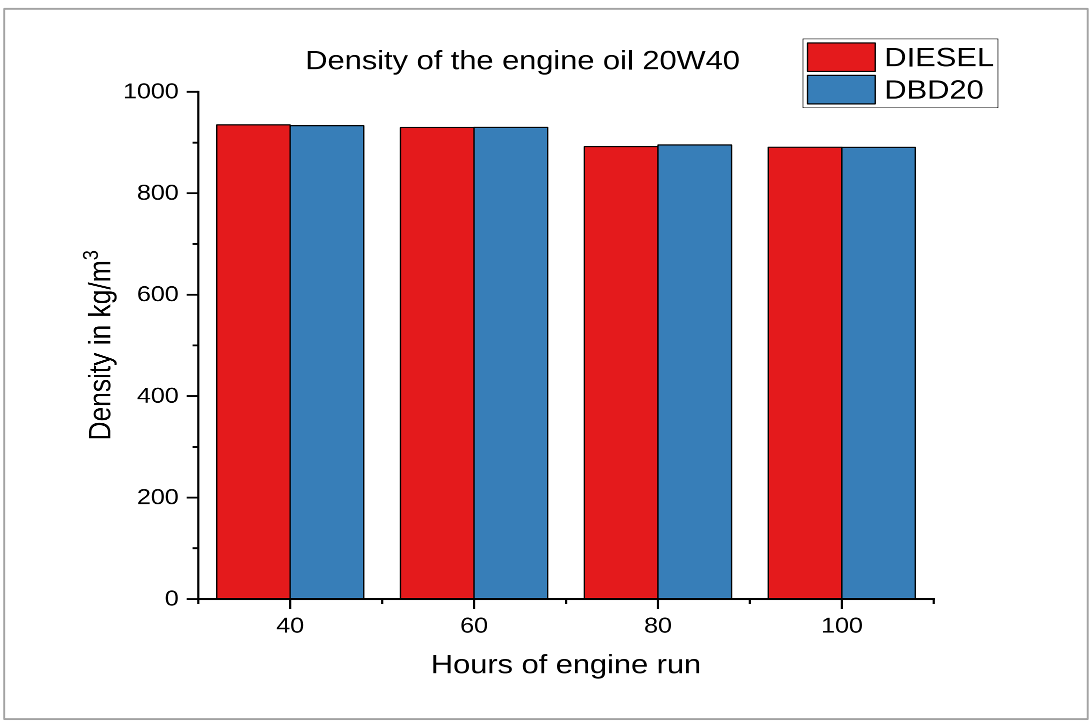


Figure 6 Variation of density of engine oil v/s engine run period

4.3Variation of viscosity with vibration signature

The viscosity of the oil is measured for each sample taken after every 20 hours at the time of the oil change. The sample is stirred in a ceramic container at 40°C. The variation of viscosity of engine oil with engine run period is plotted and shown in *Figure 7*.

4.4Variation of moisture content with vibration signature

FTIR was used to determine the amount of moisture in the engine oil, and the number of particles in the sample is determined by the transmittance or absorbance percentage. The variation of moisture content of oil with engine run period is plotted and shown in *Figure 8*.

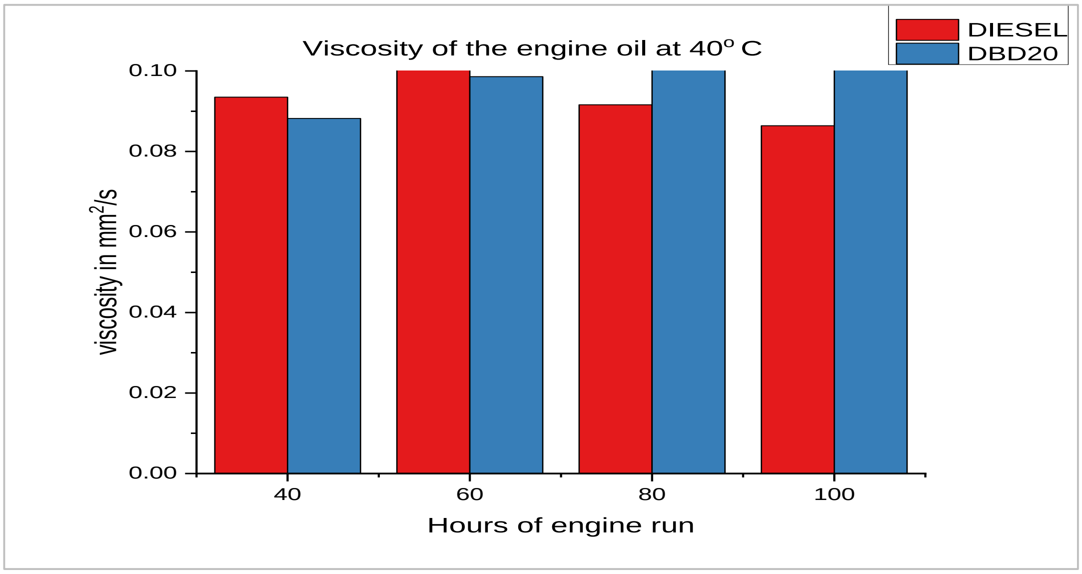


Figure 7 Impact of engine run on Viscosity of the engine oil at 40°C

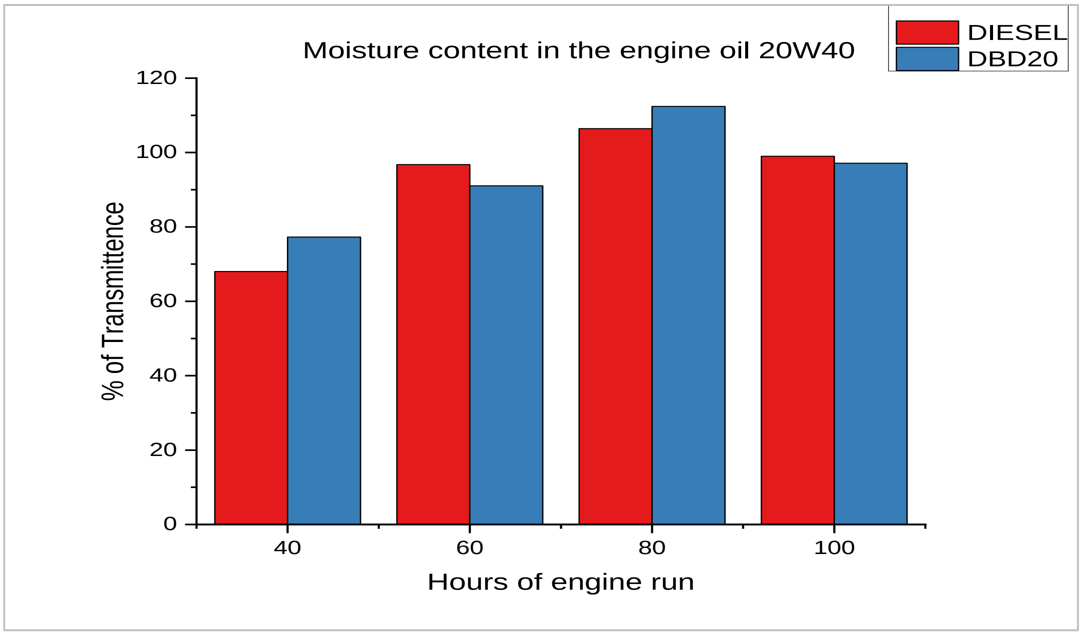


Figure 8 Impact of engine run on moisture content in the engine oil

4.5Variation of soot content with vibration signature

Soot measurements are done with the help of FTIR graphical analysis which provides the change in property in terms of % transmittance (%T) or % absorption. The variation of soot content of engine oil with engine run period is plotted and shown in *Figure 9*.

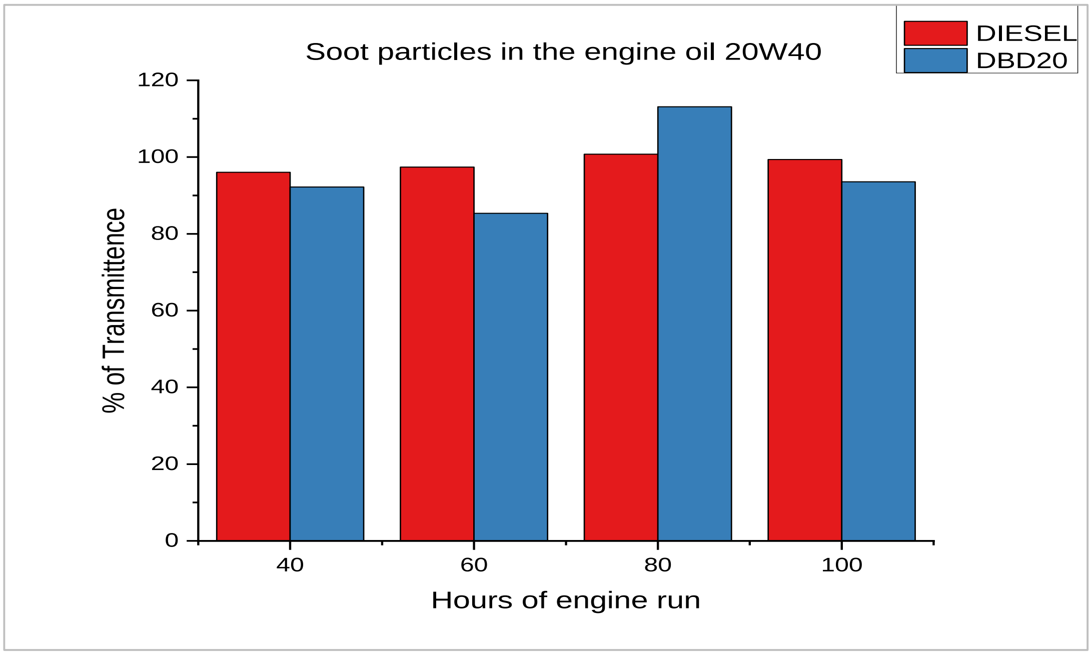


Figure 9 Impact of engine run on soot content in the engine oil

5.Discussion

5.1Vibration signatures analysis

It can be concluded from *Figure 4* and *Figure 5* that after 40 hours of engine run the longitudinal frequency for DBD20 fuelled engine is much higher, as the time progresses. It is found that the frequency of the vibration signature is increasing with time for diesel fuel and for DBD20 fuelled engine fuel it decreases with time. After 40 hours of engine run, the frequency is very high compared with diesel fuel. After 60 hours of run, the frequency of the DBD20 fuelled engine gradually reduces till 100 hours of engine run. The frequency gradually increases with time for diesel fuel and for DBD20 fuelled engines the frequency gradually decreases with time. As per the observation after 40 hours of engine run the longitudinal amplitude for DBD20 fuelled engine is much higher, as time progresses the frequency of both fuels' lowers, and after 80 hours of run the acceleration slightly increases for both fuels.

The amplitude of the vibration signatures is found to be comparatively higher for diesel than biodiesel. Biodiesel is an oxygenated fuel that improves the burning quality of the blends [45]. The initial run is termed as wear-in period, in which the wear of the engine cylinder occurs rapidly due to the breaking of the rough surfaces and that leads to higher vibrations. This is also reflected by increasing frequency trends up to 60 hours of run as shown in *Figure 5*. After this frequency again decreases till 80 hr of run. It is due the fact that after crossing the wear-in period the cylinder gets polished and the lubricant owns the hydrodynamic lubrication mechanism, this does measure the entire lubricant coating between the cylinder and piston rings; as a result, vibration was discovered to be decreasing up to 80 hours of engine operation. At the 100 hrs. of run vibration shows a rise which can be justified by lubricant degradation. This can be explained by the oxidation of engine oil, as it is subjected to high temperature and pressure conditions. The long-chain paraffin of the oil gets depleted and converted into low-chain carbon and the engine oil fails to maintain the effective oil film thickness between cylinder and piston. This leads to metal-to-metal contact and higher vibration. The same results are also reported by Peng and Kessissoglou [36] wherein the vibration of gears was found to be higher due to the higher wear causing boundary lubrication failure.

The vibration at 100 hrs are found to be lesser for DBD20-fueled engines in comparison to diesel-fueled engines. This is because an engine running on DBD20 has a lubricant with a higher viscosity (*Figure 7*). This fact is also in agreement with the findings of Santana et al. [46], the increased vibration due to the low viscosity of engine oil.

5.2Impact of density change on vibration signature

It is palpable from *Figure 6* that the density of engine oil is decreasing continuously for whole the engine run period for both fuels. A sudden drop in density at 80 hrs. of a run is observed. No notifiable change in density after 80 hrs. of a run is found. It can be observed that the amplitude of acceleration decreases with a decrease in density. However, after 80 hrs. due to fuel dilution and adsorption of moisture content the wear of engine component increases, [47] eventually, engine vibration increases at 100 hrs.

5.3Impact of viscosity change on vibration signature

From *Figure 7*, the viscosity of lubricating oil increases up to 60 hrs. of engine run for both the fuelled engine but it reduces afterward for Diesel fuelled engine and increases continuously for DBD20 fuelled engine. For DBD20 fuelled engines the vibrations are lower with increased viscosity. The basic cause of it is that the contamination by biodiesel causes the raise in viscosity after 60 hours of run until 80 hours of engine run. It seems that the lubrication should be smooth and have less engine vibration. Due to the higher viscosity of the engine oil, it was discovered after 80 hours of operation that the DBD20-fueled engine vibrated less than the diesel-fueled engine. While the frequency might reveal the source of the error, the amplitude of the vibration signature warns of how severe the issue is [36].

5.4Impact of Moisture content change on vibration signature

Figure 8 illustrates how the moisture content consistently declines for both fuel-powered engines up to 80 hours of operation before increasing. Due to the presence of an oxidant, DBD20 engine oil often contains more moisture than diesel engine oil. When compared to diesel engine oil, DBD20 engine oil has a greater beginning moisture value. In the case of DBD20, water contamination can cause corrosion and additive depletion, eventually causing micro-pitting [48].

Water that has been emulsified may go through the lubricating system, adhering to steel surfaces and bringing about corrosion. The breakdown of the lubricant is accelerated by water pollution [49]. As a result, the vibration of the blended fuel rises and this is the reason for a little higher vibration in the case of DBD20 with engine rune in comparison to negligible influence on vibration in the case of diesel-fueled engine.

5.5Impact of soot content change on vibration signature

It is palpable from *Figure 9* that the presence of the soot particles in diesel is almost flat throughout the engine run, but in DBD20 fuelled engine fuel the soot particles are less. These values are drawn from FTIR curves.

In comparison to diesel-fuelled engines, those powered by biodiesel blends have higher levels of soot particles in the engine oil. After 40 hours of engine run the soot particles in diesel are higher than DBD20. After 60 hours of engine run the soot particles in the engine oil of the DBD20 fuelled engine raises high and drop until 100 hours of engine run. The amount of soot is lower in the DBD20-fuelled engine at 80 hours of engine run. The fuel dilution in diesel-fuelled engines is almost ideal throughout the engine run period. Biodiesel supplies oxygen for proper combustion of the fuel, eventually, soot formation is reduced thus the engine oil of DBD20 fuelled engine has less soot. The diesel engine vibration is increasing with the amount of soot particles. Soot adulteration in engine oil reasons a substantial rise in the wear of engine internal components [50]. The increase in engine wear allows the leak of combustion gas which mixed with the engine oil and dilute. Hence, the vibration of the engine increased.

5.6Limitations

The study is limited to correlating the degradation of engine oil with the vibration signature. The study does not explore the correlation between engine performance and vibration signature. Moreover, in the present study as per IS:10000 code of engine endurance testing, the engine is refreshed with new engine oil after every 20 hours of run to get pure engine performance in the various segmented periods of engine run. However, in the real scenario, the same oil should be used for the entire engine run period but, in this case, the oil deterioration itself will be influencing the performance of the engine. The study was performed with constant load conditions, which is not a real scenario but the results obtained with this loading condition are significant and may provide insights for the condition monitoring with vibration signature analysis. However, the experiment may be performed at different load conditions to encapsulate the real facets of engine condition monitoring. In the present study, the probe is put over the cylinder head's top with a supposition that it will capture only the engine vibration. However, the complete machine was effectively mounted on rubber pads but still, the infiltration due to other sources of vibrations rather than the engine cannot be isolated completely. The study captured glimpses of the research for only one composition of biofuel i.e., DBD20, however, the more in-depth study may be performed with different blend compositions to get more insights into the facets. A complete list of abbreviations is shown in *Appendix I.*

6.Conclusion and future work

The present study offers valuable insights into assessing the engine condition by observing the vibration signature, which constitutes the novelty of this research. It is evident that there is no direct impact of viscosity changes on vibration in the case of a diesel-fuelled engine. However, for the DBD20-fueled engine, vibrations decrease as viscosity increases. In the case of DBD20, water contamination can lead to corrosion, additive depletion, and ultimately, micro-pitting. Consequently, higher moisture content in DBD20 fuel results in increased vibrations compared to a diesel-fuelled engine. Diesel-fuelled engines exhibit higher vibrations due to a greater presence of soot particles compared to DBD20-fueled engines. The analysis indicates that oil deterioration and corresponding vibration signatures become significant after 80 hours of engine operation. Thus, it is recommended to replace the engine oil every 80 hours of engine run for stationary field engines. As future research prospects, exploring the performance of higher biodiesel blends with diesel and establishing correlations can be valuable areas to investigate.

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Conflicts of interest

The authors have no conflicts of interest to declare.

Author's contribution statement

Ashok Kumar S: Contributed to conceptualization and writing the original draft. **Jitendra Yadav**: Contributed to the verification and visualization. **Santosh Kumar Kurre**: Contributed to writing reviews and editing.

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Appendix I

S. No.	Abbreviation	Description
1	ASTM	American Society for Testing and Materials
2	CI	Compression Ignition
3	CNG	Compressed Natural Gas
4	CRs	Compression Ratios
5	CTC	Connection Technology Center
6	DBD	Diesel Biodiesel
7	FEM	Finite Element Method
8	FFT	Fast Fourier Transform
9	FTIR	Fourier Transform Infrared
10	HP	Horse Power
11	IC	Internal Combustion
12	KSOME	Kusum Seed Oil Methyl Ester
13	NSOME	Niger Seed Oil Methyl Ester
14	SPL	Sound Pressure Level
15	S-PME	Supercharged Palm Methyl Ester
16	VPR	Variable Pressure Rating