NOISE, VIBRATION AND COMBUSTION INTER-RELATIONSHIPS FOR A COMPRESSION IGNITION ENGINE FUELLED BY ETHANOL-DIESEL BLENDS

Dev Prakash Satsangi, Nachiketa Tiwari and Avinash Kumar Agarwal

Indian Institute of Technology Kanpur (India)
email: satsangi@iitk.ac.in

Internationally, there is a strong push for using greener and cleaner fuels in lieu of diesel for compression ignition engines. Blends of alcohol and diesel could be a potential candidate for such replacement fuels. However, these alternative fuels have to be evaluated for noise and vibration in addition to their engine performance and emissions. This is because diesel engines are noisier and vibrate more relative to gasoline engine due to their higher compression ratio. Fuel composition has a direct effect on combustion phenomena of diesel engines. The combustion process is the source of mechanical impacts and cylinder pressure fluctuations which in turn are responsible for engine's noise and vibration. In the present work a comprehensive comparative evaluation of noise, vibration and combustion characteristics of a CI engine was investigated for four different ethanol-diesel blends, against diesel fuel. Ethanol was used for blending because it has a high antiknock index number, is relatively less expensive and is less corrosive. Experiments were conducted on a single-cylinder, 4-stroke, naturally aspirated direct injection diesel genset engine running at a constant speed for six different load conditions. Experimental data were analyzed in detail, and has been explained from diverse phenomenological standpoints. Results show strong correlation between specific combustion parameters like heat release rate, rate of pressure rise with noise and vibrations characteristics. The technological viability of using such blended fuels for genset applications has been explained through linkages between noise, vibration and combustion, characteristics of the diesel genset engine.

Keywords: A-Weighting Noise, 1/3rd Octave Band, Compression Ignition Engine, Vibration, Fast Fourier Transform

1. Introduction

Diesel engines are most commonly used internal combustion (IC) engines, possessing excellent drivability and fuel economy. These engines are widely used in agriculture, transportation, and industries. The contribution of diesel vehicles to air and noise pollution has increased due to their increasing demand. Air and noise pollution leads to serious health issues related to cardiovascular, respiratory diseases and hearing loss [1].Increasing global concerns over these health issues and rapid depletion of fossil petroleum reserves, is driving the search of clean and sustainable sources of energy. Diesel engines conventionally use diesel as a primary fuel. However, alternative fuels such as alcohols, biodiesels and ethers are being increasingly investigated due to their potential capability to reduce environmental pollution [2].These alternative fuels can be used in unmodified engines or engines requiring minimal modifications [3, 4].

Uludamar et al. [5] have experimentally investigated noise and vibrations characteristics in an unmodified diesel engine using different biodiesel blends. They conducted a regression analysis using linear and non-linear models to predict the relationship between fuel properties and vibration characteristics of the diesel engine. They reported a reduction in the vibrations of engine block when CI engine runs on biodiesel due to the presence of inherent oxygen in the fuel. Taghizadeh-Alisaraei et al. [6] have conducted experimental work on a diesel engine using canola and soybean biodiesel blends. They reported lower vibrations in engine when it was running on pure diesel compared to biodiesel. Fattah et al. [7] have investigated the effect of biodiesel fuel on generation of engine noise. They observed that chemical and physical properties of fuels play an important role in noise production. They reported a reduction in engine noise while using biodiesel, and correlated engine noise to the reduction in cylinder peak pressure relative to diesel. Redel-Macias et al. [8] have investigated the use of diesel fuel, and its blend with olive pomace oil methyl ester in a CI engine. They reported reduction in engine noise while using biodiesel as a fuel and attributed it to its high cetane number. Torregrosa et al. [9] have investigated the use of synthetic and vegetable oils in production of combustion noise from a direct injection diesel engine. They reported deterioration in combustion noise with increase in percentage of biodiesel. Moreover, a more apparent deterioration in combustion noise was reported with use of synthetic oil. In both cases, noise deterioration was attributed to difference in combustion phasing and fuel injection rates. How et al. [10] have conducted vibration investigation of biodiesel and diesel blends in a diesel engine equipped with high pressure common rail system. They observed a reduction of 13.7% in engine vibration amplitudes while using biodiesel-diesel blend relative to diesel fuel. This engine vibration reduction was attributed to reduction in cylinder pressure developed during the combustion process. Lee et al. [11] have studied correlation between maximum heat release rate and vibration in a diesel engine. They reported vibrations in 0.3-5 and 1.5-2.5 kHz frequency bands attributable to combustion process and piston slap respectively. Even though a significant amount of research work has been conducted on combustion, emissions and performance of diesel engines driven by alternative fuels. Not many researchers have reported on noise and vibration characteristics of such engines. Research work was conducted in two steps, first step, involves preparation of stable diesel-ethanol blends. In the second step these blends fuelled a genset engine to study combustion, noise and vibration characteristics for diesohol driven diesel engines. This work fills this gap to a certain extent.

2. Experimental setup and methodology

Present research involves, application of a single cylinder, water-cooled, 4-stroke, direct injection diesel genset. The stationary genset engine has a power capacity of 7.4 KVA, and its rated RPM is 1500. The schematic of genset engine attached with various measuring devices is shown in Fig. 1. An AC-alternator with a rated power of 7.4 KVA was coupled with the genset to convert mechanical shaft energy to electrical energy. Brake thermal efficiency of the engine was computed by measuring fuel consumption using a glass burette at each engine load. An emissions gas analyser (Digas; AVL-4000) was used to record regulated emission levels of carbon monoxides (CO) and hydrocarbons (HC) for different engine load and test fuels.

In-cylinder pressure signal was acquired using a piezoelectric pressure transducer which was installed in the cylinder head. Information of crack angle rotation was acquired by a rotary encoder which was attached to the crank shaft. The in-cylinder pressure and crank angle rotation information was acquired by a high speed combustion data processing system (computer-1). The same pressure and crank angle rotation signals were acquired by another advanced data processing system µDCAT (computer-2) for predicting combustion noise. Total engine and exhaust noise were measured by two microphones (i.e., Mic-1 and Mic-2) which were kept at two different locations (Fig. 2).These microphones are half-inch in diameter, and of pressure-field type (B & K; 4192). Consistent with ISO 9614-2, Mic-1 was kept 1m away from the genset. As per SAE- J1287, Mic-2 was placed at the end of the engine exhaust. The experimental engine was fixed on a concrete bed using vibration isolating pads made of rubber in engine laboratory. The engine was surrounded by thick brick walls (0.38 m) at two adjacent sides and other two sides were exposed to open environment (Fig. 2).

Real time pressure signals of in-cylinder, exhaust and total engine noise were acquired by various devices. These raw signals were further processed to compute into sound pressure level by using signal processing techniques in matlab environment.

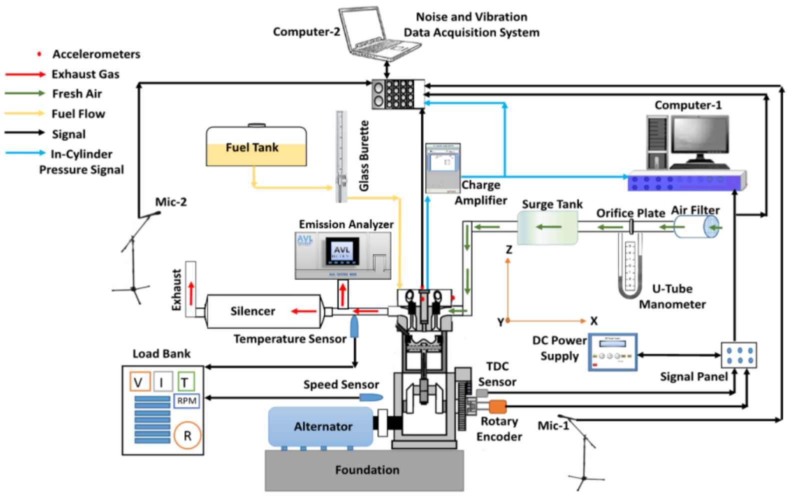

Figure 1: Schematic of experimental set-up

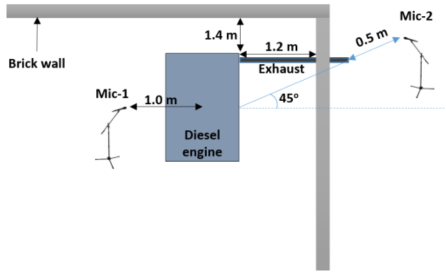

Figure 2: Location of microphones

Three single-axis accelerometers (B&K; 4517) were used to acquire engine vibrations in X, Y and Z directions as shown in Fig. 1. Acquired analog signals were digitized by A-D convertor modules. Noise and vibration signals were recorded by LabVIEW software (version-2012) at a sampling frequency of 25.6 kHz. Experiments were conducted at 1500 RPM, 200 bar fuel injection pressure (FIP) for six engine loads (i.e., from 0 to 100% in steps of 20%). In-cylinder pressure signals were acquired for 250 cycles.

2.1 Test fuel preparation and their characterization

Alternative fuels such as alcohols are considered as relatively clean. Theoretically, any, alcohol can be used as a fuel. However, technical and economic factors constrain the use of only a few alcohols in an IC engines. Alcohols can be used in the engine either in pure form or in blended form. Blends of alcohol and diesel are referred as "Diesohol". In the present investigation, ethanol was chosen to blend with diesel fuel. An important consideration that needs to be taken into account while blending ethanol with diesel is to prevent phase separation of diesel and ethanol constituents. The use of emulsifiers or co-solvents are possible solutions to get a stable blend. In present research, co-solvent, 1-dodecanol was used to avoid phase separation between ethanol and diesel. Co-solvent 1-dodecanol possesses nearly the same heating value, high ignition temperature and high viscosity as that of diesel [12, 13].

Diesel fuel was procured locally. Ethanol (99.9% pure) was procured from Changshu Hongsheng Fine Chemical Co., Ltd (China), and 1-dodecanol (98% pure) was procured from Loba-chemie private limited (India). Fuel blends were prepared on the basis of their oxygen content. Tables 1 and 2 show test fuel's constituents and their properties respectively.

Table 1: Composition of Test Fuel

Test fuel name	Diesel (%v/v)	Ethanol (%v/v)	1-Dodecanol (%v/v)	Oxygen (%w/w)
Diesel	100	-	-	0
DEDOD1	96.1	2.9	1	1
DEDOD2	93.0	6.0	1	2
DEDOD3	90.0	9.0	1	3
DEDOD4	86.9	12.1	1	4

Table 2: Physical properties of Test Fuels

Test fuel name	Density (kg/m^3 @ 30^{o}C)	Kinematic viscosity (m^2/s@ 40^{o}C)	Calorific value (MJ/kg)
Diesel	828	2.89e-6	43.86
DEDOD1	826	2.61e-6	43.56
DEDOD2	824	2.67e-6	42.81
DEDOD3	823	2.81e-6	42.71
DEDOD4	822	2.63 e-6	42.69

3. Results and discussion

3.1 Noise analysis

Plots of combustion noise, exhaust noise and total engine noise for different engine load and test fuel combinations are shown in Figs. 3, 4, and 5 respectively. Based on these data, we make the following observations.

3.1.1 Combustion noise

- Combustion noise is produced due to combustion of fuel inside the engine cylinder and the consequential pressure rise in it. These pressure fluctuations inside the cylinder cause the cylinder to radiate noise, the magnitude of which is strongly dependent on cylinder stiffness as well as the spectrum of these pressure cycles. Data on pressure cycles inside the cylinder was acquired by pressure transducer as shown in Figure 1. The acquired in-cylinder pressure signal was transformed into frequency domain using FFT. Next, the effect of cylinder stiffness was accounted by using a Lucas structural attenuation decay [14] over the FFT of the original signal. Finally, A-weighting filter for 1/3rd octave bands was applied to these processed data to account for the relative loudness perceived by the human ear.

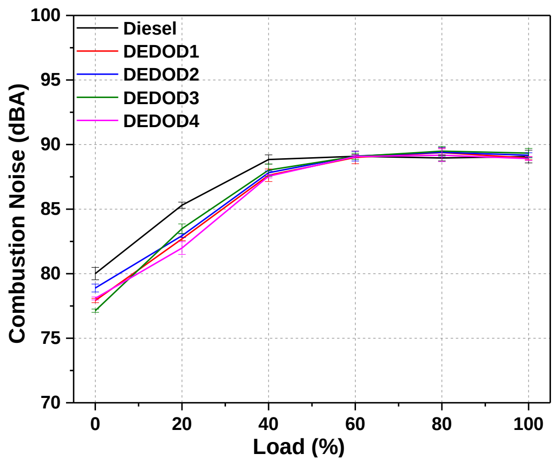

Figure 3: Combustion noise for different engine loads and fuels

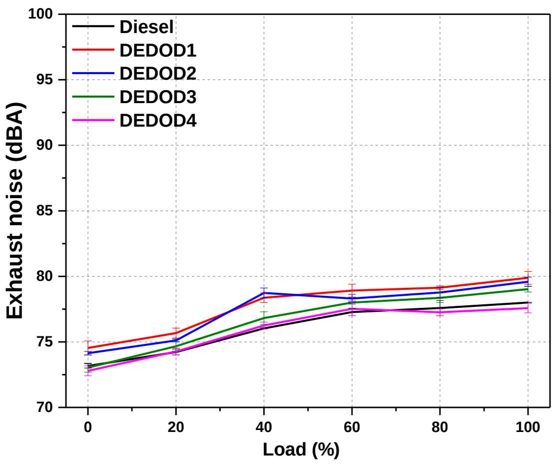

Figure 4: Exhaust noise for different engine loads and fuels

- For loads less than 60%, diesel fuel produces maximum noise other test fuels for this load range, the difference in noise produced by diesel run engine and diesohols gradually decreases. We also note that as alcohol content increases, combustion noise reduces. For a specific low- load level, combustion noise is seen to vary by as much as 2.7 dBA between different test fuels.

- At loads exceeding 60%, combustion noise levels corresponding to all fuels become more or less similar. However, upon closer scrutiny, we note that diesohols in general tend to be slightly more noisy compared to diesel. This extra noise produced by diesohols is not more than 0.5 dBA at 80% and 100 % load levels.
- We finally note that for all loads, combustion noise initially increases with load and then flattens out at loads in excess of 60%.
- Similar trends for combustion noise have also been reported by Giakoumis et al. [15].

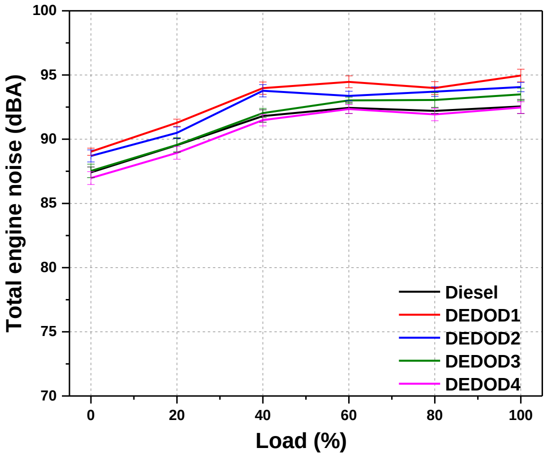

Figure 5: Total engine noise for different engine loads and fuels

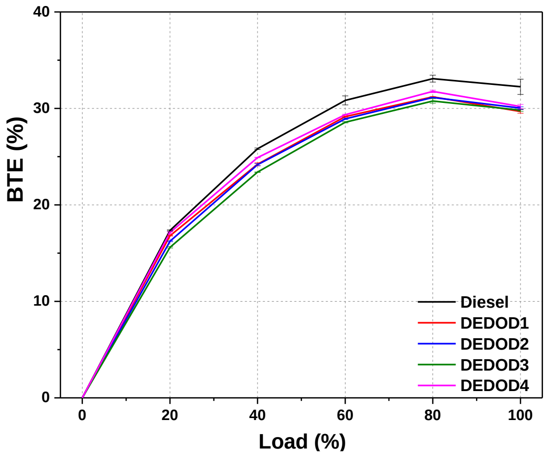

Figure 6: BTE for different engine loads and fuels

3.1.2 Exhaust noise

Exhaust noise gets attenuated while travelling from exhaust manifold coupled with the silencer. It was observed that exhaust noise increases with increase in the engine load irrespective of the test fuels. Exhaust noise level was observed between 73-80 dBA for all test fuels. Diesohols shows relatively higher exhaust noise compared to diesel fuel. Specifically, exhaust noise is highest for DEDOD1, then for DEDOD2, followed by DEDOD3 and then for DEDOD4among diesohols. The spread of noise for a given load between test fuels is approximately 2.0 dBA.

3.1.3 Total noise from the engine

Total noise from the engine is overall noise produced from the engine. It is a combination of combustion noise, mechanical noise and exhaust noise. Raw data in real time for this noise was acquired from Mic 1 (Fig. 2). These data were mapped onto frequency domain using the FFT technique. Finally, A-weighting filter was used to account for the relative loudness perceived by the human ear. The characteristics of total noise from engine are similar to that of exhaust noise, since this component is the most dominant. However, the overall level of total engine noise is more than that for exhaust noise. Diesohols run genset engine generates more total engine noise than diesel run genset engine. In general, DEDOD1 produces maximum noise and DEDOD4 is least noisy. Next, we explore combustion characteristics of the engine correlate those with its noise characteristics.

3.2 Combustion analysis

Combustion noise is made up of high as well as low frequency content. While low frequency content in combustion noise is attributable to peak pressure level, the high frequency content is attributable to rate of pressure rise [14]. Figs. 7 and 8 depict pressure, and rate of pressure rise (ROPR) response for the test engine corresponding to different fuel-load combinations. It is observed from these figures that peak pressure increases with increase in engine load. It is also noted that the ROPR response initially increases steadily but somewhat slowly, then very rapidly, and finally it decays to very low levels. In this context, we note the following.

- The engine's pressure curves as a function of crank angle position are more or less same across all test fuels. The same may be said for the ROPR response.
- A detailed analysis of ROPR plots shows that diesohols tend to start burning a few crank angle degrees later. However, this delay in start of combustion is not significant.
- However, it should be noted that the calorific value of diesel is somewhat higher compared to other test fuels. Thus, we would expect higher heat and hence higher peaks of ROPR. This is explicitly seen in ROPR plot at 0% engine load.
- Further, ethanol has inherent oxygen content which is absent in the case of diesel. The presence of oxygen tends to smoothen the combustion process, especially at low engine loads. This has also been reported by Giakoumis et al. [15].
- The duel effects of oxygen content and lesser calorific values tends to facilitate a quieter combustion process at loads for diesohols. The larger is the magnitude of these effects, lesser is combustion noise.

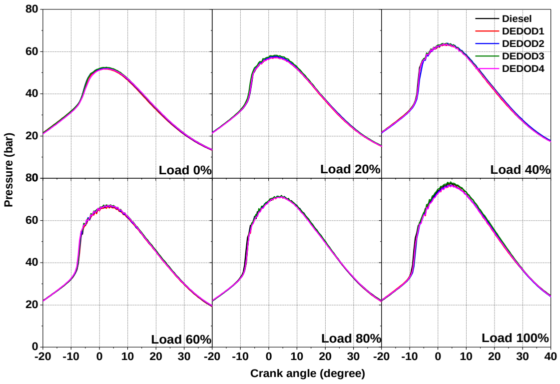

Figure 7: Pressure for different engine loads and fuels

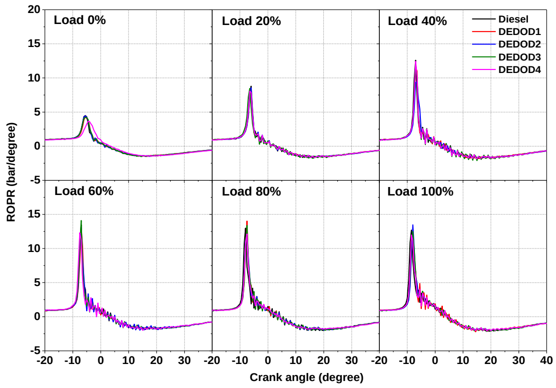

Figure 8: ROPR for different engine loads and fuels

- With increasing engine load, fuel-air mixture becomes progressively richer. Consequently, knocking starts [16]. The extent of knocking is reportedly higher for alcohols than diesel. This phenomena is also seen in ROPR curves, especially for high engine loads through their non-smooth nature. The phenomena of knocking tends to compensate the effect of inherent oxygen content. Hence at higher engine loads, combustion noise tends to be more or less same for all test fuels.

Next, the phenomena of exhaust noise is discussed in context of engine combustion and performance parameters. Fig. 6 shows the variation of engine efficiency for different loads and fuels. It is seen that diesohol-driven engine is less efficient at all engine loads compared to a diesel-driven engine. The difference in this efficiency does not change significantly over engine operating load range. A lesser efficient engine implies higher values of brake specific hydrocarbon (BSHC) and brake specific carbon monoxide (BSCO) emissions (Figs. 10 and 11), as well as higher amount of waste energy (Fig. 9). Much of this waste energy is emitted out to atmosphere through exhaust. Thus, it would be expected that diesohol run engines would produce more exhaust noise than diesel run engines. This is indeed what is seen in Fig. 4. It is noted that diesohols produce more exhaust noise relative to diesel across at all engine loads. Finally it should be noted that in the experimental setup, exhaust gases ran through a long pipe and a large silencer placed in a closed room. The outlet of the silencer was placed out in the open. Thus the silencer and pipes acted as sources of vibro-acoustic noise which got radiated out in the room only to be picked up by the mic-1 as a significant component of total engine noise. The reverberation in the engine laboratory also enhanced this noise further. For this reason, the characteristics of exhaust noise and total noise are very similar.

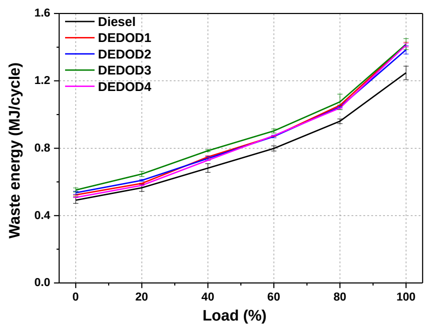

Figure 9: Waste energy for different engine loads and fuels

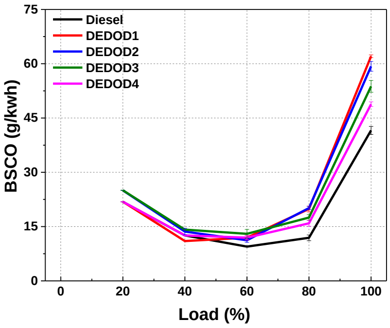

Figure 10: BSCO for different engine loads and fuels

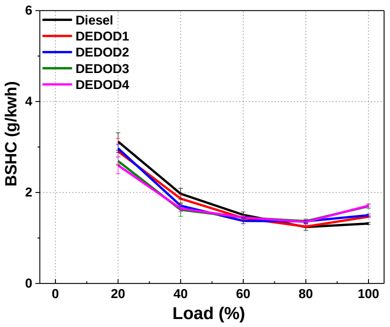

Figure 11: BSHC for different engine loads and fuels

3.3 Vibration analysis

Fuel burns inside the combustion chamber leads to pressure rise and exerts a large pressure on internal wall of the combustion chamber. This highly fluctuating pressure phenomena is responsible for the engine to vibrate and leads to resonance of engine block. Engine vibration is mainly affected by movement of piston attached to the crank, engine foundation, timing gear system, coolant flow, inlet and outlet gases, fuel inlet and outlet through injector system and inertia of moving components [17]. Vibration signals were measured by accelerometers and their root mean square (rms) value were calculated in X, Y and Z directions. As shown in Fig. 12, the acceleration value was observed least

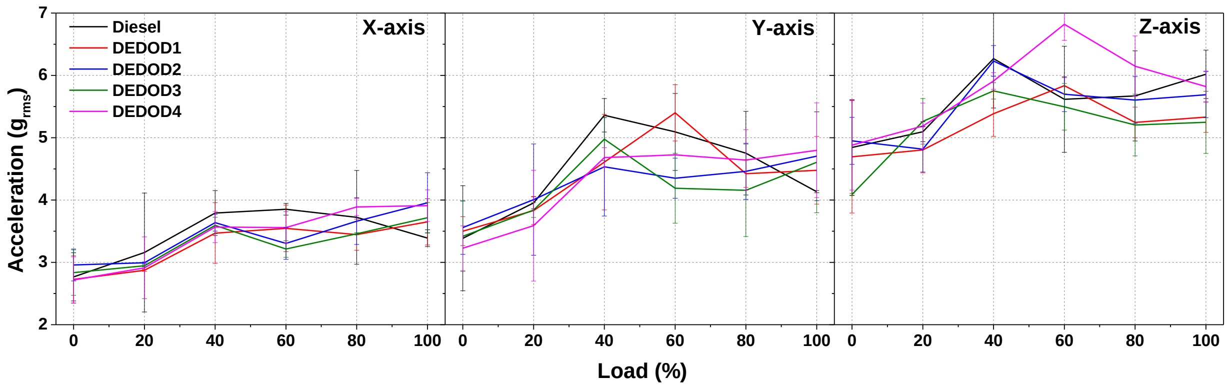

Figure 12: Accelerations for different engine loads and fuels

in X-direction followed by Y and Z-directions. It is seen that for a given engine load vibration amplitudes are highest in Z-direction. This is because the Z-direction is aligned with the direction of piston motion. It is also noted that vibrations amplitudes in the Y-direction are somewhat higher than those in the X-direction. This is because the piston pushes against cylinder walls in the Y-direction. Further, it is noted that acceleration amplitudes increase with engine load. Finally we note that while g-levels across fuels are similar at low engine loads, diesohols tends to excite the engine more at high engine loads. This may be attributable to the effect of knocking which becomes pronounced for diesohols at high engine loads.

4. Conclusions

In this work noise, vibration and combustion characteristics of diesohols were compared to those for commercial diesel fuel for a genset application. Diesohols produce less combustion noise relative to diesel at low engine loads, and comparable combustion noise at higher loads. Further, exhaust as well as total engine noise for diesohols is about 2.5 dBA higher across all load levels. Further, diesohol run engines show somewhat increased vibration in all measured directions compared to diesel at high engine loads.

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