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Exploring Noise and Vibration Challenges in Variable Compression Ratio Diesel Engines: Impact, Factors, And Mitigation Strategies

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Abstract

With diesel engines maintaining their significance across various sectors, there is a critical necessity to recognize and address noise and vibration concerns. This contribution explores the sources of combustion noise and vibration, particularly in variable compression ratio (VCR) diesel engines. It evaluates the impact of these factors on engine performance and overall comfort. Additionally, the study discusses advancements in reducing noise and vibrations through design enhancements and noise control strategies. The results show that heat release rate (HRR), biodiesel blends, and VCR technology strongly influence the noise and vibration characteristics of VCR diesel engines. Future research directions to optimize engine performance, reduce vibrations and noise, and enhance comfort are also highlighted in this work.

Keywords:Diesel engines, noise, vibration, variable compression ratio, combustion, heat release rate, biodiesel blends.

Abbreviations

VCR	Variable compression ratio	HES	Hydrogen energy share
HRR	Heat release rate	CWT	Continuous wavelet transform
OEM	Original equipment manufacturers	KB20	Karanja biodiesel blend
AVL	Approved vendor list	KB100	Karanja biodiesel (KB100)
JB100	Jatropha biodiesel	ZnO	Zinc oxide
JB20	Jatropha biodiesel-diesel blend	BOME20	Baheda oil biodiesel blend
ON	Overall noise	DSP	Diphenyl sulfone
TDC	Top dead centre	FSOME	Flaxseed biodiesel
CR	Compression ratio	NSOME	Neem oil biodiesel
MOB	Mustard oil biodiesel	RMS	Root mean square

1 Introduction

Noise and vibration are inevitable outcomes of operating variable compression ratio (VCR) diesel engines, stemming from the intricate interplay of mechanical components and combustion processes within the engine. Diesel engines are recognized for generating diverse sources of noise, with combustion noise and mechanical noise emerging as primary contributors [1,2]. Combustion noise, originating from the swift ignition of diesel fuel in the cylinders, can fluctuate based on injection timing and combustion chamber design [3]. Moreover, valve train noise, resulting from the operation of intake and exhaust valves, adds to the overall noise produced by the engine. On the other hand, the complexity of vibrations in diesel engines arises from various factors influencing the oscillating movement of engine components. Unbalanced weight distribution in rotating components such as the crankshaft or flywheel can create vibrational forces that impact the engine's smooth operation [4, 5]. Reciprocating elements like pistons and connecting rods contribute to vibrations due to their movement within the cylinders. The efficacy of engine mounts in isolating and dampening vibrations plays a critical role in alleviating engine-induced vibrations.

To combat noise and vibration challenges in diesel engines, several techniques can be implemented. These include optimizing the balance and alignment of engine components to minimize vibrations, incorporating vibration-absorbing materials in critical areas to reduce oscillation transmission, and integrating soundproofing materials to decrease noise levels [6, 7]. Recent studies emphasize the importance of addressing fundamental aspects of noise and vibration in diesel engines to improve engine performance, longevity, and user comfort. This article explores the noise and vibration characteristics, particularly in VCR diesel engines, clarifying various factors that influence combustion noise, vibrations, and their impact on engine operation, reliability, and overall comfort. The significance of comprehending combustion noise, heat release rate (HRR) dynamics, the effects of biodiesel blends, and VCR technology on noise and vibration characteristics, as well as the necessity of exploring future research directions to optimize engine performance and reduce vibrations, is highlighted.

2 Noise characteristics

2.1 Combustion noise

Combustion noise in diesel engines, also known as diesel knock or combustion knock, originates from the abrupt ignition of the fuel-air mixture in the combustion chamber [8]. It is characterized by a distinctive metallic clanking sound that can be quite pronounced, especially in older or poorly maintained engines. Diesel knock occurs when fuel combustion is disrupted due to factors such as inadequate fuel quality, injection timing issues, engine calibration discrepancies, or injector malfunctions [8, 9]. Excessive combustion noise can be discomforting and may indicate underlying issues like engine misfires, decreased fuel efficiency, or compromised engine performance. Regular maintenance and calibration play a crucial role in minimizing combustion noise and ensuring optimal engine functionality [10]. Furthermore, other studies suggest that combustion noise can be mitigated through exhaust gas recirculation (EGR) [11, 12]. Figure 1 illustrates the baseline combustion noise level of a modern diesel engine passenger car, calculated following the combustion noise level standards set by AVL List GmbH.

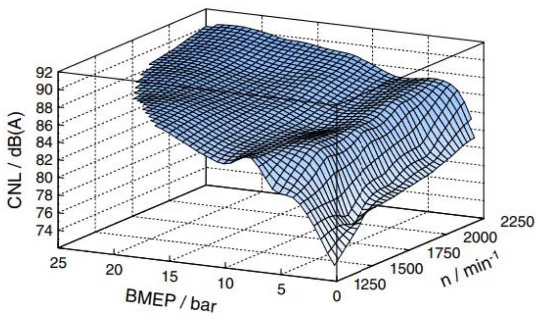

Figure 1: Combustion noise of an actual diesel engine passenger car [10].

Biodiesels/blends exhibit substantially increased combustion noise due to variations in combustion phasing and injection rates [13]. Patel et al. [14] examined the impact of mineral diesel, Jatropha biodiesel (JB100), and a combination of Jatropha biodiesel and diesel (JB20) on the levels of combustion noise and vibrations. The researchers conducted a comparison of the variations in noise levels between a motored engine and a fired engine, as depicted in Figure 2. At some specific frequencies, the noise produced by the operation of a motor exceeds the noise generated by an engine that has been ignited.Despite such exceptions, they noted that the majority of the engine's noise is mostly caused by combustion (Figure 3). Torregrosa et al. [15] found that the overall noise (ON) is correlated with three indicators: one operation indicator that quantifies the contribution of engine speed to noise, and two combustion indicators, I_1 and I_2, which characterize the sudden in-cylinder pressure rise and the induced high-frequency gas oscillation inside the combustion chamber, respectively. The overall noise level can then be estimated by the following equation [15, 16,17]:

$$ON = C_O + C_n I_n + C_1 I_1 + C_2 I_2 \quad (1)$$

where C_O are coefficients which depend on the engine size and architecture.

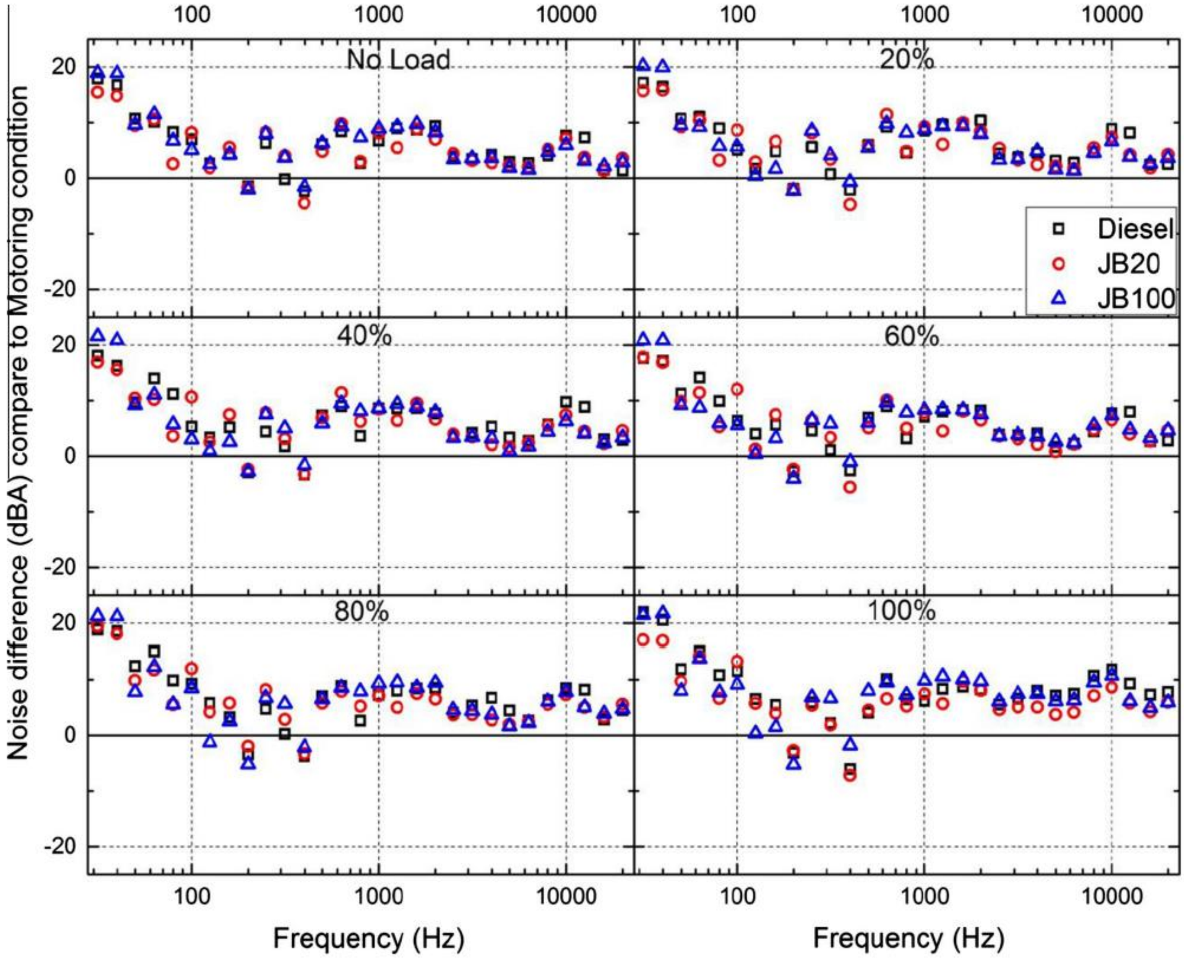

Figure 2: Difference in noise levels of a motored engine relative to a fired engine using different test fuels at varying loads [14].

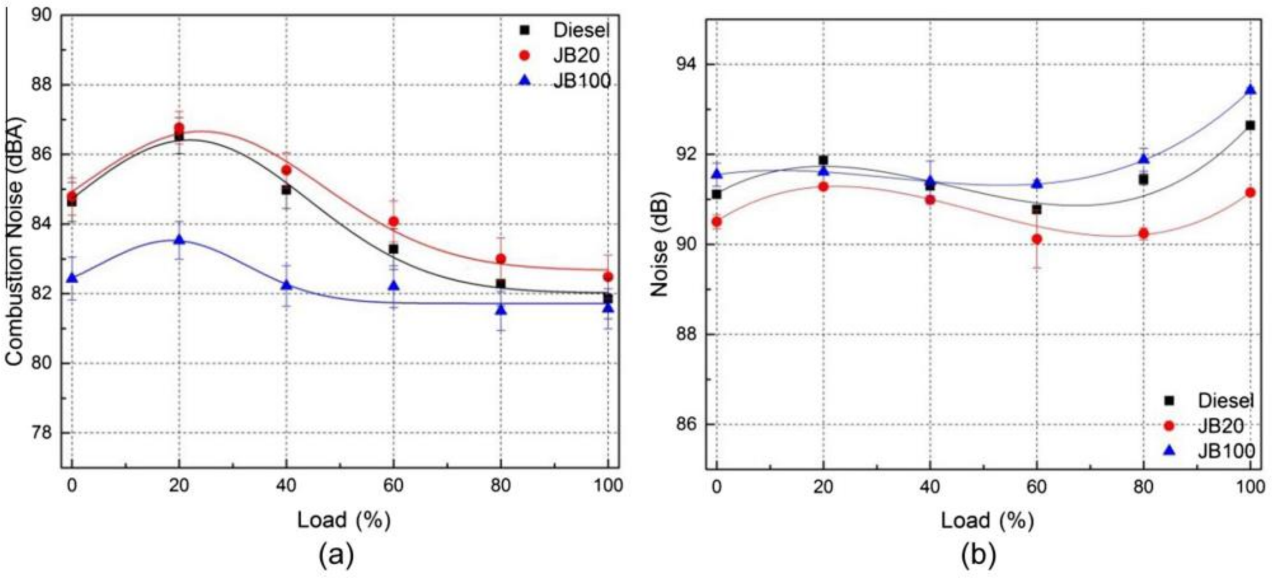

Figure 3: (a) Combustion noise, and (b) External noise using different test fuels [14].

Wang et al. [18] conducted a study comparing homogeneous combustion mode with conventional combustion mode, as illustrated in Figure 4. They found that homogeneous combustion significantly influences the interior noise of vehicles. Most existing noise isolation solutions in vehicle bodies are effective only for high frequencies (>1000 Hz). Therefore, for diesel engines operating in homogeneous combustion mode, it is crucial to focus on enhancing engine structural attenuation, especially in the mid-frequency range to keep the engine's radiated combustion noise within acceptable limits. In contrast, Torregrosa et al. [19] demonstrated that engine noise is strongly affected by factors like the start of injection and intake oxygen concentration, while injection pressure has minimal impact. The most favourable engine noise quality was achieved with the lowest intake air oxygen concentration (10%) and a more advanced injection timing (between -46 and -30 degrees after the top dead center) for reduced pollutant emissions, as depicted in Figure 5.

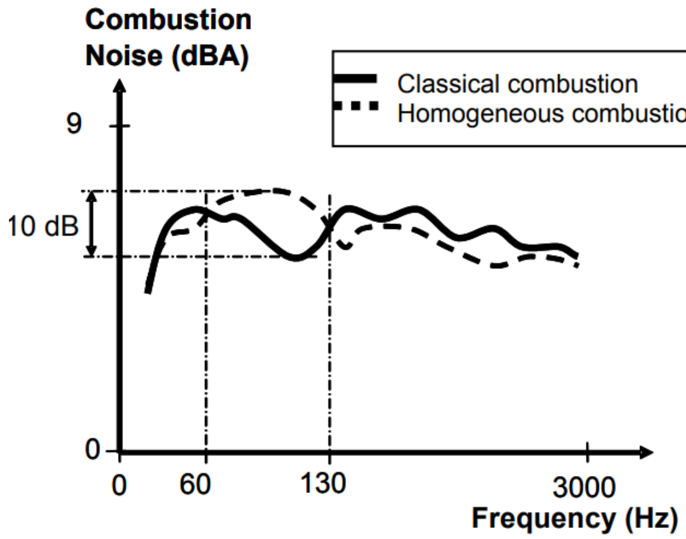

Figure 4: Comparison of combustion noise spectrum between classical combustion and homogeneous combustion [18].

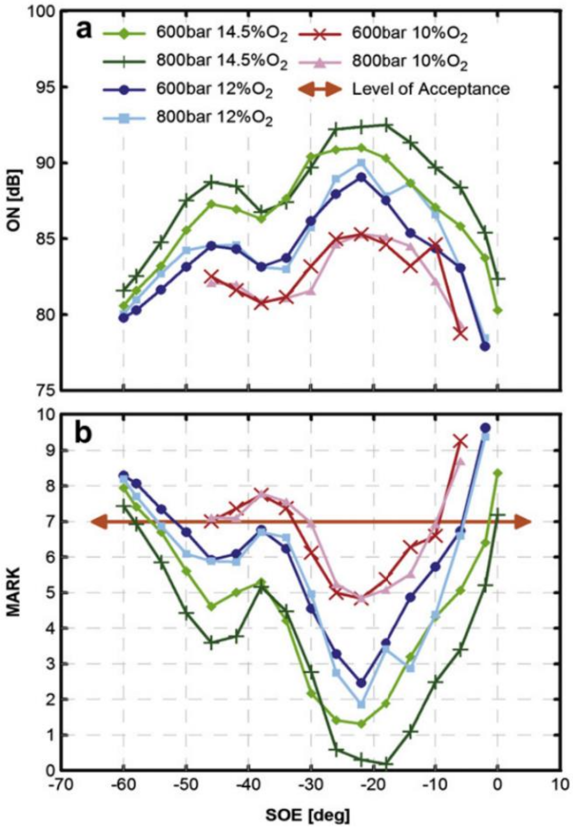

Figure 5: Combustion noise characterization at all tested conditions:

(a) Overall noise and (a) Sound quality [19].

2.2 Impact of heat release rate

The HRR in VCR diesel engines has a direct impact on combustion noise levels. Studies have shown that a faster HRR typically leads to a more abrupt pressure rise during combustion, resulting in increased noise levels [20, 21]. This phenomenon is often referred to as combustion noise or diesel knock. Researchershave been striving to implement optimization strategies that will control the HRR in VCR diesel engines to minimize combustion noise while maintaining optimal engine performance. Thus, strategies such as optimizing injection timing, adjusting compression ratios (CRs), and enhancing combustion chamber design have been found useful in mitigating the impact of HRR on combustion noise in VCR diesel engines, leading to quieter and more refined engine operation [22].

Numerous studies have indicated that controlling the heat release phases can effectively reduce combustion noise in premixed diesel engine combustion. Labeckas, Slavinskas, and Kanapkienė [23] demonstrated that a lower HRRmax value is associated with decreased combustion noise, while a higher HRRmax value leads to increased noise levels. Sarıdemir and Polat [24] also highlighted a strong connection between HRRmax and combustion noise/vibrations along the engine's piston movement direction. Giakoumis, Rakopoulos, and Rakopoulos [25] suggested that higher combustion noise is linked to elevated HRRmax during the premixed combustion phase. Additionally, Shibata, Ushijima, and Ogawa [26] experimentally showed that extending the combustion duration and reducing the maximum HRR value can effectively reduce combustion noise.

The reviewed literaturehasemphasized the importance of considering factors like engine speed, in-cylinder pressure rise, HRR, and high-frequency gas oscillations in characterizing overall combustion noise. This suggests a need for more comprehensive studies to develop precise models for estimating and reducing combustion noise levels in diesel engines.With that being said, future research efforts could focus on optimizing combustion phasing, injection timing, and intake oxygen concentration to minimize combustion noise while maintaining engine efficiency. Additionally, exploring innovative solutions for engine structural attenuation in the mid-frequency range could be beneficial for reducing radiated combustion noise in vehicles with homogeneous combustion modes [18].

3 Vibration characteristics

Vibrations in VCR diesel engines are a common concern that can arise from various sources within the engine system. These vibrations can impact engine performance, durability, comfort, and overall operation [27]. Sources of these vibrations may include engine imbalance, misalignment of components, worn or damaged parts, combustion irregularities, and resonance of engine structures [27, 28]. Studies have shown that excessive vibrations can lead to increased stress on engine components, accelerated wear, reduced engine efficiency, and potential overall discomfort [29, 30]. In addition, other researchers have reported that sound pressure level and vibration acceleration of the test engine increases with engine speed [31, 32]. This suggest that engine speed has a considerable effect on engine vibration. For example, when engine speed increases, vibration level also increases.

3.1 Effect of hydrogen addition

Hydrogen addition in diesel engines is known to have a few effects on vibrations. The combustion characteristics of hydrogen differ from diesel fuel, leading to changes in the combustion process. Hydrogen's fast combustion rate can alter the pressure rise profile during combustion, potentially affecting the level and frequency of vibrations in the engine [33]. Additionally, hydrogen combustion tends to be more stable and complete, which can reduce combustion noise and some forms of vibration associated with incomplete combustion [33, 34]. However, few studies have shown that the introduction of hydrogen may also lead to changes in engine dynamics and operating conditions, which could result in new sources of vibrations [35, 36]. Thus, it is essential to carefully monitor and optimize engine parameters when incorporating hydrogen to minimize any adverse effects on vibrations and ensure smooth engine operation.

Tüccar [37] conducted a research study investigating the impact of dual-fuel operation on engine vibration. The study involved fuelling the test engine with diesel fuel, mustard oil biodiesel (MOB), and a blend of MOB, diesel fuel, and hydrogen gas. The findings of the study revealed that the introduction of hydrogen gas resulted in a reduction in engine vibration. This was attributed to improved operational stability achieved through easier ignition of MOB and hydrogen mixtures. Similarly, Çelebi, Uludamar, and Özcanlı [38] illustrated that introducing hydrogen gas through the intake manifold led to a decrease in engine vibration for both conventional diesel engines and biodiesel blends.Nguyen and Mikami[39] revealed that the variations in sound pressure level due to hydrogen addition were dependent on engine speed, while vibration acceleration decreased consistently with the addition of gas across all engine speeds. These findings were corroborated by Nag et al. [40], when they demonstrated the advantageous effects of hydrogen supplementation on noise and vibration levels, particularly at low and mid-range loads. Their experimental investigations were conducted at load conditions of 25%, 50%, and 75%, substituting diesel with hydrogen at energy shares of 0%, 5%, 10%, and 20%. The calculation of the hydrogen energy share (HES) was determined using the following equation:

$$HES = \frac{\dot{m}_{hydrogen} LCV_{hydrogen}}{\dot{m}_{hydrogen} LCV_{hydrogen} + \dot{m}_{diesel} LCV_{diesel}} \quad (2)$$

Where $LCV_{hydrogen} = 120 \times 10^3 \frac{kJ}{kg}$ $and\ \dot{m}_{hydrogen,}\ \dot{m}_{diesel}\left(\frac{g}{s}\right)$ $are\ fuel\ mass\ flowrate$

3.2 Influence of heat release rate

The HRR in diesel engines plays a crucial role in determining engine performance, emissions, and efficiency. Many studies have previously shown that a higher HRR typically results in increased combustion intensity and peak cylinder pressures, leading to improved engine power output [41, 42]. However, excessively rapid heat release can also contribute to higher levels of vibration and engine stress. It is essential to strike a balance in the HRR to ensure optimal combustion efficiency, fuel economy, and emissions control. Other studies have indicated that advanced engine design strategies, such as optimizing fuel injection timing, spray characteristics, and air-fuel mixing, can help manage the HRR effectively. This optimization can maximize engine performance while minimizing undesirable consequences like engine vibration and mechanical wear [43, 44].

Recent findings have suggested a strong connection between the maximum HRR and the intensity of vibrations. For instance, Ashok et al. [45] observed a direct relationship between changes in maximum HRR and the level of engine vibrations. On the other hand, Lee et al. [46] noted that the correlation between the 0.3–5 kHz vibration signal and the maximum RoHR (Figure 6) was inconclusive due to the non-linear nature of the relationship between these factors and slap motion vibration strength. However, the 0.3∼5 kHz vibration signal was identified to be linked with the combustion process. In a separate study, Lee et al. [47]analysed the vibrations on an engine block induced by combustion in a diesel engine. The frequency of direct combustion-induced vibrations ranged from 0.1 to 8 kHz immediately post-combustion, indicating a proportional relationship between vibration and RHR.

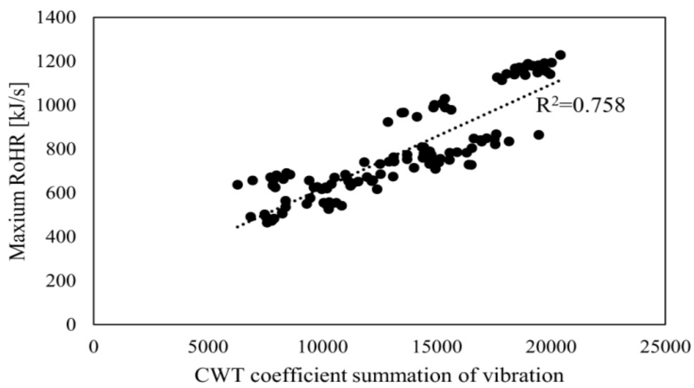

Figure 6: Correlation between the maximum RoHR and continuous wavelet transform (CWT) summation of the 0.3∼5 kHz region [46].

Previous works have certainly explored how changes in hydrogen addition and HRR can impact engine vibrations, providing valuable insights for future research directions.The addition of hydrogen to diesel engines has shown promise in reducing vibrations, although there are still gaps in understanding the entire spectrum of effects it may introduce to engine dynamics. On the other hand, the correlation between HRR and vibrations has been demonstrated in studies, highlighting the need for precise management of combustion processes to mitigate vibrations effectively. Future research should focus on fully comprehending the interplay of combustion characteristics, fuel qualities, operational factors, and vibration levels in VCR diesel engines to optimise performance, reduce vibrations, and improve overall engine reliability and comfort.

4 Effect of biodiesel blends

The integration of biodiesel blends into diesel engines has sparked significant interest due to its potential environmental benefits and renewable nature. When examining the effects of biodiesel blends on the vibration and noise characteristics of diesel engines, several key factors come into play. One primary consideration is the different combustion properties of biodiesel compared to traditional diesel. Biodiesel has been known to exhibit differences in combustion efficiency, ignition characteristics, and flame propagation rates, which can directly impact engine noise levels and vibration patterns during operation [48, 49]. Recent studies have suggested that the lubricating properties of biodiesel also play a role in influencing engine noise and vibration. Biodiesel blends often possess higher lubricity compared to conventional diesel, potentially reducing friction between moving engine components and leading to smoother engine operation [50, 51]. This improved lubrication can result in reduced mechanical noise and vibrations, enhancing overall engine performance and reducing wear on engine parts. However, some studies have indicated that biodiesel often contributes to increased engine emissions. Therefore, it is vital to carefully weigh the options of employing biodiesel blends as a means of reducing noise and vibration in diesel engines.

Patel et al. [52] observed increased combustion noise in the case of a 20% (v/v) Karanja biodiesel blend (KB20) due to a shorter ignition delay and higher HRRmax, while the noise level was comparatively lower for Karanja biodiesel (KB100). Giaokoumis et al. [53] noted slightly higher noise levels with a 30% biodiesel blend compared to baseline mineral diesel. However, other researchers [54, 55, 56] documented reductions in both noise and vibrations when using biodiesels or blends. These were attributed to improved lubricity, vibration-damping properties, and the relatively lower HRRmax of biodiesel. Patel, Tiwari, and Agarwal [57] reported a decrease of 1–3 dB(A) in combustion noise and external noise when using a 20% (v/v) SVO blend with mineral diesel compared to the baseline mineral diesel.Additionally, Jaikumar et al. [58] examined combustion noise and vibration characteristics on a Gen-set engine using soybean and rapeseed biofuels. The study involved the usage of three uniaxial accelerometers to gather vibration data in three perpendicular directions, along with a microphone for measuring external engine noise. The findings indicated that external noise levels for biofuels displayed mixed variations, with the majority demonstrating lower noise levels compared to conventional diesel.

Many researchers have taken a keen interest in studying the impact of fuel variation on noise, vibrations, and engine combustion characteristics. For example, Sivash et al. [59] found that a single-cylinder diesel engine fuelled with biodiesel-diesel blends exhibited noise with peak spectral content around 315 Hz, with lower noise levels observed for blends containing less biodiesel. Bao and He [60] performed experiments on a single-cylinder diesel engine using a 30% rapeseed oil blend with diesel and analyzed the effect of four engine operating parameters, as depicted in Figure 7, on engine noise. Through parameter optimization, they managed to reduce engine noise by 2–4 dB(A). Uludamar et al. [61] noted a decrease in sound pressure level and vibrations with an increase in the percentage of biodiesel in the test fuel. Elshaib et al. [62] reported a reduction in noise levels when blending biodiesel with mineral diesel. Furthermore, Saravanan, Musthafa, and Asokan [63] observed that incorporating biodiesel derived from waste cooking oil into conventional diesel fuel resulted in lower engine block vibrations.

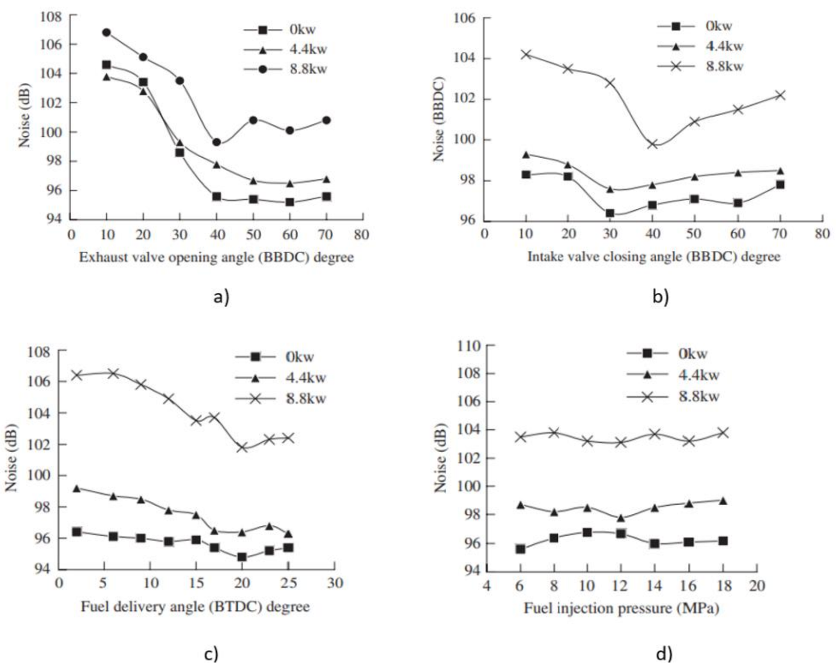

Figure 7:a) Exhaust valve opening, b)Intake valve closing angle,

c) Fuel delivery angle, and d) Fuelinjection pressure [60].

Future research in the field of biodiesel blends and their influence on diesel engine noise and vibration characteristics should prioritise the investigation of various biodiesel sources, understanding the long-term effects on engine performance, determining optimal blending ratios, and conducting application-based studies to evaluate practical outcomes. Standardized testing protocols should be established to facilitate comparisons across studies, while multi-factor analysis and advanced simulation techniques can provide a more comprehensive understanding of how biodiesel blends influence engine noise and vibration [64]. Collaborative research efforts involving researchers, industry partners, and regulatory bodies can immensely assistin accelerating progress in this area, leading to more informed decisions regarding the use of biodiesel blends in reducing noise and vibration in diesel engines.

5 Effects of VCR technology

VCR technology in diesel engines has been found to have a notable impact on noise and vibration characteristics [65]. The ability to adjust the CR dynamically allows for optimized fuel combustion, which can influence the levels and patterns of noise and vibrations produced by the engine. VCR technology can help in enhancing combustion efficiency, which in turn can lead to smoother engine operation and reduced noise levels [66]. Additionally, by optimizing the CR based on different operating conditions, VCR engines can potentially minimize vibrations associated with engine imbalances or irregular combustion. However, variations in CRs may introduce new challenges related to engine dynamics and structural resonance, which could affect noise and vibration characteristics. Few studies that are focused on this area have shown that investigating the effects of VCR on noise and vibration characteristics can provide valuable insights for improving engine performance and overall comfort.

In previous years, many studies have focused on understanding the impact of noise and vibration particularly in conventional diesel engines.Therefore, there is a growing need to understand how varying the CR may impact the diesel engine in terms of noise and vibrations. For instance,Elbanna et al. [67] discovered that a high CR and auto-ignition lead to a rapid pressure increase resulting in vibrations transmitted to the cylinder and engine block. Sanatha, Bhatti, and Jaikumar [68] conducted a vibration and noise analysis on a VCR diesel engine operating with a blend of zinc oxide (ZnO) nanoparticles dispersed in baheda oil biodiesel (BOME20). They observed that increasing the CR led to a gradual increase in vibration and noise levels. Specifically, at a CR of 16.5 (refer to Figure 8), the vibration intensity and noise levels for BOME20 with 75 ppm ZnO and 75 ppm DSP were measured at 0.0792 m/s and 55.2 dB, respectively.

Jaikumar et al. [69] analyzed vibration and noise levels for a VCR diesel engine using blends of flaxseed biodiesel (FSOME). They noted a significant reduction in both vibration and noise levels with FSOME blends, although the CR variation showed a negative impact on vibration and noise. In a related study, More et al. [70] estimated vibration and noise levels for a VCR diesel engine with blends of Neem oil biodiesel (NSOME) and hydrogen at different CRs. They found that combining NSOME and hydrogen enrichment led to lower root mean square (RMS) vibration and noise levels. However, they observed an increase in vibrations and noise with higher CRs.

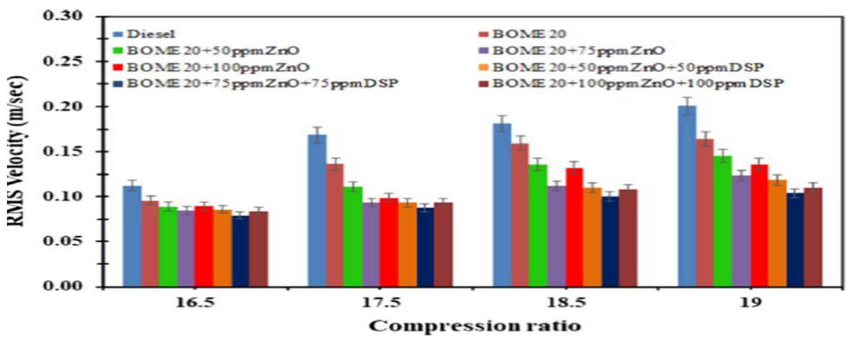

Figure 8: RMS velocity with compression ratio [68].

While research in this area remains limited, certain researchers have contributed significantly to understanding how varying CR affects noise and vibration in diesel engines. Most studies have shown a common trend: an increase in CR leads to higher levels of noise and vibration. However, there is a notable gap in exploring the interactions between CRs, different fuel types, and additives to optimize the balance between engine efficiency and noise/vibration control in VCR diesel engines. Investigating the effects of fine-tuning CRs on specific noise and vibration frequencies to determine the optimal settings for reducing excessive engine noise and vibrations could prove beneficial. Moreover, focusing on the integration of advanced noise and vibration control technologies, such as active noise cancellation or vibration damping systems, with VCR engines, could present innovative solutions for enhancing overall engine comfort and minimizing perceived noise levels. This exploration could pave the way for more refined and efficient VCR diesel engines with improved noise and vibration characteristics.

Conclusions

In this paper, a comprehensive review ofthe noise and vibration characteristics of exhaust systems, particularly in VCR diesel enginesis conducted. The study highlights the critical need to address these issues for improved engine performance, comfort, and reduction of structural wear. The following key findings are drawn from this work:

- The literature survey has strongly emphasised that noise and vibration concerns are significant due to their impact on engine comfort and integrity.
- Combustion noise and mechanical noise are major contributors to overall noise levels.
- Studies have shown that excessive vibrations can lead to increased stress on engine components and reduced efficiency.
- Hydrogen addition can influence combustion characteristics, potentially affecting (reducing) vibrations.
- Optimizing the HRR is essential for managing combustion noise and vibrations.
- Biodiesel blends can reduce engine noise and vibrations due to differences in combustion properties and lubricating effects.
- VCR technology has a significant impact on noise and vibration characteristics by allowing adjustments in the CR for optimized fuel combustion.Thus, increasing the CR has been shown to increase noise and vibration levels.
- Overall, the results emphasize the importance of understanding and optimizing factors such as combustion processes, fuel properties, and engine design to mitigate noise and vibrations in VCR diesel engines effectively.

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