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EXPERIMENTAL STUDY ON COMBUSTION AND VIBRATION CHARACTERISTICS OF LOW-SPEED MARINE DIESEL ENGINE FUELLED WITH BIODIESEL

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ABSTRACT

This study, conducted on a six-cylinder low-speed marine diesel engine (MAN 6S35ME-B9) test bench, systematically investigates the effects of biodiesel-diesel blends (B10, B30, B50) on combustion and vibration characteristics for the first time, addressing a research gap in this area. Using multi-sensor synchronised acquisition of in-cylinder pressure and vibration signals, combined with time-domain (RMS), frequency-domain (FFT), and continuous wavelet transform (CWT) analysis, the research reveals the combustion mechanisms and vibration response characteristics of biodiesel. The results show that biodiesel's high cetane number and oxygen content advanced the peak in-cylinder pressure, with the maximum pressure increasing as the blend ratio increased. However, its lower heating value caused higher brake-specific fuel consumption (BSFC) than D100 fuel. Vibration analysis indicated that biodiesel's RMS values were generally higher than D100's, especially in the 1.0-1.75 kHz mid-frequency band, which is closely related to combustion impacts. Vibration changes in the high-frequency band (1.9-2.5 kHz) might stem from knocking or mechanical impacts, with vibration characteristics showing nonlinear patterns across different blend ratios. This study's application of the CWT method to low-speed engine vibration analysis offers theoretical and experimental support for optimising biodiesel use in ship power systems and new ideas for combustion state monitoring and fault diagnosis based on vibration signals.

Keywords: marine low-speed diesel engine; biodiesel; combustion characteristics; vibration characteristics; continuous wavelet transform

INTRODUCTION

In recent years, with the rapid development of the global economy and the continuous growth of international trade, the global shipping industry's reliance on fossil fuels has deepened. As the primary method for international trade cargo transportation, maritime transport carries over 90% of the global freight volume and its energy consumption issues have garnered significant attention. According to the latest statistics from the International Maritime Organization (IMO), global ocean transport consumes as much as 300 million tons of fossil fuels annually, directly resulting in approximately 35.64 million tons of CO_2 emissions, which accounts for about 2.2% of global anthropogenic CO_2 emissions [1]. Against the current backdrop of intensified global warming and the increasing depletion of traditional fossil resources, especially within the context of the international community actively advancing "carbon peak and carbon neutrality" policies, the development and application of clean and renewable alternative fuels has become an urgent necessity for the sustainable development of the shipping industry.

Biodiesel is a promising alternative to petroleum-based fuels and is gaining attention due to its unique physicochemical properties. Unlike conventional diesel, biodiesel's high oxygen content promotes complete combustion, its high cetane number enhances combustion performance, and its low aromatic and sulphur content leads to better emission control [2-3]. These features allow biodiesel to be used directly or as a blend in existing engines without major modifications, facilitating its practical application. Extensive research has shown that biodiesel effectively reduces major pollutant emissions from diesel engines. Nikolic et al. [4] found that blending second-generation biodiesel with diesel at 7% and 20% significantly lowered NO_x, CO, and SO_2 emissions in marine low-speed engines. Gharehghani et al. [5] observed a 30% reduction in HC and CO emissions in a single-cylinder diesel engine using waste fish oil biodiesel blends. Nabi et al. [6] reported an 84% decrease in parrticulate matter (PM) emissions across all operating modes in a six-cylinder turbocharged diesel engine using biodiesel derived from waste cooking oil. In China, Sun Ying et al. [7] demonstrated that using waste oil biodiesel blends in large marine diesel engines significantly reduced black carbon (BC) emissions, with greater carbon emission reductions at higher engine loads. These studies confirm biodiesel's significant advantage in reducing ship pollutant emissions, positioning it as a more environmentally friendly and sustainable fuel option.

In the field of alternative engine fuels research, the focus has traditionally been on power, economy, and emissions. However, recent studies have highlighted the significant impact of engine cylinder combustion-induced vibrations on fatigue life and maintenance costs. This makes the comprehensive study of alternative fuels' combustion and vibration characteristics crucial. The vibration signals in internal combustion engines are complex, stemming from multiple sources like fuel combustion pressure, piston lateral thrust, valve impacts, and inertial forces from the crank-connecting rod mechanism. These sources are periodic but non-stationary, with combustion-induced pressure and piston thrust being the main vibration excitation sources. Therefore, any change in fuel combustion affects the engine's vibration characteristics. Research shows that vibration signals can help identify combustion characteristics and diagnose engine faults, improving performance and maintenance efficiency [9-12]. Notably, biodiesel's unique physicochemical properties lead to distinct engine vibration performance [13,14]. Studies into biodiesel's impact on engine vibrations have yielded several findings. Çalık et al. [15] found that adding biodiesel to diesel reduces engine vibration, with even better results occurring when hydrogen is added. Taghizadeh-Alisaraei et al. [16] discovered that B40 and B20 biodiesel blends cause the highest vibrations at full load, while D100 and B80 cause the lowest. Rajam et al. [17] observed that B20 biodiesel outperforms B10, B30, and B40 in vibration characteristics. Li et al. [18] linked biodiesel's advanced ignition to a non-linear increase in vibration RMS near the top dead centre (TDC), offering a new perspective on biodiesel's vibration characteristics. These studies underscore the importance of vibration analysis in understanding biodiesel's performance in engines.

Alternative fuels with unique physical and chemical properties can lead to distinct vibration characteristics in engines, compared to conventional fuels [19]. This must be given due attention in engineering application assessments. When evaluating alternative fuel performance comprehensively, it is essential to not only consider conventional aspects, such as combustion and emission characteristics, but to also delve into vibration behaviour, including key parameters like amplitude and frequency distribution. However, current biodiesel research has limitations: most studies focus on automotive diesel engines, with significant gaps remaining in the study of combustion and vibration characteristics of biodiesel in marine low-speed two-stroke diesel engines. Additionally, there is a lack of systematic vibration analysis methods. This research gap is important because marine low-speed diesel engines, with their large bore and long stroke, have fundamentally different combustion and vibration response characteristics from automotive engines, necessitating specialised studies on the impact of biodiesel on their performance.

The power system of ocean-going vessels, primarily using long-stroke low-speed diesel engines as propulsion, adds unique engineering value to vibration characteristic studies when using biodiesel. Literature reviews reveal that existing research on marine biodiesel has mainly focused on emission and combustion characteristics, with insufficient emphasis being given to vibration characteristics, particularly when combined with time-frequency analysis methods like continuous wavelet transform (CWT). This research deficiency can lead to serious engineering issues, as vibrations not only affect engine reliability and lifespan but can also exacerbate hull fatigue and compromise overall safety. Therefore, understanding biodiesel's vibration behaviour is crucial for practical applications. Moreover, the unique physicochemical properties of biodiesel (e.g. its higher cetane number, lower calorific value, higher viscosity, etc.) may influence engine vibration responses by altering the combustion process but the specific mechanisms in low-speed diesel engines remain under-researched and unclear.

Based on the research context and gap analysis, this paper comprehensively explores the combustion and vibration characteristics of marine low-speed diesel engines operating on various biodiesel blends. It innovatively employs a multi-dimensional vibration analysis approach, combining traditional root mean square (RMS) analysis in the time domain, fast fourier transform (FFT) analysis in the frequency domain, and continuous wavelet transform (CWT) analysis in the time-frequency domain. This integrated methodology aims to deeply uncover the intrinsic link between biodiesel combustion and vibration responses, offering an inventive technical solution for combustion state monitoring and fault diagnosis in low-speed diesel engines. Conducted on a 6S35ME-B9 low-speed diesel engine test bench, the study strictly controls experimental conditions and compares the performance of D100, B10, B30, and B50 fuels across a 25-100% load range, with a focus on the impact patterns of biodiesel's combustion and vibration characteristics. The findings underpin the practical application of biodiesel in shipping and inform engine optimisation design.

MATERIALS AND METHODS

TESTING EQUIPMENT

All of the experiments described in this paper are based on the automation laboratory for marine engines at Shanghai Maritime University. The main engine studied was a 6S35ME-B9 low-speed diesel engine (constructed by MAN B&W) with a piston stroke of 1550 mm and a cylinder bore of 350 mm, which classified it as a large-bore, long-stroke low-speed diesel engine. For detailed performance parameters, refer to Table 1.

Tab. 1. Performance parameters of two-stroke low-speed diesel engine

Item	Parameter
Type	In-line 6-cylinder
Number of strokes	2
Firing order (from free end)	1-5-3-4-2-6
Rated power /kW	3570
Continuous power /kW	3250
Rated speed /(r/min)	142
Connecting rod ratio	0.5
Compression ratio	17
Piston /L	894
stroke /mm	1550
Cylinder bore /mm	350
Maximum firing pressure/bar	180

The experimental layout diagram and the experimental site diagram are shown in Fig. 1 and Fig. 2, respectively. Vibration signals from the low-speed engine were captured by two tri-axial vibration sensors. One sensor was mounted on the No.4 cylinder head, to measure vibrations perpendicular to piston movement, and the other was placed on the No.3 cylinder body. A pressure sensor on the No.5 cylinder head obtained in-cylinder pressure signals and a crank sensor measured the crankshaft angle signal. A hydraulic dynamometer measured the low-speed engine's speed, torque, and power, with a load control system adjusting the operating load. Signals from these sensors were transmitted to a data acquisition and analysis instrument, then relayed to a laptop via data cables. The detailed parameters of the vibration sensors and pressure sensors are presented in Tables 2 and 3.

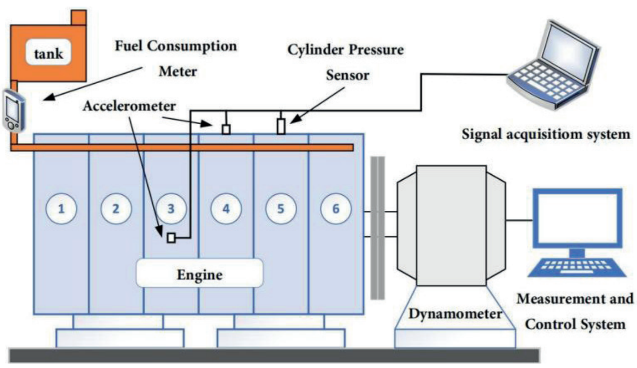


Fig.1. Experimental layout diagram

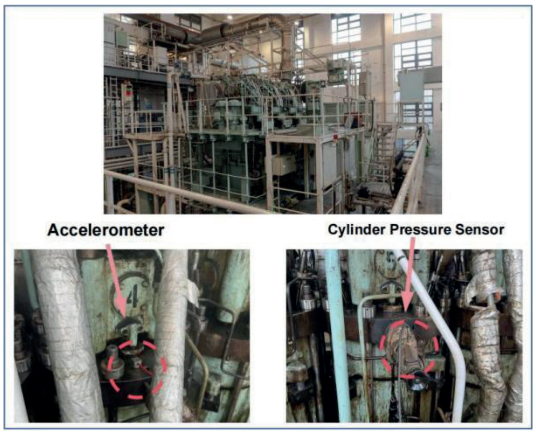


Fig.2. Experimental site diagram

The experiment was conducted under four operating conditions: 89, 113, 129, and 142 r/min, which corresponded to 25%, 50%, 75%, and 100% loads, respectively. After maintaining a stable engine load for 10 minutes, data was collected for 10 seconds at a sampling frequency of 5000 Hz.

Tab. 2. Accelerometer specifications

Parameter	Details
Type	INV9832-50
Sensitivity	100 mV/g
Measuring range	0.4–12,000 Hz
Weight	12 g
Size	19×19×19 mm3
Temperature	−50 to 120 °C

Tab. 3. Parameters of Kistler Pressure Sensor

Item	Parameter
Model	6613CG2
Sensitivity	0.05 mA/bar
Measurement range	0~250 bar
Mass	165g
Temperature	-20~350 ℃

TEST FUEL

In this study, four fuel samples were created by blending biodiesel and petroleum diesel volumetrically: D100 (100% conventional diesel), B10 (90% conventional diesel and 10% biodiesel), B30 (70% conventional diesel and 30% biodiesel), and B50 (50% conventional diesel and 50% biodiesel). Table 4 compares the key physicochemical properties of petroleum diesel and biodiesel, which significantly affect engine ignition, combustion, and emission performance. The base diesel D100 used in this study was China VI 0# diesel, while the B10, B30, and B50 biodiesel blends were formulated by mixing catering waste oil biodiesel provided by SGS Standard Technical Services (Shanghai) Co., Ltd. with China VI 0# diesel in corresponding volume ratios.

The cetane number is crucial for evaluating the ignition quality of diesel fuel in compression - ignition engines. A higher cetane number means better ignition performance, shorter ignition delay, more uniform combustion, and smoother engine starting. Biodiesel's higher cetane number, compared to conventional diesel, indicates superior combustion performance.

Tab. 4. Fuel composition analysis

Type	D100	B10	B30	B50
Density (20 °C) kg/m³	837.3	842.8	845.0	849.9
Viscosity (40 °C) mm²/s	3.287	3.267	3.283	3.437
Cetane index	49.5	53.0	53.2	53.5
Low heat value MJ/kg	42.652	41.697	41.037	40.236
Flash point °C	70.0	77.0	79.0	82.0

RESULTS AND DISCUSSION

BRAKE SPECIFIC FUEL CONSUMPTION

As a key parameter for assessing low-speed diesel engine performance, the brake specific fuel consumption (BSFC) shows systematic variations with biodiesel blending ratios and engine load, as depicted in Fig. 3. Within the 25-100% load range, the BSFC of all tested fuels decreases monotonically with increasing load, mainly due to improved combustion efficiency from higher combustion chamber temperatures at higher loads. However, compared to D100, biodiesel exhibits significant differences. The average BSFC of B10, B30, and B50 fuels across the four load conditions increases by 3.6%, 3.9%, and 6.1%, respectively, compared to D100, with the most pronounced differences at 100% load (reaching 4.4%, 4.7%, and 6.7%, respectively). These fuel economy differences stem from biodiesel's inherent characteristics and their impact on combustion. Biodiesel's lower heating value is the primary factor causing the BSFC increase. To deliver the same power, the MAN engine adjusts the injection volume, injecting more fuel into the combustion chamber to maintain power output. Additionally, biodiesel's higher kinematic viscosity affects fuel atomisation quality, especially at low loads and low fuel temperatures, leading to poorer air - fuel mixing quality and reduced combustion efficiency.

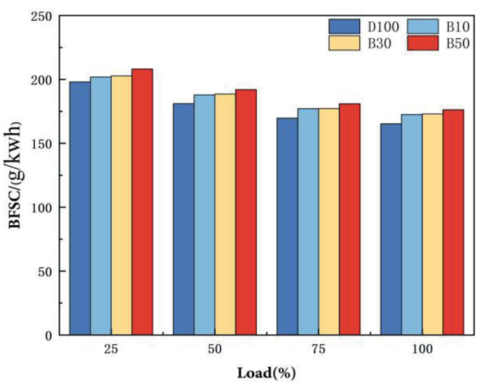


Fig. 3. Fuel consumption rate

IN-CYLINDER PRESSURE AND PRESSURE RISE RATE CURVES

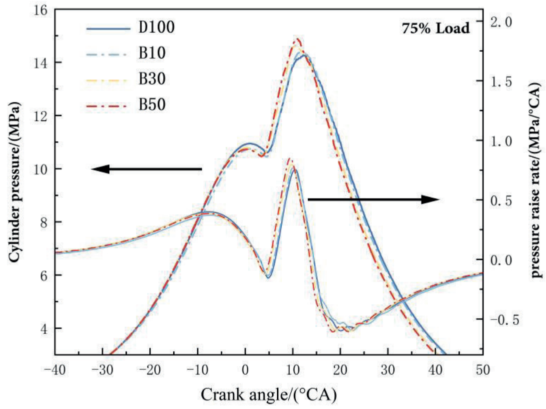


Fig. 4. In-cylinder pressure and pressure rise rate curves of different fuels at 75% load

Fig. 4 offers a comparative analysis of the combustion characteristics of different fuels at 75% load. The pressure diagrams, captured by a cylinder pressure sensor, show similar pressure curve shapes for all fuels, and yet biodiesel exhibits distinct combustion feature variations. As the biodiesel blend ratio increases from B10 to B50, the Peak Pressure in the cylinder rises incrementally, with B50 reaching 14.8 MPa, a 4.9% increase over D100. This pressure rise is mainly attributed to biodiesel's high cetane number and oxygen content, which significantly enhance ignition performance. The change in combustion phase also shows a linear feature: the combustion start point of B10 is 0.5 °CA earlier than D100, and that of B50 is 1.8 °CA earlier. The analysis of the pressure rise rate curve further reveals the dynamic characteristics of the combustion process. The maximum cylinder pressure rise rate of biodiesel increases with the blend ratio and is closely related to the need to increase the injection volume, to maintain the same power output due to biodiesel's lower heating value.

TIME-DOMAIN ANALYSIS OF VIBRATION SIGNALS

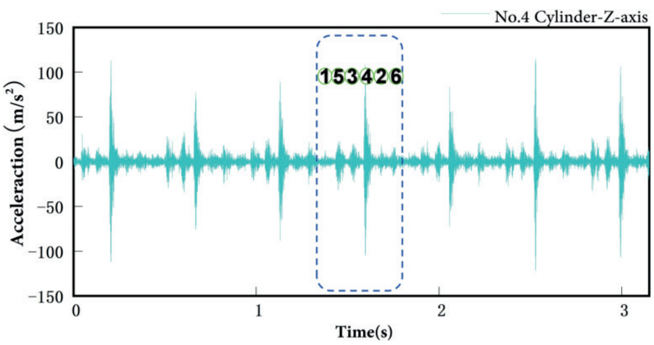


Fig. 5. Time-domain complete firing cycle of low-speed engine cylinder head

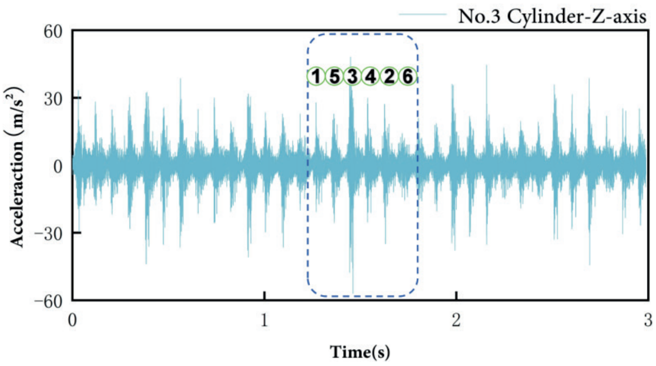
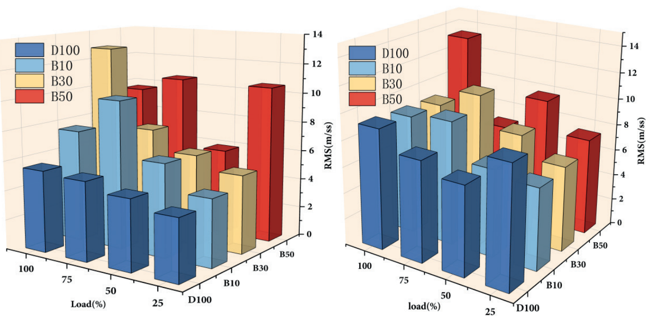


Fig. 6. Time-domain complete firing cycle of low-speed engine cylinder body

During the operation of a low-speed diesel engine, fuel combustion impact and lateral piston slap are the main excitation sources representing the combustion-induced excitation features. Fig. 5 presents a 3-second vibration signal snippet from the cylinder head when the low-speed engine is fuelled with D100 diesel at 25% load; the maximum amplitude is approximately 110 m/s^2. To facilitate detailed information acquisition, especially regarding firing cycles and cylinder amplitudes, a complete firing cycle is marked with a dashed line. The firing order is 1-5-3-4-2-6 and, as shown, the amplitude of the vertical vibration signal from cylinder 4 is the largest, whilst that of cylinder 1 is the smallest. This is because the triaxial vibration sensor is mounted on the cylinder 4 head, with amplitude decreasing as the distance from cylinder 4 decreases. Similarly, as shown in Fig. 6, the horizontal vibration signal measured at the cylinder 3 engine body shows the highest amplitude at cylinder 3, with amplitude decreasing as the distance from cylinder 3 increases.

ROOT MEAN SQUARE VALUE ANALYSIS OF VIBRATION SIGNALS



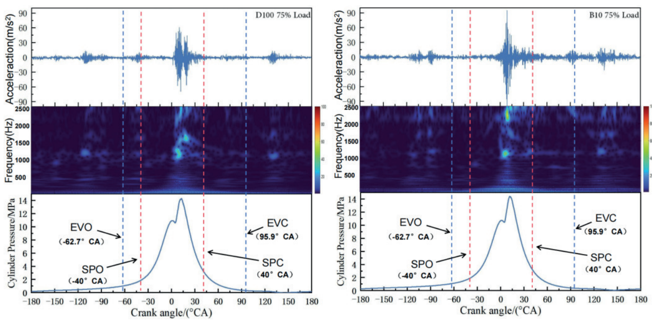
(a) The cylinder head *(b) The engine block*

Fig. 7. Diesel engine RMS value

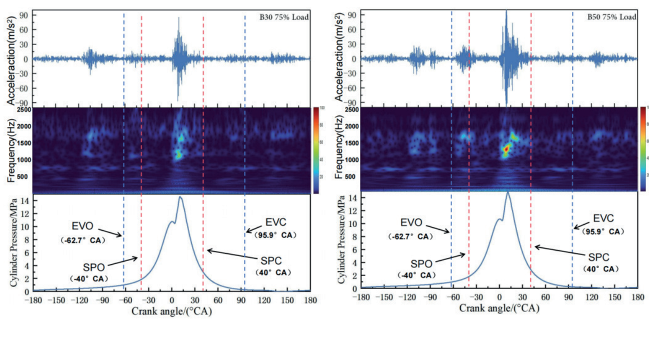
Fig. 7(a) presents the RMS values of cylinder head vibrations for different fuels at four loads. The RMS value, indicating vibration amplitude or intensity, rises with increasing load and speed due to greater combustion pressure changes. Biodiesel generally shows higher RMS values than D100 diesel across different propulsion conditions. D100's RMS values show little variation. B10 at 75% load and B30 at 100% load have larger RMS increases, while their RMS values are closer to D100's in other conditions. B50 biodiesel exhibits significant RMS fluctuations, clearly exceeding D100's.

Fig. 7(b) illustrates the RMS values of engine block vibration responses under four load conditions. Time-domain analysis of vibration signals shows that vibration intensity increases with load due to the combined effects of combustion and mechanical excitations. Biodiesel generally has higher RMS values than D100 diesel across different propulsion conditions. At 25% load, D100 diesel has a higher RMS value than biodiesel, possibly because biodiesel's high cetane number shortens the ignition delay, leading to smoother combustion and less block vibration. At 25%, 50%, and 100% loads, the block RMS values increase with biodiesel blending ratios.

CONTINUOUS WAVELET TRANSFORM ANALYSIS OF VIBRATION SIGNALS



a) D100 *b) B10*



(c) B30 *(d) B50*

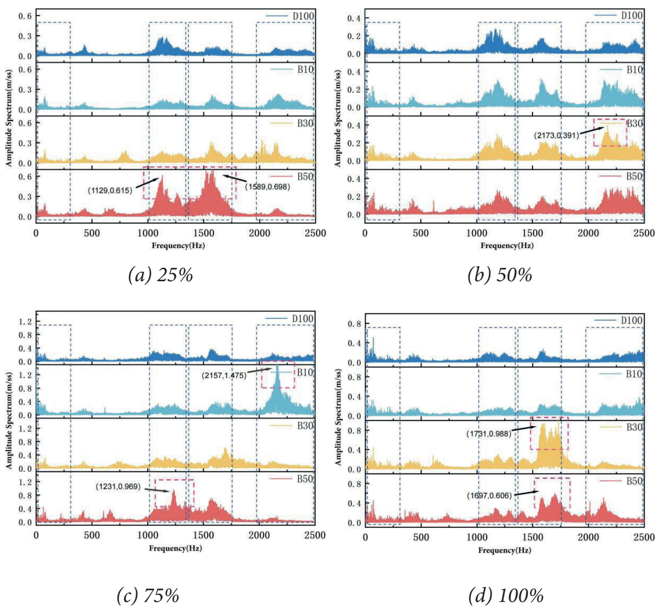
Fig. 8. Continuous Wavelet Transform diagram

In this study, the vibration characteristics of a low-speed diesel engine were analysed in depth using the continuous wavelet transform (CWT) method. Fig. 8 shows the results of applying CWT analysis to the raw acceleration signals collected at the cylinder head when burning four kinds of fuels. The intrinsic correlation between the combustion process and the vibration response is revealed by comparing the vibration signals with the synchronously collected cylinder pressure curves.

From the time-frequency energy distribution plot, it can be observed that the vibration signal of the cylinder head shows significant time-varying energy concentrations in the frequency band of 1000-1800 Hz, which is highly correlated with the characteristic frequency of pressure fluctuation in the combustion chamber. It is worth noting that the moment of peak vibration energy is highly consistent with the moment of the pressure peak of the cylinder pressure curve (around 12-15 °CA), which fully verifies the fact that the combustion excitation is the main source of vibration. In a firing cycle, it can be clearly identified that, after entering the main combustion period (5-20 °CA), the mid-frequency and high-frequency energies increase sharply, reflecting the pressure fluctuations generated by the violent combustion process.

By synchronously comparing CWT results with key parameters like cylinder pressure curves and valve timing, a comprehensive vibration-combustion-valve timing relationship model was established. This multi-parameter analysis offers multi-dimensional features for fault diagnosis. It also helps build a vibration characteristics database for healthy two-stroke low-speed diesel engines, enhancing our understanding of engine vibration mechanisms, and providing crucial technical support for developing intelligent condition-monitoring systems.

FAST FOURIER TRANSFORM ANALYSIS OF VIBRATION SIGNALS



(a) 25% *(b) 50%*

(c) 75% *(d) 100%*

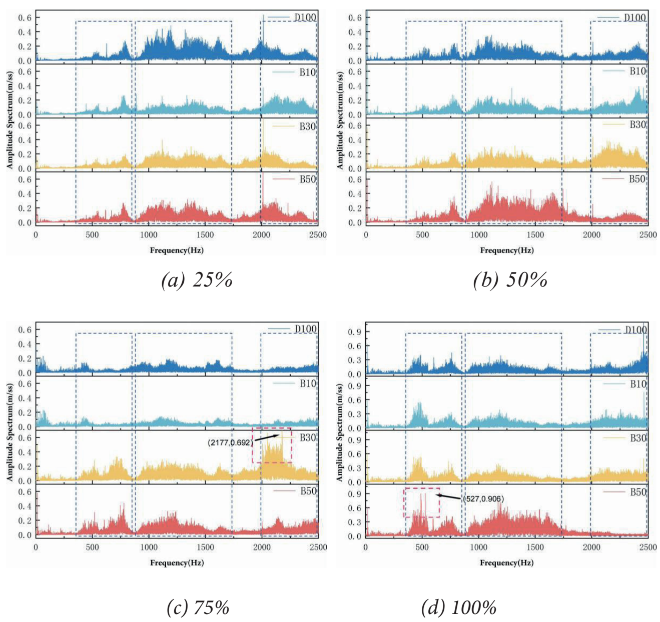
Fig. 9. Frequency-domain curves of vibration acceleration signal at the cylinder head of a low-speed engine

In this study, the vibration signals of a six-cylinder low-speed diesel engine were analysed in the frequency domain using the fast Fourier transform (FFT) method for four typical propulsion conditions: 25%, 50%, 75%, and 100% load. The analysis focused on the vibration acceleration signals from two critical measurement points, the cylinder head and the engine block, to reveal the impact mechanism of biodiesel blending ratios on engine vibration characteristics.

As shown in Fig. 9, the frequency spectrum analysis of the cylinder head vibration signals revealed that the vibration energy was primarily distributed across four characteristic frequency bands: a low-frequency band of 0.0-0.3 kHz, mid-frequency bands of 1.00-1.35 kHz and 1.35-1.75 kHz, and a high-frequency band of 1.9-2.5 kHz. In the low-frequency band, the vibration amplitude curves for all fuels coincided, indicating that biodiesel blending had minimal impact on the low-frequency vibrations caused by the inertia of reciprocating piston motion and mechanical component movement.

In the mid-frequency band (1.00-1.75 kHz), the vibration energy exhibited a pronounced bimodal distribution, peaking in the 1.00-1.35 kHz and 1.35-1.75 kHz sub-bands. Comparing the simultaneously acquired cylinder pressure signal curves revealed a strong correlation between mid-frequency vibrations and combustion pressure fluctuations. Quantitative frequency spectrum analysis showed that at loads less than 25%, the vibration amplitude of B50 fuel in the 1.00-1.35 kHz band reached 0.698 m/s^2. At loads less than 100% load, the vibration amplitude of B30 fuel in the same band increased to 0.988 m/s^2. This vibration enhancement is mainly attributed to changes in the combustion process, caused by the high cetane number and oxygen content of biodiesel.

The vibration characteristics in the high-frequency band (1.9-2.5 kHz) exhibited pronounced load dependence. At loads less than 75%, the vibration amplitude of B30 fuel reached 1.475 m/s^2. Time-frequency analysis revealed that the vibration energy in this band primarily occurred during the late combustion phase (15-40 °CA), potentially associated with pressure oscillations from the incomplete combustion of biodiesel or secondary impacts between the piston and cylinder liner, due to combustion pressure changes.



(a) 25% *(b) 50%*

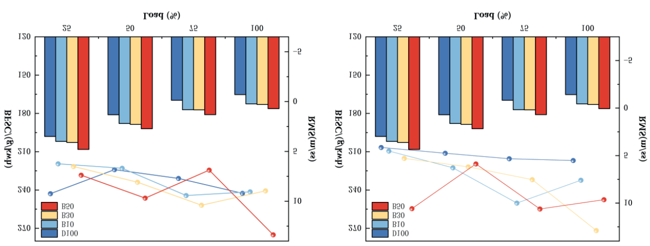
(c) 75% *(d) 100%*

Fig. 10 Frequency-domain curves of vibration acceleration signal at the engine block of a low-speed engine

The engine block vibration spectrum (Fig. 10) shows a different characteristic distribution from the cylinder head. In the mid-to-low-frequency range 0.3-0.8 kHz and 0.8-1.75 kHz, the amplitude of all fuels increases with the load and speed of the low-speed engine. This frequency band's vibrations are caused by the gas forces from fuel combustion pushing the piston, which moves and exerts a force perpendicular to the cylinder liner's axis, inducing vibration on the engine block's external surface. As the engine's load and speed rise, the amplitude of these vibrations also increases. At low loads of less than 25%, biodiesel has a slightly lower amplitude than D100 diesel; however, in the other three load conditions, the amplitude curves of B50 and B30 biodiesel are slightly higher than those of D100 diesel. Under medium-load (50-75%) conditions, B30 fuel shows the most significant high-frequency vibration characteristics, possibly due to changes in combustion characteristics from its optimal air-fuel mixture. Because of biodiesel's lower calorific value, more fuel is injected into the combustion chamber to maintain power output, prolonging the combustion time and subsequently increasing the overall vibration level [19].

This study also reveals a nonlinear change pattern in the vibration characteristics of different biodiesel blends. Some research indicates that the vibration level of a diesel engine can change significantly with different biodiesel blend ratios, with D100 fuel having a lower vibration level than biodiesel, and B5, B30, and B50 biodiesel having the highest vibration levels [20]. These findings provide crucial references for evaluating biodiesel's applicability and optimising blend ratios in marine engines.

CORRELATION ANALYSIS BETWEEN FUEL CONSUMPTION AND VIBRATION RMS VALUES



a) The cylinder head *b) The engine block*

Fig. 11. Correlation plots between fuel consumption and vibration RMS values

Fig. 11 shows that the BSFCs of all fuels show a decreasing trend with increasing load, while the vibration RMS values show an increasing trend overall. This phenomenon stems from the dual effect of improved combustion efficiency and increased combustion pressure fluctuations at high loads. On the one hand, the increased combustion chamber temperature optimises the fuel energy conversion efficiency and reduces the fuel consumption per unit of power but, on the other hand, higher injection volume and combustion intensity lead to an increase in the in-cylinder pressure gradient, which is transferred to mechanical vibration energy through the piston-connecting-rod mechanism. The high oxygen content and cetane number of biodiesel further amplify this phenomenon. While the RMS value of B50 fluctuates greatly in full load, further studies are needed on the vibration characteristics of high percentage biodiesel in low speed engines.

CONCLUSION

This study investigated the effects of different biodiesel-diesel blends on the combustion and vibration characteristics of a six-cylinder marine low-speed diesel engine across various load conditions.

Regarding combustion characteristics, biodiesel's high cetane number and oxygen content advanced the combustion phase and increased the maximum in-cylinder pressure with higher blend ratios. However, its lower heating value led to a significant increase in brake-specific fuel consumption (BSFC) compared to D100, especially at 100% load, where B50's BSFC increased by 6.7%.

In terms of vibration characteristics, time-domain analysis showed that biodiesel generally had higher root-mean-square (RMS) vibration values than D100, with more significant fluctuations for B50. Frequency-domain analysis revealed that biodiesel significantly increased vibration amplitudes in the 1.00-1.75 kHz mid-frequency band, directly linked to combustion impacts. Changes in the high-frequency band (1.9-2.5 kHz) might result from knocking or mechanical impacts. Biodiesel's vibration characteristics differed significantly from D100 across loads and showed nonlinear changes with different blend ratios, mainly due to its physicochemical properties, such as its high cetane number, low calorific value, and high viscosity. Meanwhile, as the load increases, the fuel economy improves (indicated by a decrease in brake-specific fuel consumption, BSFC).

The continuous wavelet transform (CWT) method linked vibration signals to cylinder pressure curves, precisely associating combustion excitation with vibration responses. This offers a new approach for condition monitoring and fault diagnosis in marine low-speed diesel engines.

While biodiesel reduces emissions, it may enhance vibrations in medium and high-frequency bands, potentially affecting engine reliability. It is recommended that biodiesel blend ratios are optimised, to strengthen vibration monitoring in practical applications. Future research should focus on further optimising biodiesel proportions in order to balance environmental and mechanical durability aspects. The findings provide valuable insights for the application of biodiesel in marine low-speed diesel engines and expand the application of vibration signal analysis in ship power systems.

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AUTHOR CONTRIBUTIONS

Yuhao Yuan: Investigation, Writing-original draft & editing. Guohe Jiang: Conceptualization. Gang Wu: Methodology, Writing-original draft & Writing-review. Hao Guo: editing. Jiachen Chen: Experimentation. Zhe Zhang: Investigation.

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