

A Knock Detection Method for a Marine Micro-Ignition Dual-Fuel Engine Based on Vibration Signals

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ABSTRACT

A simple and unified index is proposed to achieve knock detection under various engine loads. Maximum amplitude vibration oscillation (MAVO) and maximum amplitude pressure oscillation (MAPO) were compared and were found to have no consistency. This means that MAVO cannot accurately reflect knocks inside the engine cylinder in the time domain. However, a knocking index built with MAVO can effectively detect engine knocking under various engine loads, which implies that some important information connected to the knock may be hidden within it. In this circumstance, a frequency domain analysis and a wavelet transform were conducted to study the energy changes of vibration signals during engine knocking. The energy proportion of the D1 frequency band during knocking increased drastically. Therefore, it was used to build a knocking judgment index, which builds the relationship between MAVO and MAPO. The judgment index has good applicability under different engine loads and a value greater than 0.5 can be used effectively for knock detection.

Keywords: Knock detection; Vibration signal; Wavelet transform; Energy proportion; Unified knock detection index

Nomenclature		Functions and variables	
A	approximately	E^j	energy of the j^{th} frequency band
AR	auto regressive	E	total energy of the signal
ATDC	after top dead centre	M_i	MAVO of the i^{th} cycle
BTDC	before top dead centre	$\overline{M_r}$	mean of the reference MAVO
CFD	computational fluid dynamics	P_j	percentage of the energy of the j^{th} frequency band
D	detail	$ \widehat{p_\theta} $	in-cylinder pressure after high-pass filtering
DFT	discrete Fourier transform	$ \widehat{V_\theta} $	vibration after high-pass filtering
DWT	discrete wavelet transform	θ	crankshaft angle
EEMD	ensemble empirical mode decomposition	ω	circular frequency
KIr	new criterion	σ_r	standard deviation of the reference MAVO
L15	15% engine load	<i>Units</i>	
L100	100% engine load		
LDO	light diesel oil	$^{\circ}\text{C}$	degree Celsius
Max	maximum	CA	crankshaft angle
MAVO	maximum amplitude vibration oscillation	dm^3	cubic decimetre
MAPO	maximum amplitude pressure oscillation	dB	decibel
PDr	probability density from reference	g	gravitational acceleration
rpm	rotations per minute	kg	kilogram
SI	spark ignition	kHz	thousand hertz
SNR	signal-to-noise ratio	mm	millimetre
STFT	short time Fourier transform	MPa	mega pascal
TDC	top dead centre	MJ/mol	mega joule per mole
WPD	wavelet packet decomposition		

INTRODUCTION

‘Knock’ is one of the abnormal combustion phenomena encountered in engines and it is generally believed to be caused by rapid combustion due to spontaneous ignition of the unburnt mixture at the end of the cycle [1]. Knock leads to fluctuations of in-cylinder pressure acting back and forth on the cylinder wall. Intense knocking causes insufficient combustion and increased emissions. Besides this, it can cause strong vibrations of the engine body and overheating of the cylinder head. Therefore, a relatively stable and accurate judgment index for assessing the operating status of an engine could be significant [2]. Currently, the primary methods for detecting engine knock are based on in-cylinder pressure and vibration signals. Ricci et al. [3] used artificial intelligence

technology to predict engine knocks from in-cylinder pressure signals. A knocking prediction model was trained by recording the engine’s pressure trajectory and temperature parameters. Lee et al. [4] identified knocking frequency by analysing in-cylinder pressure signals under various engine loads and created a common threshold by using dimensionless knocking intensity. Nevertheless, a large amount of work needs to be done to determine the value of the common threshold; cylinder pressure, cylinder head vibration and noise signals all need to be analysed first of all. Maximum amplitude pressure oscillation (MAPO) quantitatively evaluates knocking intensity by filtering cylinder pressure signals; it is extensively used to detect engine knock. Liu et al. [5] used the differential pressure method, combined with the MAPO method and energy distribution analysis, to

detect knock. The large-bore natural gas engine has a unique knocking mechanism, which means that knock can be inhibited by changing the pilot fuel mass and equivalence ratio. Siano et al. [6] conducted a knocking prediction study based on MAPO and AR (Auto Regressive) models. MAPO was found to increase with the increase in engine speed. Therefore, the MAPO threshold must also be changed when the engine operating load changes. Nevertheless, the fundamental disadvantages of using cylinder pressure signals for knock detection lie in the sensor's extremely high cost and short service life [7].

Vibration sensors are extensively used for knock detection due to their cheap price and non-invasive installation [8]. Varbanets et al. [9] first proposed a formula that can accurately determine the TDC position, based on vibration and cylinder pressure sensors. They accurately monitored and analysed data from multiple consecutive operating cycles, to clearly evaluate the stability of the host system's operation, the optimal adjustment of the engine system, and the monitoring of results during operations. Besides this, they developed a portable real-time parameter diagnosis system for marine engines. Ismail et al. [10] used a single vibration sensor mounted on a cylinder block to detect engine knock. Kenji et al. [11] and Vulli et al. [12] used a short-term Fourier transform (STFT) method to process the acquired vibration signals. The STFT method can effectively distinguish the time-frequency characteristics of knocking signals from valve closure signals. Pierpaolo et al. [13] proposed a knock detection strategy combining vibration signal detection and a combustion model. The threshold evolution of different combustion cycles has higher accuracy and flexibility than the fixed threshold of the MAPO method. In the above studies, various detection indices were adopted under different engine loads. However, a unified knock detection index would be preferable. Rosas et al. [14] analysed the effect of fuel injection on the intensity of knock for a small dual-fuel engine, then a unified knock detection index (PD_p , Probability Density from reference) with a threshold value of '5' was proposed to detect the knock under various engine fuel types and loads. It would be interesting to investigate whether the proposed knock detection index is suitable for a medium-speed marine micro-pilot dual-fuel engine.

The wavelet transform has the superior advantages of high flexibility, multi-resolution, and high signal processing accuracy [15,16], and it has been increasingly applied in signal noise reduction, feature extraction, and fault diagnosis [17,18]. Signals in different frequency bands can be obtained by discrete wavelet decomposition, which can distinguish the knocking information and the region where it occurs [19]. The knocking signal is a typical non-smooth signal containing low-frequency noise components and high-frequency knocking feature signal components. The typical characteristics are the peak difference, average power, mean, standard deviation, and root mean square value, extracted from decomposed knocking signals [20,21]. When knocking occurs, there is a sharp increase in high-frequency signals [22,23]. Furthermore, the energy of vibration signals is also

concentrated in the high-frequency range [24]. Thus, this feature can be used to detect engine knock. Qiao et al. [25] decomposed the cylinder pressure signals for knocking diagnosis by wavelet transform. A good accuracy was achieved by comparing their energy proportions under different engine working conditions. However, the vibration signals of knock were not investigated at all. Additionally, few studies have proposed a unified knock detection index under various loads based on vibration signals.

A simple and unified index is proposed in this study, to achieve knock detection under various engine loads. Firstly, the time-domain signals are used to observe the response of individual indicators to knock. The knock detection method proposed by [14] is validated under different engine loads. Secondly, a frequency-domain analysis is employed to analyse the energy of vibration signals during the engine combustion phase. Finally, wavelet analysis is used to decompose the vibration signals during the combustion phase. The energy proportions of these frequency bands are calculated and the sensitive parameters used to establish a unified index for knock detection under various engine loads.

EXPERIMENTAL METHODOLOGY

TEST ENGINE AND FUEL

This study was carried out on an ACD320DF marine medium-speed diesel/natural gas dual-fuel engine. The engine can operate in either fuel mode or gas mode. When it works in fuel mode, the engine operates as a traditional diesel engine. When it works in gas mode, the natural gas is injected into the intake manifold through multi-point injection. Natural gas is ignited by micro-injection diesel oil (only about 1% of the required total calorific value of the fuel) through a high-pressure common-rail fuel injection system in the final stage of the compression stroke. The air-fuel ratio can be adjusted through the exhaust bypass valve, to control the air's boost pressure. The technical specifications of the engine are shown in Table 1 and the schematic diagram of the engine test rig is shown in Fig. 1.

Tab. 1. Technical specifications of the engine

Items	Characteristics
Engine type	In-line six-cylinder 4-stroke
Fuel system	Diesel and Natural gas
Bore, mm	320
Stroke, mm	420
Compression ratio	12.5
Speed, rpm	750
Firing order	1-3-5-6-4-2
Swept Volume, dm ³ /cylinder	33.80
Intake valve open/close, degree CA ATDC	-46/156
Exhaust valve open/close, degree CA ATDC	-213/50

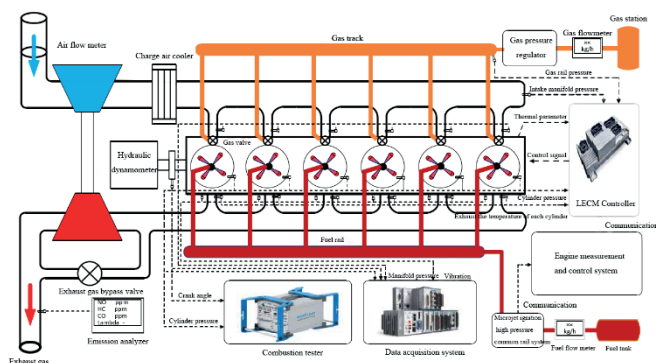


Fig. 1. Schematic diagram of the engine test rig

EXPERIMENTAL SETUP

BOSCH non-resonant acceleration vibration sensors were used for transforming the vibration signals of each cylinder. An NI data acquisition system and a Kistler combustion analyser were utilised to obtain these signals. The diesel used in the test was light diesel oil and the natural gas was Sichuan natural gas. The physical properties of the two fuels are given in Table 2.

Tab. 2. Properties of LDO and Natural gas

Properties	LDO	Natural gas
Chemical formula	$C_{10}-C_{22}$	CH_4
Molar mass g/mol	290.00	16.04
Density kg/m ³	0.81-0.86	0.72
Boiling point°C	180-410	-161.50
RON	-	130
Lower heating value (MJ/kg)	42.80	47.83
Octane number	52.50	-
Cetane number	14.69	17.10
Stoichiometric air-fuel Ratio	623	903
	87.00	72.35

EXPERIMENTAL PROCEDURE

If a cylinder misfires, the cylinder in the next firing sequence is prone to knock. This principle can be used to induce a knock in a certain cylinder. So, a test was carried out at load L15 by stopping the gas injection of the 1# cylinder, advancing the injection timing of ignition oil injection of the 3# cylinder, and opening the exhaust gas bypass valve at the same time. In this circumstance, the knock in the 3# cylinder was induced. Load L15-1 represents the normal working condition and L15-2 represents the knocking condition. Although the knock was not induced under L100, there were still some knocking cycles. In the following chapters, the normal and knocking cycles under L100 are marked as L100-N and L100-K, respectively. The working conditions for the dual-fuel engine are shown in Table 3.

Tab. 3. Working condition for the dual-fuel engine

Load	Cylinder Number	Fuel advance angle, degree CA BTDC	Speed, r/min	Cylinder de-activation	Knock induced
L15-1	#3	0	750	None	No
L15-2	#3	14	750	1# Cylinder	Yes
L100	#3	0	750	None	No

KNOCKING SIGNAL ANALYSIS

The in-cylinder pressure signals are abnormal when knocking occurs and so are the vibration signals, as shown in Fig. 2 and Fig. 3. The red curves represent the in-cylinder pressure signals. The black curves represent the cylinder head vibration signals. The in-cylinder pressure signal in the combustion section indicates a significant increase in oscillation amplitude and frequency when knocking occurs. At the same time, the amplitude of the vibration signal in the combustion section also increases significantly, with the amplitude reaching up to 100 g, as shown in Fig. 3. This is due to the auto-ignition of the end gas, leading to explosive combustion, which generates a rapid rise in the heat release rate. The engine body vibrates at a certain frequency because the shock waves strongly impact the cylinder wall and reflect within the cylinder.

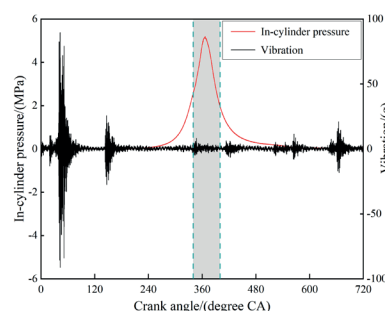


Fig. 2. In-cylinder pressure and vibration signals of L15-1

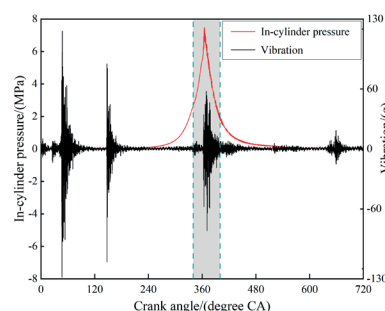


Fig. 3. In-cylinder pressure and vibration signals of L15-2

Fig. 4 compares the vibration signals between 60 degrees CA BTDC and 120 degrees CA ATDC under knocking and

normal conditions. It can be seen that the vibration signal of the engine in the knocking condition has huge fluctuations, whose amplitude is several orders of magnitude higher than that in the normal state. This means that the vibration signals are sensitive to knock.

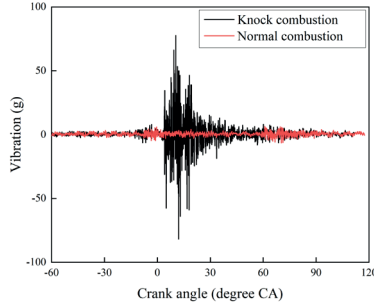


Fig. 4 Comparison of vibration signals between normal combustion and knocking combustion

THE RELATIONSHIP BETWEEN MAVO AND MAPO

The in-cylinder pressure signal exhibits strong oscillations during combustion when the engine experiences knocking. The MAPO method is extensively used to detect knock. MAPO is defined as follows:

$$MAPO = \max(|\widehat{p}_\theta|) \quad (1)$$

where $|\widehat{p}_\theta|$ is the pressure value of the in-cylinder pressure after high-pass filtering and the high-pass filtering cut-off frequency is set as 4 kHz. θ is the crankshaft angle range of the combustion section, which is generally taken to be from 20 degrees CA BTDC to 40 degrees CA ATDC.

Maximum amplitude vibration oscillation (MAVO) represents the filtered vibration signals, defined as follows:

$$MAVO = \max(|\widehat{v}_\theta|) \quad (2)$$

where $|\widehat{v}_\theta|$ is the vibration value of the cylinder head vibration signal after high-pass filtering and the high-pass filtering cut-off frequency is set as 4 kHz. θ is the crankshaft angle range of the combustion section, which is generally taken to be from 20 degrees CA BTDC to 40 degrees CA ATDC.

Fig. 5 indicates the relationship between MAPO and MAVO under various engine working conditions. There is little correlation between MAVO and MAPO in the combustion phase when the engine operates under either load. It is evident that MAVO cannot distinguish between the L15 knocking condition and the L100 normal condition, as shown in Fig. 6. Since MAPO is an index directly reflecting knocking, it can be assumed that MAVO cannot accurately reflect the oscillation of in-cylinder pressure inside the combustion chamber.

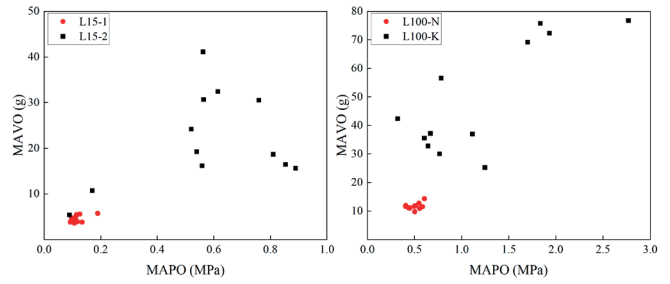


Fig. 5. The relationship between MAPO-MAVO under various working conditions

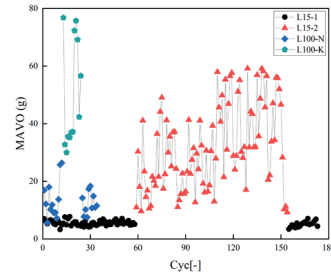


Fig. 6. MAVO under various engine loads

From the above analysis, it can be concluded that the MAVO value exhibits good sensitivity to the occurrence of engine knocking, which enables further analysis of the correlation between the relevant parameters of vibration data and MAVO values, such as the root mean square value, variance, and peak to peak value, by comparing and analysing the MAVO values of different cycles with the corresponding vibration-related parameters. Fig. 7 indicates that these relevant vibration data parameters do not show a good relationship with the MAVO value, which indirectly indicates that these parameters are not sensitive to the response of detonation.

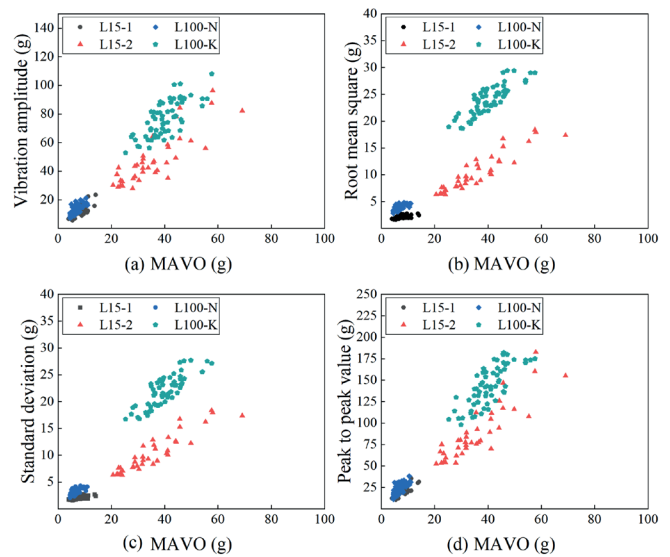


Fig. 7. The correlation between MAVO and related parameters

VALIDATION OF THE PD_r KNOCKING INDEX

Rosas et al. [14] proposed a unified knock detection index based on vibration signals in a dual-fuel engine, which can judge knock under different engine loads. The author indicated that neither too few nor too many parameters can comprehensively describe the characteristics of knocking impacts. The mean and standard deviation of the reference cycle of vibration signals were used to construct the knock detection index. The formula for the knock detection index is as follows [14]:

$$PD_r = \frac{\sqrt{\frac{1}{M} \sum_{i=0}^{M-1} (KI_i - \overline{KI_r})^2}}{\sigma_r} \quad (3)$$

where M is the number of cycles of the detected vibration signal, KI_i is the MAVO value of the i^{th} cycle, $\overline{KI_r}$ is the mean MAVO value of the reference cycle vibration signals, and σ_r is the standard deviation of the reference cycle vibration signals.

The normal vibration signals under 60% engine load were adopted as the reference cycle in the work carried by [14]; however, none of the vibration data of the 60% load was collected in this study. Therefore, the non-knocking cycle under each operating condition was used as a reference cycle for PD_r validation testing. The vibration data collected from L15-1, L15-2, and L100 were validated, as shown in Fig. 8. It can be seen that the PD_r criterion successfully distinguishes knocking cycles from normal cycles, regardless of engine loading, which is consistent with [14]. More specifically, PD_r values of less than 10 indicate that the engine is not knocking; PD_r values above 10 indicate that the engine is experiencing knocking. The PD_r value used for detecting engine knocking is 10 for the medium-speed micro-ignition dual-fuel engine, which is different from the value of 5 given in [14]. This may be due to the use of different reference cycles. In addition, the construction of the PD_r detection index requires the simultaneous use of parameters such as the mean and standard deviation of the reference cycle, and the MAVO value of detected cycles, which increases the complexity of knock detection, to a certain extent. A simple and unified knock detection index which can meet the requirements of knock detection under various engine loads would be preferable.

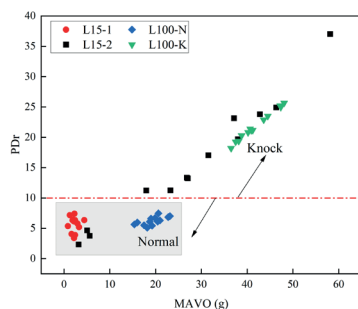


Fig. 8. Validation of the PDr for engine knock detection

FREQUENCY DOMAIN ANALYSIS OF VIBRATION SIGNALS

A frequency domain analysis of the vibration signal was conducted to explore a simple and unified index which can meet the requirements of knock detection under various engine loads. Fourier transform is a classical signal processing method that transforms a time domain function (with time as the independent variable) into a frequency domain function (with frequency as the independent variable) through an integral operation. In engineering applications, the actual collected signal is a finite-length discrete signal. The collected signal should be analysed and processed by Discrete Fourier Transform (DFT), in which the time series $x(n)$ ($n=0, 1, \dots, N-1$) is defined as follows:

$$D(k) = \sum_{n=0}^{N-1} x(n) e^{-j \frac{2\pi}{N} nk} \quad (4)$$

where $x(n)$ is a finite sequence of length N , n is the sample moment, that varies from 0 to $N-1$, and k is the frequency exponent corresponding to the fundamental frequency.

The energy corresponding to each frequency is processed by the power spectrum density of the signal. The power spectral density describes the frequency and energy density distribution of the signal in the frequency domain and is defined as follows:

$$G_x(f) = 2S_f = 2 \int_{-\infty}^{+\infty} R_x(\tau) e^{-2\pi f \tau} d\tau \quad (5)$$

where $R_x(\tau)$ is the autocorrelation function of $x(n)$ and f is the signal oscillating frequency.

Fig. 9 and Fig. 10 indicate the vibration signals filtered by the Butterworth filter and their PSD (Power Spectral Density) during the combustion section under misfire conditions L15-1, L15-2, L100-N, and L100-K. It can be seen that the filtered vibration signals of Fig. 9(a) and Fig. 10(a) are in a stable state. The vibration signal energy is mainly concentrated around 5 kHz, and the signal energy is at a relatively small level. When the knocking occurs, the vibration signal amplitudes of Fig. 9(b) and Fig. 10(b) increase significantly to 100 g. At the same time, the energy of the high-frequency band of 10-20 kHz increases drastically. It is obvious that the knocking signals are reflected in the frequency domain of the vibration signals and a detailed study of the frequency domain is needed.

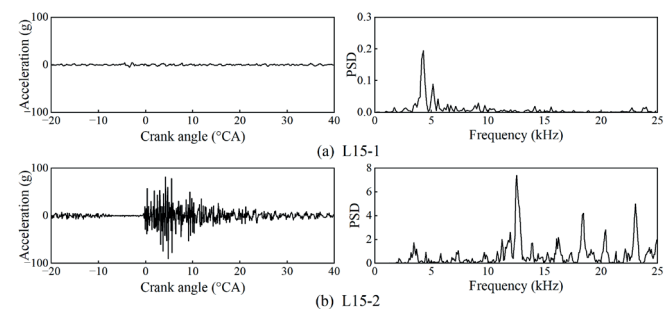


Fig. 9. Time domain analysis and PSD for L15

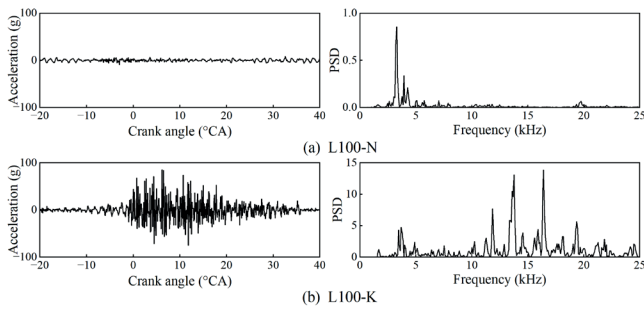


Fig. 10. Time domain analysis and PSD for L100

A SIMPLE AND UNIFIED KNOCK DETECTION INDEX UNDER VARIOUS ENGINE LOADS

Wavelet transform analysis

Discrete Wavelet Transform (DWT) has the advantage of being a multi-resolution analysis feature, compared with Fourier transform, which makes it highly effective for non-stationary signals. The engine vibration signal during the combustion section mainly consists of the normal combustion signal and the strong vibration signal generated by knock. The normal combustion signal mostly contains low-frequency components which represent the outline of the signal. On the contrary, the knocking signal contains high-frequency components which describe the details of the signal changes. The multi-resolution analysis in wavelet transform decomposes signals to multiple scales.

The lower right-hand corner of Fig. 11 is a schematic diagram of the three-level multi-resolution decomposition structure of the original signal S . Symbol A represents the low-frequency components of the signal (approximate part) and symbol D represents the high-frequency components of the signal (detail part). The decomposition relationship can be written as: the original signal $S = A_3 + D_3 + D_2 + D_1$. Since the sampling frequency of the signal is 50 kHz, the frequency ranges represented by each node after three-level wavelet decomposition are shown in Fig. 11. The three-level wavelet decomposition is performed on the vibration signals of the L15 and L100 combustion sections. The Daubechies wavelet db10 is used as the wavelet basis, with a wavelet transform scale of 2^3 . The results are shown in Fig. 12 to Fig. 15. There are significantly large fluctuations in the decomposed signals when the engine experiences knocking, especially in the range D1 (12.5-25.0 kHz), as shown in the lower left-hand corner of Fig. 13 and Fig. 15. These results are in accordance with the analysis of the Fourier transform described in Section 3.3.

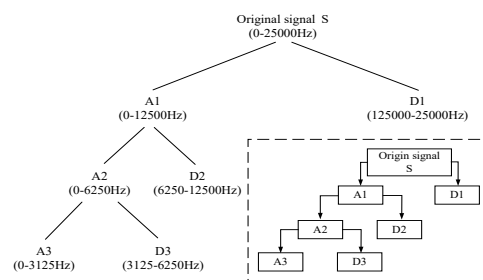


Fig. 11. Schematic view of three-layer wavelet decomposition for vibration signals

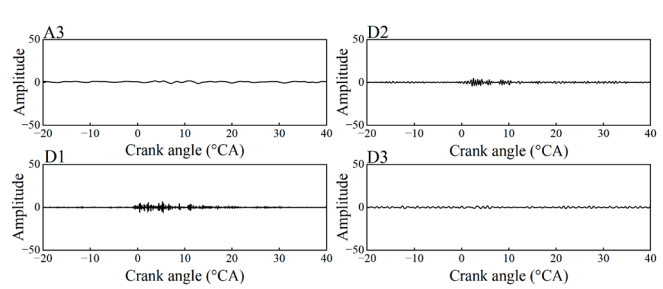


Fig. 12. DWT analysis of vibration signal under L15-1

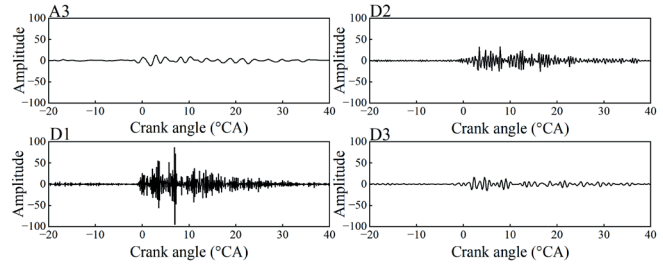


Fig. 13. DWT analysis of vibration signal under L15-2

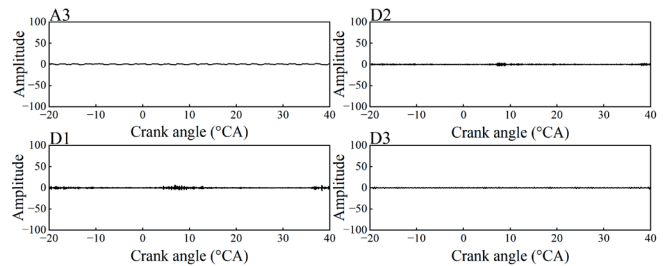


Fig. 14. DWT analysis of vibration signal under L100-N

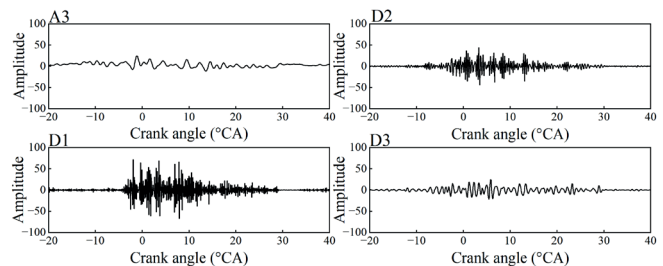


Fig. 15. DWT analysis of vibration signal under L100-K

A unified knock detection index under various engine loads

The total energy equals the sum of the energies in each wavelet decomposition frequency band (A3, D1, D2, D3) and the energy calculation formula is given by Eq. (6). The energy proportion is calculated by dividing the energy of each frequency band by the total energy. Thereby the energy proportion of each frequency band is determined under different engine loads. The process procedure is as follows:

(1) Perform n -layer wavelet decomposition on the vibration signal to obtain a $n+1$ coefficient decomposition sequence $\{d_j, j = 1, 2, \dots, n+1\}$. This article takes n as 3, which is the three-layer wavelet decomposition.

(2) Calculate the energy of the decomposition coefficient sequence for each layer. If E_j is the energy of the j^{th} frequency band wavelet decomposition coefficient sequence d_j , then:

$$E_j = \sum_{m=1}^N |d_j^m|^2 \quad (6)$$

In the formula, is the m^{th} component of the j^{th} layer high-frequency wavelet decomposition sequence and N is the number of components in the sequence.

(3) Calculate the proportion of energy in each frequency band to the total energy of the signal. If P_j is the percentage of the energy of the j^{th} frequency band wavelet decomposition sequence to the total energy of the signal, then:

$$P_j = \frac{E_j}{E} \quad (7)$$

$$E = \sum_{j=1}^{n+1} E_j \quad (8)$$

Table 4 and Fig. 16 indicate the energy proportions of different frequency bands after wavelet transform analysis of the normal and knocking vibration signals under L15 and L100. It can be seen that the energy proportions of the low-frequency bands A3 and D3 in the knocking cycles (red bars) sharply declined compared to the normal cycles (yellow bars). On the contrary, the energy proportions of D1 at the knocking cycles increase by approximately five times. This indicates that the energy proportion of D1 is an effective index for knock detection.

Tab. 4. The energy proportion of each frequency interval to the total energy of wavelet decomposition

Operation conditions	The energy proportion of each frequency interval to the total energy			
	A3	D1	D2	D3
L15-1	0.331	0.148	0.110	0.411
L15-2	0.023	0.737	0.095	0.145
L100-N	0.437	0.175	0.133	0.255
L100-K	0.073	0.728	0.157	0.042

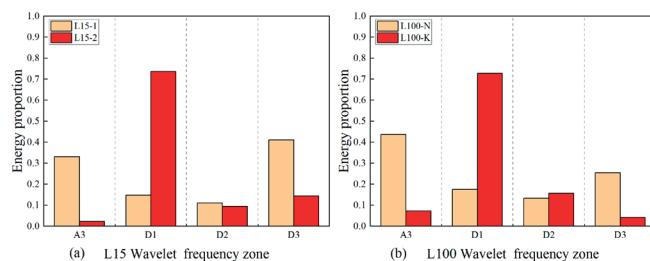


Fig. 16. Comparison of energy proportion of each frequency interval under various loads

The relationship between the energy proportion of D1 and knock under L15 should be explored further. The overall operation of L15 is divided into three stages of continuous operation: normal operating conditions (L15-1), induced knocking conditions (L15-2), and restoration to normal

conditions (L15-1). Knock was induced from the 59th cycle and ended at the 154th cycle. When the engine changes the operating condition to L15-2, there is an abrupt increase in the energy proportion of the D1 frequency band. More specifically, the energy proportion of the D1 frequency band remains below 0.5 when the engine operates at L15-1; the energy proportion of the D1 frequency band suddenly changes to over 0.5 when the engine operates at L15-2, as shown in Fig. 17. Therefore, the energy proportion of the D1 frequency band is effective in distinguishing knock.

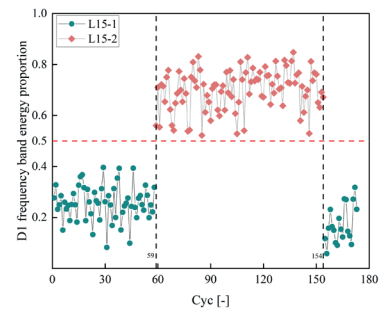


Fig. 17. D1 frequency band energy proportion under L15 operating status

To further verify the reliability of using energy ratio for knock detection, further analysis of the D1 frequency band energy proportion versus MAPO and MAVO, under L15 and L100, was conducted, as shown in Fig. 18 and Fig. 19, respectively. Fig. 18(a) clearly shows that the engine experiences knocking when MAPO is more significant than 0.2 MPa. At this point, the energy proportion indicates a distinct boundary in which the energy proportion of the knocking cycle is stable above 0.5. Additionally, as the MAPO values increase, the energy proportion value does not change significantly. Similarly, this characteristic is also evident in the vibration signals in Fig. 18(b). In Fig. 19 (a), the MAPO should be larger than 1.2, to distinguish the knock. Interestingly, the D1 frequency band energy ratio can still accurately distinguish knocking cycles, even with only a few knocking cycles, and exhibit good stability. Therefore, it can be concluded that the engine is in a knocking state when the D1 proportion is greater than 0.5.

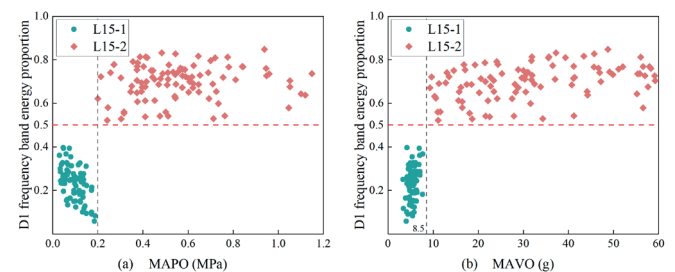


Fig. 18. D1 frequency band energy proportion versus MAPO and MAVO under L15

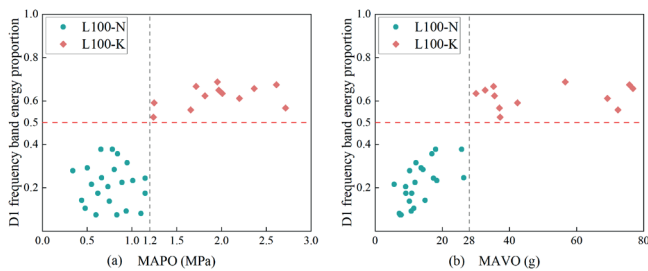


Fig. 19. D1 frequency band energy proportion versus MAPO and MAVO under L100

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CONCLUSIONS

A simple and unified index is proposed in this study, to detect knock under various engine loads. Firstly, a time-domain analysis was conducted to compare the vibration and cylinder pressure signals of the engine between MAVO and MAPO. Secondly, a knocking index built with MAVO can effectively detect engine knocking under various engine loads; the knocking index was validated for this engine under various engine loads. Furthermore, a frequency domain analysis and a wavelet transform were conducted to study the energy changes of vibration signals during knocking. Finally, a knock detection index is proposed, based on the energy proportion of vibration signals. The main conclusions are as follows:

(1) The vibration signal of the engine in the knocking condition has huge fluctuations, whose amplitude is several orders of magnitude greater than that in the normal state.

(2) There is little correlation between MAVO and MAPO in the combustion phase when the engine operates at either load.

(3) MAVO cannot accurately reflect the oscillation of in-cylinder pressure.

(4) PD_r values of less than 10 indicate that the engine is not knocking; the PD_r values above 10 indicate that the engine experiences knocking.

(5) Energy proportions of the D1 band during knocking cycles increase by approximately five times that of normal conditions. This indicates that the energy proportion of D1 is an effective index for knock detection.

(6) A simple and unified index with the energy proportions of the D1 frequency band is proposed. It can be used for knock detection under various loads.

(7) The engine is determined as being in a knocking state when the D1 proportion is greater than 0.5.

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