Characterization of Cycle-to-Cycle Variations in Conventional Diesel Engine Using Wavelets

Mohit Raj Saxena and Rakesh Kumar Maurya

Abstract Higher cycle-to-cycle variations in combustion engines lead to efficiency losses, engine roughness, lower power output, and higher exhaust emissions. Cycle-to-cycle variations in combustion engines are typically characterized by several techniques such as statistical method, symbol sequence statistics, chaotic methods, and wavelet analysis. Each strategy for cyclic variation characterization has its benefits and limitations depending on the application. Wavelet transform has a potential to analyze non-stationary signal in time domain as well as frequency domain simultaneously. This strategy has better temporal and spectral resolution; thus, wavelet analysis can be used to analyze the periodicities as well as magnitude of variations in the engine combustion cycles. This chapter presents the characterization of cycle-to-cycle variations in conventional diesel engine using statistical technique as well as wavelet technique. Cyclic variations in various combustion parameters (such as indicated mean effective pressure, total heat release rate, and peak pressure) are discussed in diesel engine operated at different operating conditions with diesel as well as butanol/diesel blends. Typically, cyclic variations in indicated mean effective pressure, peak pressure, and total heat release rate are found higher at lower engine loads and decrease with increase in engine load.

Keywords Diesel engine · Cyclic variations · Combustion · IMEP
THR · Wavelets

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1 Introduction

The World is facing the crises of depletion of fossil fuels and increase in the cost of petroleum products. To fulfill the energy demand, the development of clean and efficient combustion engines is required. Reciprocating internal combustion (IC) engines are the basic prime movers in transportation sector of the modern society. Two types of reciprocating IC engines are widely used for transportation in current society, i.e., spark ignition (SI) and compression ignition (CI) engines.

The CI engines (typically operated on diesel) are more preferred over the SI engines (typically operated on gasoline) due to its higher power output and thermal efficiency, particularly in heavy-duty vehicles and commercial applications. However, diesel engines emit nitrogen oxides (NO_x) and particulate matter (PM) in relatively higher concentration. In order to reduce the emissions and decrease the dependency on fossil fuels, various alternative fuels (such as methanol, ethanol, butanol, biodiesel) are proposed and demonstrated for the diesel engines [1–5]. However, some of these fuels are not prominently used for automotive engines due to some limitations (such as miscibility, higher viscosity).

Combustion process in a diesel engine depends on various factors such as mean in-cylinder temperature, fuel injection timing, injection pressure. Consecutive engine combustion cycles of IC engines are not exactly the same, like fingerprints of two human beings. The variations in the engine combustion cycles are known as cyclic variations. Variation in combustion characteristics leads to cyclic variations in the cylinder pressure of engine, which is the most widely measured and analyzed signal by researchers for the analysis of engine combustion. Figure 1 presents the variations in the cylinder pressure of 100 consecutive engine cycles of a four-stroke single cylinder conventional diesel engine.

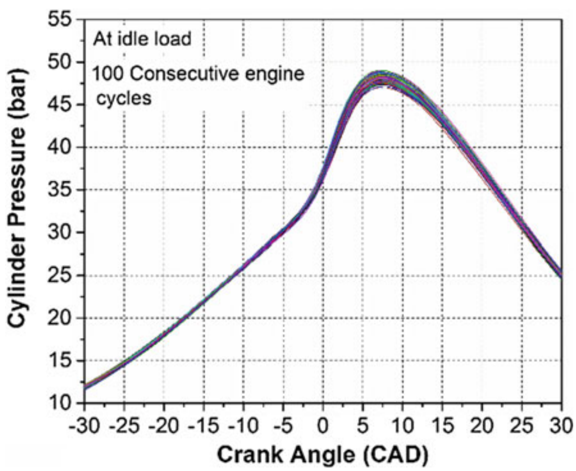

Fig. 1 In-cylinder pressure history of 100 consecutive engine cycles at idle condition

Since the two consecutive engine cycles are not similar (Fig. 1), it affects the combustion as well as emission characteristics of the engine. Higher cyclic variations in combustion lead to efficiency losses, lower fuel economy, variations in engine torque and speed, higher emissions, and limiting the actual operating range of the engine for practical applications. Excessive variations in engine cycles, particularly at higher engine loads, may cause damage to engine or reduce the engine life. To run an engine with stable combustion, these cyclic variations need to be minimized. The phenomenon of cyclic variability in combustion is more common in SI engines, which is mainly due to the variations in the charge burning rate of consecutive engine cycles. There are several factors responsible for cyclic variations in engines such as excessive dilution, variations in the amount of fuel and air inducted in each cycle, low ignition energy, variations in charge preparation (droplet size, cone angle, targeting, swirl, etc.), and variation in the in-cylinder flows. As compared to SI engine, cyclic variations are typically less significant in CI engines. In spark ignition, combustion is mainly governed by flame kernel development and flame propagation. These processes are highly sensitive to variations in engine operating conditions. In conventional diesel engines, the heterogeneous combustion (in which air–fuel mixing is governed by fuel injection in the cylinder and then combustion occurs with autoignition) occurs. Modern automotive diesel engine with electronic fuel injection systems has multiple fuel injection which reduces the ignition delay. Therefore, mostly in diesel engines, combustion occurs by diffusion combustion mode especially at higher engine load. However, there exist significantly high cyclic variations in diesel engines at lower engine loads, where ignition delay is longer. In advanced compression ignition engines known as low-temperature combustion engines, cyclic variations are very high at some of the operating conditions because of premixed charge engine operations [6].

A study demonstrated that cyclic variations in indicated mean effective pressure (IMEP) of diesel engine cycle occur due to the variations in the injected fuel quantity per cycle [7]. Another study investigated the fuel line pressure with respect to ignition delay, which indicates that fuel pump system has no significant effect on the cyclic pressure variations [8]. Rakopoulos et al. [9] experimentally investigated the effect of different biofuel blends with fossil diesel (i.e., 15% ethanol, 24% butanol, and 24% diethyl ether) on cycle-to-cycle variations in the CI engine using statistical techniques. In-cylinder pressure history data for 400 consecutive engine cycles was measured to diagnose the cyclic variations in peak pressure, peak pressure rise rate (P_{max}), and IMEP. Their results indicate that by using biofuels, the cyclic variations slightly increase as compared to fossil diesel. The coefficient of variation increases in the order of fossil diesel, n-butanol/diesel blend, ethanol/diesel blend, and diethyl ether/diesel blends. Increase in cyclic variations in biofuel blends is possibly due to corresponding increase in the ignition delay of blended fuel. In previous studies [9–14], different strategies were suggested to investigate the cyclic variations in the IC engine such as statistical technique, chaotic method, symbol sequence statistics analysis, wavelet analysis. Each of the techniques has its own benefits and limitations depending on the application. In past few years, several researchers prominently used wavelet transform (WT) to diagnose the cyclic variations in an IC engine cycle [14–21]. Wavelet transform has a potential to analyze non-stationary signal in frequency domain as well as time domain simultaneously. This strategy characterizes better temporal and spectral resolution; thus, wavelets can be used to analyze the periodicities as well as magnitude of variations in the engine combustion cycles. STFT (short-term Fourier transform) or WFT (windowed Fourier transform) can also be used for this purpose but these techniques have poor temporal resolution.

Sen et al. [14] used wavelet analysis to determine the cyclic variation in peak pressure at different operating loads of spark ignition engine. Their results indicate that for lower engine load conditions, the variation in the peak pressure is higher and it reduces with increase in engine load. In other studies, Sen et al. [16–18] investigated the different aspects of cyclic variations for different combustion parameters of SI engine. The cyclic variations in MIP (mean indicated pressure) by using wavelets at various engine speeds are investigated in compression ignition engine [15]. The results showed that with an increase in engine speed, the variations in IMEP reduce. It attributes to higher piston speed, which enhances the charge swirl motion and combustion process. Ali et al. [20] investigated the effect of diethyl ether addition in biodiesel/diesel blend on the cyclic variations for IMEP of diesel engine and found that with an increase in the diethyl ether fraction in the biodiesel/diesel blend, the cyclic variations increase. The cyclic variations possibly increase because of the higher volatility and lower flash point of the diethyl ether, which may lead to increase the variations. Maurya et al. [21] experimentally investigated the impact of engine load and the CR (compression ratio) on the cyclic variability in the combustion parameters of a stationary diesel engine. Their results demonstrated that cyclic variations in THR are higher at lower load and reduce with increase in operating load. Maximum cyclic variations were obtained at idle load with lower CR. Cyclic variations were also reduced with an increase in the CR.

As discussed above, since the cyclic variations have significant effect on the performance of the engine, it is essential to perceive the cyclic variations in the diesel engine to operate the engine efficiently at any particular fuel. This chapter focuses on the investigation of cyclic variations in diesel engine at different operating conditions using statistical technique as well as wavelet technique. The effect of engine load, compression ratio, and butanol addition in diesel fuel on the cyclic variations in combustion parameters such as total heat release (THR), IMEP, and maximum pressure (P_{max}) of compression ignition engine is discussed in Sect. 3. Before discussing the cyclic variation, the methodology of cyclic variation analysis is discussed in the following section.

2 Methodology of Cyclic Variation Analysis

To investigate and characterize the cyclic variations in combustion parameters, the estimation of combustion parameter is required on cycle-to-cycle basis. Typically, in-cylinder pressure is measured for analyzing combustion characteristics of

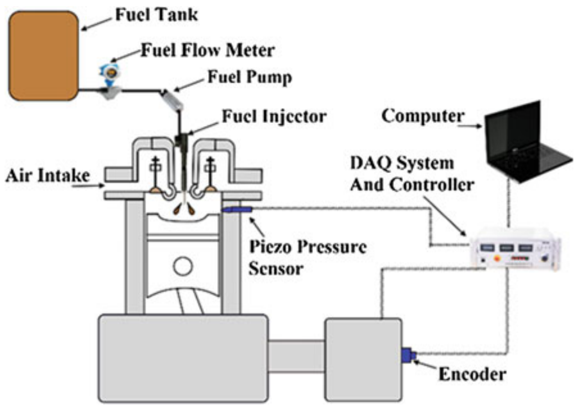

Fig. 2 Schematic diagram of typical cylinder pressure measurement setup

reciprocating engines. Current piezoelectric pressure sensors have fast response, which is required for engine combustion analysis. Heat release characteristics are calculated from experimentally measured data of cylinder pressure. Combustion parameters are calculated from heat release curve estimated from cylinder pressure data. For cycle-to-cycle variation analysis, in-cylinder pressure traces of several consecutive engine cycles for diesel engine are generally recorded. For the measurement of in-cylinder pressure, a piezoelectric pressure transducer is installed in the cylinder head of the engine. The crank angle position is measured by using a crank angle encoder which is installed on the axis of crankshaft. Typical experimental setup required for the measurement of cylinder pressure (which is used for the calculation of combustion parameters on cyclic basis) is illustrated in Fig. 2. A high-speed data acquisition system is used for online logging the experimental cylinder pressure data.

For the investigation of cycle-to-cycle variations, in-cylinder pressure of several (2000 in present study) consecutive engine cycles is recorded. For each cycle, combustion parameters are calculated by heat release analysis. Equations used for calculating the combustion parameters are given below:

Rate of heat release (ROHR) is determined by using Eq. (1)

$$\frac{\mathrm{d}Q(\theta)}{\mathrm{d}\theta} = \left(\frac{1}{\gamma - 1}\right) V(\theta) \frac{\mathrm{d}P(\theta)}{\mathrm{d}\theta} + \left(\frac{\gamma}{\gamma - 1}\right) P(\theta) \frac{\mathrm{d}V(\theta)}{d\theta} \tag{1}$$

where

'Q' represents the rate of heat release (ROHR),

'γ' denotes the specific heat ratio, and

'$P(\theta)$' and '$V(\theta)$' denote the in-cylinder pressure and volume as a function of crank position.

$$V(\theta) = V_c + \frac{\pi}{4} B^2 \left(L + R - R\cos(\theta) - \sqrt{L^2 - R^2 \sin^2(\theta)} \right) \tag{2}$$

where
'B' denotes the bore of the cylinder,
'L' is the connecting rod length,
'R' denotes the radius of crank, and
'V_c' denotes the clearance volume.

THR is determined by integrating the ROHR between start of combustion (SOC) and end of combustion (EOC). Figure 3c, b shows the time series of P_{max} and THR for 2000 consecutive engine cycles for diesel engine at idle load (0% engine operating load) condition.

IMEP is defined as the ratio of indicated work (W_{ind}) to the swept volume (V_s).

$$\text{IMEP} = \frac{W_{ind}}{V_s} \tag{3}$$

where
'W_{ind}' denotes the indicated work and
'V_s' is the swept or displacement volume.

$$W_{ind} = \frac{2\pi}{360} \int_{-180}^{180} \left(P(\theta) \frac{dV}{d\theta} \right) d\theta \tag{4}$$

Figure 3a illustrates the time series of IMEP for 2000 consecutive engine cycles for diesel engine at idle load (0% engine operating load) condition.

After calculating the time series of combustion parameters, cyclic variations are analyzed by statistical method and wavelet methods, which are described in the following subsections.

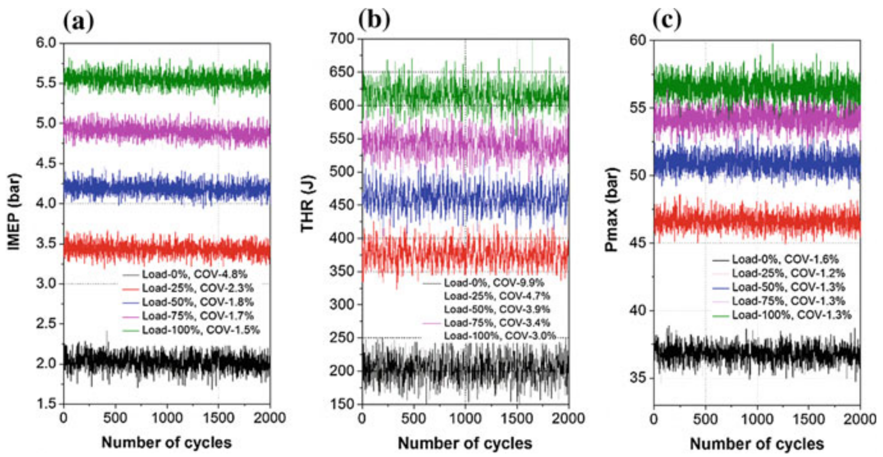

Fig. 3 Time series of **a** IMEP; **b** THR; **c** P_{max} for diesel fuel different engine operating load conditions at 17:1 compression ratio. Adapted from [24]

2.1 Statistical Methods

Statistical methods are used most commonly for the quantification of the cycle-to-cycle (cyclic) variations in the engine combustion parameters. Standard deviation and coefficient of variation are two commonly used parameters to quantify the variation in any combustion parameter. Standard deviation of the combustion parameter determines how far the values are spread from the mean values, and it is defined as follows:

$$\text{Std. deviation in 'X'} = \sqrt{n\sum_{i=1}^{n}\frac{(X_i - X)^2}{(n-1)}} \tag{5}$$

where
'X represents the combustion parameter,
'n is the number of samples, and
'i is the sample of interest.

Coefficient of variation (COV) for any combustion parameter represents the variations in that parameter and is calculated by using Eq. (6)

$$\text{COV}(\%) = \frac{\text{Std. deviation of 'X'}}{\text{mean of 'X'}} \times 100 \tag{6}$$

From statistical technique, temporal variations in the time series can be easily quantified. However, spectral variations in combustion parameters cannot be quantified by using statistical technique, which is the main limitation of this technique.

2.2 Wavelet Transform

Wavelet analysis is a common technique used for quantifying the local variations in a time series of non-stationary signal. In wavelet analysis, the time series is decomposed into frequency domain as well as time domain, which helps to quantify the leading mode of combustion variability. Additionally, with the help of this technique, one can also quantify how that mode varies with time [23]. A wavelet is considered as an instantly decaying oscillation or wave. That means amplitude of the wavelet starts increasing from zero, and within a short period of time, it comes back to initial condition. A wavelet is defined as a function, which has a finite energy and has zero mean. A continuous wavelet transform (CWT) for a wavelet function $\Psi(t)$ is represented as follows:

$$\text{CWT}(a,b) = \frac{1}{\sqrt{|a|}}\int_{-\infty}^{\infty} x(t)\Psi^{*}\left(\frac{t-b}{a}\right), \quad a,b \in R, \quad a \neq 0 \tag{7}$$

where

'$\Psi(t)$' and '$\Psi^*(t)$' imply the mother wavelet and its conjugate,

'$x(t)$' implies a continuous signal, and

'a and 'b' denote the scaling and translating parameters.

To analyze the cyclic variations in combustion parameters, WPS (wavelet power spectrum) and GWS (global wavelet spectrum) are used. WPS gives the information about the fluctuation of variance at different frequencies or scales. The square modulus of CWT represents the magnitude of signal energy at a certain scale 'a' and at a particular location 'n' which is called WPS or scalogram. WPS is normalized by dividing with 'σ^2' so that power relative to white noise is obtained [23]. WPS is determined as follows:

$$\mathrm{WPS} = |\mathrm{CWT}_n(a)|^2 \tag{8}$$

WPS can be normalized by using Eq. (9)

$$\mathrm{WPS}_n = \frac{|\mathrm{CWT}_n(a)|^2}{\sigma^2} \tag{9}$$

where 'σ^2' denotes the standard deviation.

CWT is complex function; thus, modulus of CWT actually represents the amplitude of CWT. WPS depends on the scale (frequency) as well as time represented by a surface. Timescale representation of WPS can be obtained by plotting a contour of surface on a plane. From WPS, higher variance in the time series and their frequency of occurrence can also be easily determined. In addition, time duration of prevailing periodicities can be easily determined. GWS is defined as time average of WPS and represented by 'W_s'. Peak locations in the GWS represent the dominant periodicities in the given time series. GWS is calculated from Eq. (10).

$$\mathrm{GWS} = W_s = \frac{1}{N}\sum_{n=1}^{N} |\mathrm{CWT}_n(a)|^2 \tag{10}$$

3 Cycle-to-Cycle Variation Analysis

In this section, the effect of engine load, compression ratio, and butanol addition on cycle-to-cycle variations in combustion parameters is discussed. The cyclic variations are discussed using wavelet analysis as well as statistical methods.

3.1 Effect of Engine Load on Cyclic Variations

The cyclic variations have significant effect on the performance of diesel engine, and it leads to higher emissions and lower fuel economy. In this section, the effect of engine load on cyclic variations in combustion parameters of conventional diesel engines is analyzed using statistical approach as well as wavelet approach. Figure 3 shows the time series of IMEP, THR, and P_{max} for 2000 consecutive engine cycles. Time series is generated by the analysis of measured cylinder pressure (as discussed in Sect. 2) for each engine cycle. Figure 3 illustrates that IMEP, THR, and P_{max} increase with an increase in the engine operating load condition as higher amount of fuel is burned in the cylinder. Figure also reveals that with an increase in the engine operating load, the coefficient of variation (COV) decreases for all the combustion parameters. The decrease of the COV in combustion parameters with engine load indicates the reduction in the cycle-to-cycle variations. At 0% engine operating load, the amount of fuel injected is lower which results in lower combustion temperature. Lower combustion temperature leads to higher cyclic variations. At lower engine load, combustion phasing is relatively retarded and significant amount of combustion occurs during expansion stroke. Oxidation reactions occurring away from TDC are more sensitive to cyclic variations in temperature. Therefore, cyclic variation in combustion parameters is higher at lower engine loads. With increase in the engine load, more amount of fuel is injected in the cylinder, which leads to increase the mean in-cylinder combustion temperature and results in lower cyclic variations in combustion parameters.

Wavelet transform is used to analyze the frequency of cyclic variation with time in 2000 consecutive engine combustion cycles. It provides the time and frequency information simultaneously [19, 23]. With the help of CWT, wavelet power spectrum (WPS) and global wavelet spectrum (GWS) are created from the time series of IMEP, THR, and P_{max} of 2000 consecutive cycles. WPS reveals the energy of the signal, and it is the square modulus of CWT. In this chapter, spectrogram is mainly used to investigate the frequency band contribution to the signal energy. Additionally, it is used to determine how periodicity changes with time. The time average of WPS is called GWS.

Figure 4 illustrates the GWS and WPS of IMEP for neat diesel (D100) fuel at 0, 50, and 100% engine operating loads. Horizontal axis in WPS represents the engine combustion cycles, and the vertical axis indicates the periodicities of particular data series. Horizontal axis in GWS represents the power, and the vertical axis indicates the period. Peaks in the GWS plot reveal the prevalent periodicities in the data series of particular parameters. Colors shown in the WPS graph represent the energy of the signal, which represents the WT magnitude [23]. Red and blue colors indicate the maximum and minimum energy of the signal, respectively, over that interval. U-shaped curve in the bottom of WPS is known as the cone of influence (COI). It indicates the 5% significant level. It is the area where edge effect is important [23]. The area above the COI is only considered. Figure 4a depicts the GWS and WPS for IMEP at 0% engine operating load condition. Figure 4a

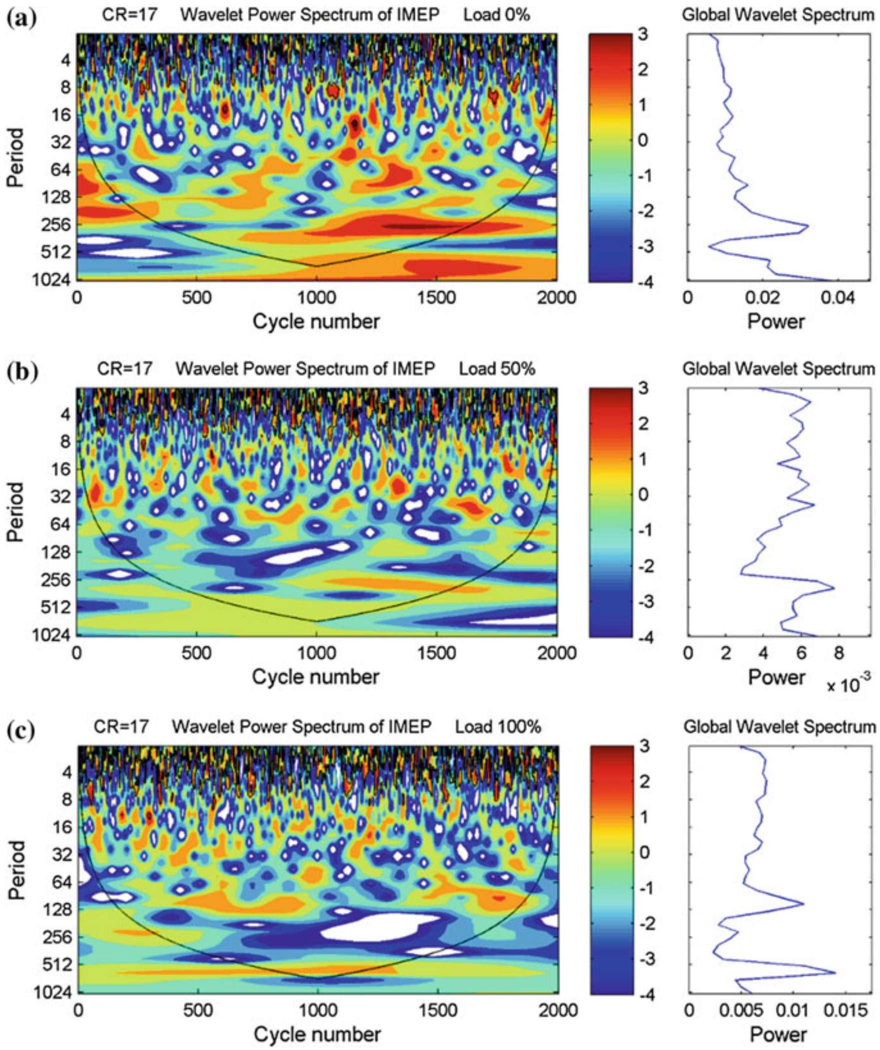

Fig. 4 WPS and GWS of IMEP for neat diesel **a** at 0% engine load; **b** at 50% engine load; **c** at 100% engine load for compression ratio of 17 in a CI engine. Adapted from [24]

indicates that band of periods 11–16, 16–28, 55–93, and 186–373 have higher cyclic variations in the cycles ranging between 596–639, 1128–1187, 1215–1405, and 982–1644, respectively. The strong intensity periodic band indicates higher cyclic variability at 0% engine operating load condition. Figure 4b shows the WPS and GWS for IMEP at 50% engine operating load condition. It has been observed from the Fig. 4b that fewer periodic bands of 20–32 and 32–39 with strong intensity of variance occur in the cycles ranging between 128–136 and 1576–1689, respectively. GWS at 50% engine load is also reduced in comparison with 0%

engine operating load which indicates reduction in cyclic variations. The decrease in cyclic variations is due to the higher mean in-cylinder combustion temperature at higher load condition (because more amount of fuel is injected) which leads to better combustion. Figure 4c shows the WPS and GWS for IMEP at 100% engine operating load condition. The GWS in Fig. 4c shows that the peak power of GWS is higher for 100% engine load condition which reveals higher cyclic variations. WPS at 100% engine load represents that a periodic band of 90–128 with higher intensity occurs between the cycles ranging from 1460 to 1870. Some weaker periodic bands are also observed in Fig. 4c. However, the power of GWS is higher at lower intensity periods. It is possibly due to the amplification of GWS power at higher periods [25].

Figure 5 shows the WPS and GWS of THR at 0, 50, and 100% engine operating load conditions for a fixed compression ratio of 17. Figure 5a shows the WPS and GWS for THR at 0% engine operating load condition. Figure 5a indicates a periodic band of 14–20 with strong intensity of variance observed during the cycles ranging between 51–410, 571–875, 927–950, 1015–1075, 1180–1555, and 1650–1870. The presence of strong periodicity in large number of engine cycles represents the higher cyclic variability. Additionally, some weaker bands of 46–54 and 128–157 periods with moderated or low intensity occur—in the cycle range of 145–160 and 625–770, respectively.

Figure 5b shows the WPS and GWS for THR at 50% engine operating load condition. Figure 5b shows that strong intensity of periodic band of 32–64 is observed in the cycles ranging from 72 to 1950. This periodic band of strong, moderated, and lower intensity (shown by decrease in the intensity of red color) of variance seems continuous throughout the cycles ranging from 72 to 1950. Lower intensity band represents the reduction in the cyclic variations. The decrease in the cycle-to-cycle variations attributes to higher mean in-cylinder combustion temperature at higher load condition which leads to better combustion. It can also be noticed from Fig. 5a, b that the peak power of the GWS at 50% engine load is higher in comparison to 0% (idle) engine load, which indicates higher cyclic variations at 50% engine load condition. A shift from lower periodicity to higher periodicity represents the lower frequency cyclic variations (as shown in WPS of Fig. 5a, b). However, GWS power decreases at 100% engine operating load condition, which indicates the decrease in the cyclic variations. Figure 5c shows the WPS and GWS for THR at 100% engine operating load condition. Figure indicates that a periodic band of 10–16 with strong intensity occurs intermittently in the cycles ranging between 140–255, 325–426,467–499, 552–580,642–714, 738–780, 1023–1194, 1260–1497, 1505–1580, and 1889–1960 cycles.

Figure 6 illustrates the WPS and GWS of P_{max} at different engine operating load conditions. Figure 6a shows that periodic bands of 157–313, 40–60, 55–93, and 55–78 with strong intensity of variance occur in the cycles between 1135–1620, 222–382, 821–953, and 1305–1440, respectively. Figure 6b depicts the WPS and GWS of P_{max} at 50% engine operating load condition. Figure indicates that the power of GWS increases in comparison with 0% engine operating load condition. It

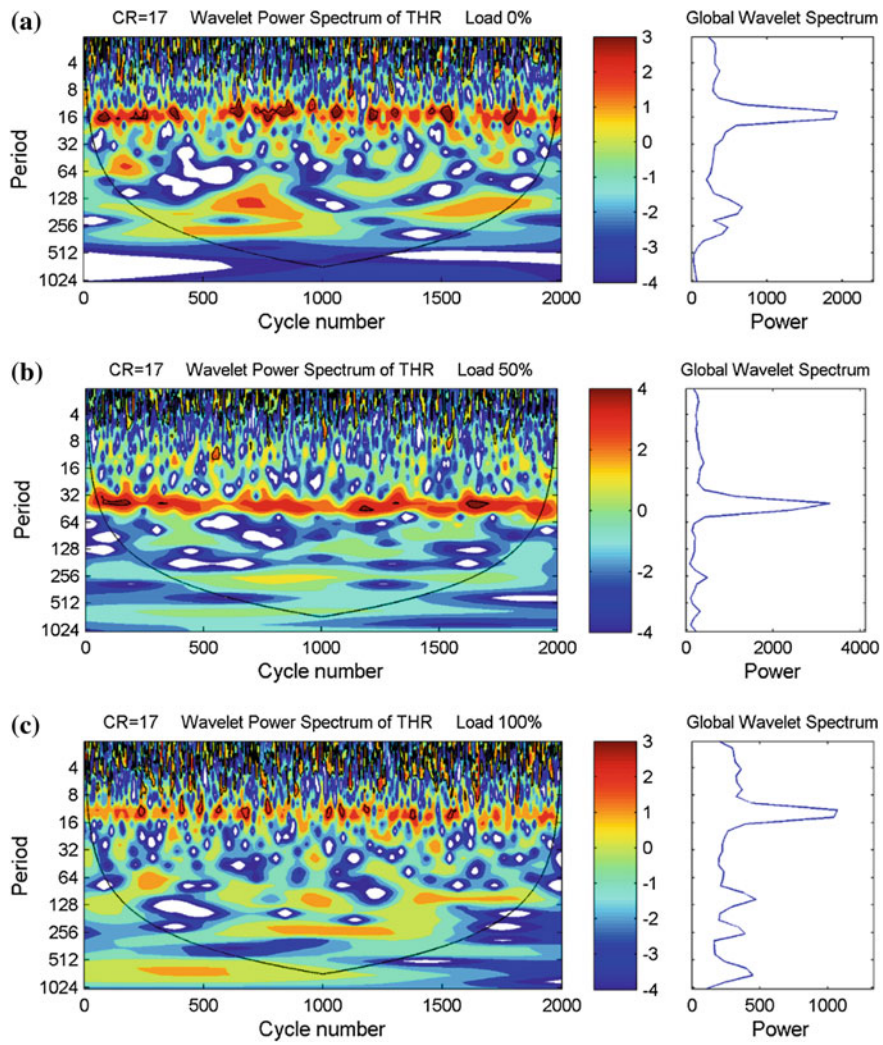

Fig. 5 WPS and GWS of THR for neat diesel **a** at 0% engine load; **b** at 50% engine load; **c** at 100% engine load for compression ratio of 17. Adapted from [24]

can be observed that peak GWS power is corresponding to intensity of period that is outside the cone of influence which is not significant. Fewer strong intensity periodic bands of 16–30, 21–28, and 30–38 occur in the cycle range of 818–845, 1333–1365, and 9420–1015 cycles, respectively. At 100% engine operating load condition, periodic bands of 112–225 and 39–64 with weak intensity of variance occur in the cycles ranging between 640–1055 and 960–1370 cycles, respectively.

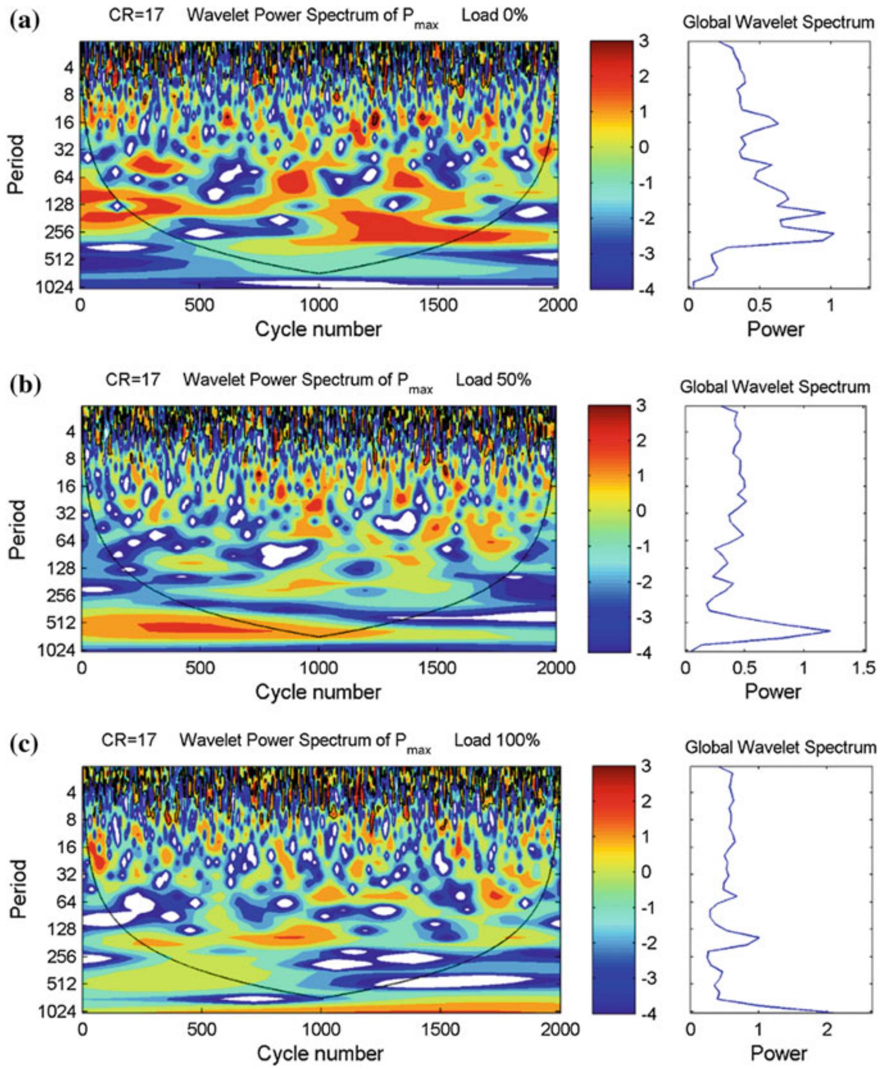

Fig. 6 WPS and GWS of P_{max} for neat diesel **a** at 0% engine load; **b** at 50% engine load; **c** at 100% engine load for compression ratio of 17. Adapted from [24]

3.2 Effect of Compression Ratio on Cyclic Variations

This section presents the effect of compression ratio on cyclic variation in combustion parameters of diesel engine. Figure 7 shows the time series of THR for different compression ratios (CR) at lower engine load (0.28 bar BMEP) condition.

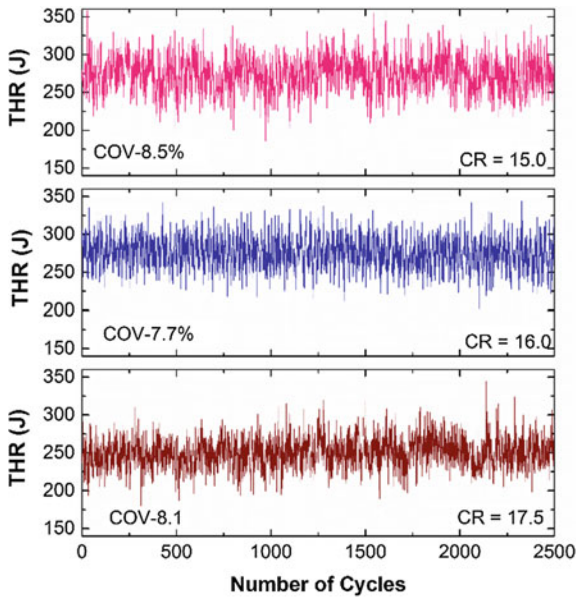

Fig. 7 Time series of THR for different compression ratios at 0.28 bar BMEP (lower engine operating load) [21]

Since the cyclic variations are higher at lower load condition, the effect of CR of compression ratio on the cyclic variation was investigated at lower load condition [21]. Cyclic variations in total heat release are highest at lowest compression ratio (Fig. 7).

Figure 8 illustrates the WPS and GWS of THR at compression ratios (CRs) of 15, 16, and 17.5 at lower load condition (0.28 bar BMEP). Figure 8 depicts that with an increase in the CR, the peak power of the GWS decreases which indicates that cyclic variations reduce with increase in the CR. At a CR of 17.5, periodic bands of 105–256, 64–110, and 100–540 with strong intensity occur between the cycles 380–890, 1090–1410, and 1290–2080, respectively (shown in Fig. 8a). Periodic bands with strong intensity and moderated intensity of variance indicate the higher cyclic variations. At CR of 16, a periodic band of 16–32 occurs intermittently throughout the cycles (shown in Fig. 8b). It can also be seen from Fig. 8b, a that with an increase in the CR from 16 to 17.5, a shift occurs from lower periodicity to higher periodicity which represents the variations occur with lower frequency. It can also be depicted from the figure that peak power in GWS slightly increases in case of CR of 16 in comparison with CR of 17. Figure 8c shows the WPS and GWS of THR at CR of 15. Figure 8c reveals that the periodic bands of 220–315 and 430–650 occur between the cycles 445–1054 and 981–1807, respectively. Figure 8c also reveals that power of GWS further increases with decrease in the CR which indicates the higher cyclic variations.

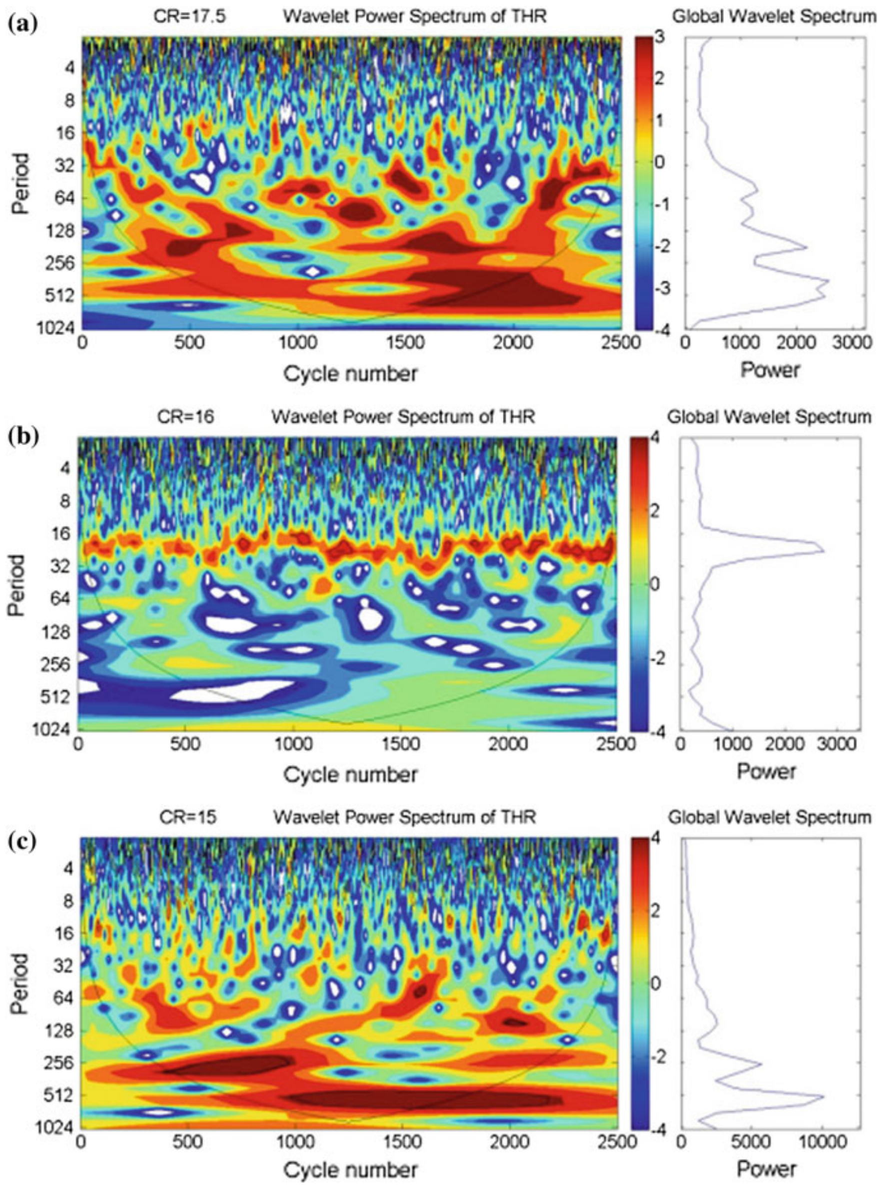

Fig. 8 WPS and GWS of THR for neat diesel at **a** CR of 17.5; **b** CR of 16; **c** CR of 15 for 0.28 bar BMEP [21]

3.3 Effect of Butanol Blends on Cyclic Variations

In recent years, butanol is evolved as an alternative fuel for compression ignition engine [1, 27–30]. The properties of butanol make it suitable candidate fuel for the replacement of conventional diesel fuel for diesel engines. Butanol can be easily mixed with diesel fuel, and no further additive is required for the preparation of stable blend (i.e., no fuel layer separation). Butanol also has a higher cetane number as compared to other primary alcohol fuels. Typical properties of butanol and diesel are provided in the study [22]. Previous study [26] investigated the cyclic variations in P_{max} for neat diesel and butanol blends at different engine operating load conditions. The results reveal that with an increase in the engine operating load, the peak power of GWS decreases which means that the cyclic variability reduces with increase in engine operating load. The increase in the butanol fraction in the blended fuel up to a certain limit leads to the reduction in the cyclic variations.

Figure 9 shows the time series of IMEP for neat diesel (D100), 10% butanol/diesel blend (B10), 20% butanol/diesel blend, and 30% butanol/diesel blend (B30) of 2000 consecutive engine cycles at 0%, 50%, and 100% engine load conditions. Figure 9 illustrates that the mean IMEP increases with an increase in the engine

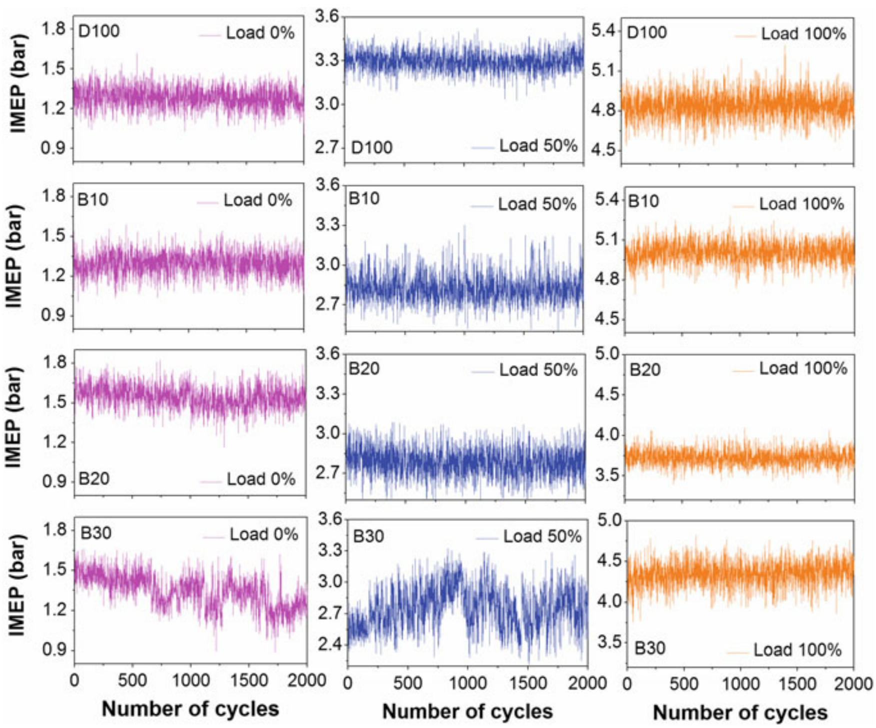

Fig. 9 Time series of IMEP for D100, B10, B20, and B30 at 0%, 50%, and 100% load conditions in CI engine

operating load condition. At higher engine load, more fraction of fuel is burned in each cycle which leads to increase the IMEP.

Figure 10 illustrates the COV in IMEP for 2000 consecutive engine combustion cycles at different load conditions for D100, B10, B20, and B30 blends. Figure 10 reveals that the higher cyclic variations were obtained at 0% load condition. At 0% engine operating load, the amount of fuel injected is lower which results in lower combustion temperature. Lower combustion temperature leads to increase the cyclic variations. Figure 10 also indicates that at lower load condition, up to 20 or 25% addition of butanol in the diesel fuel, COV in IMEP is close to COV in IMEP with neat diesel fuel. However, higher COV in IMEP was observed above 25% butanol fraction in the blended fuel. Figure reveals that the cyclic variations decrease with the addition of butanol fraction in the diesel fuel up to a certain limit. However, with further increase in butanol fraction, cyclic variation increases at 0% engine load condition. With increase in the butanol fraction in the blended fuel, the combustion phasing is retarded which results in higher cyclic variations. When combustion phasing is retarded, the velocity of the piston is comparatively higher, which leads to more sensitivity for temperature and pressure because of change in cylinder volume. Therefore, retarded combustion phasing results in higher cyclic variations. At higher load condition, higher fraction of butanol could be added in diesel fuel up to a certain limit which further needs to be investigated.

Since the cyclic variations were higher at 0% load, wavelet analysis is only presented for D100, B10, B20, and B30 at 0% load condition. Figure 11a indicates a periodic band of 16–32 with moderated intensity observed during the cycles 126–185. The presence of strong periodicity represents the higher cyclic variability. In addition to this, a periodic band of 4–16 with moderated or low intensity occurs intermittently till the 800 cycles. Figure 11b shows periodic bands of 16–32, 32–128, 64–128, and 256–512 with strong intensity observed during 458–524,

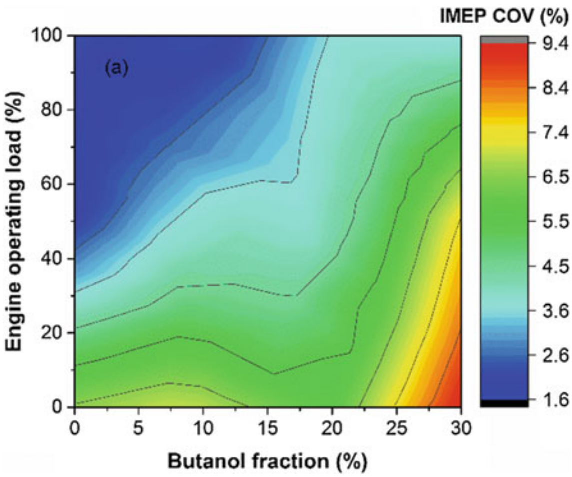

Fig. 10 Effect of engine load on the COV in **a** IMEP for different diesel/butanol blends in compression ignition engine

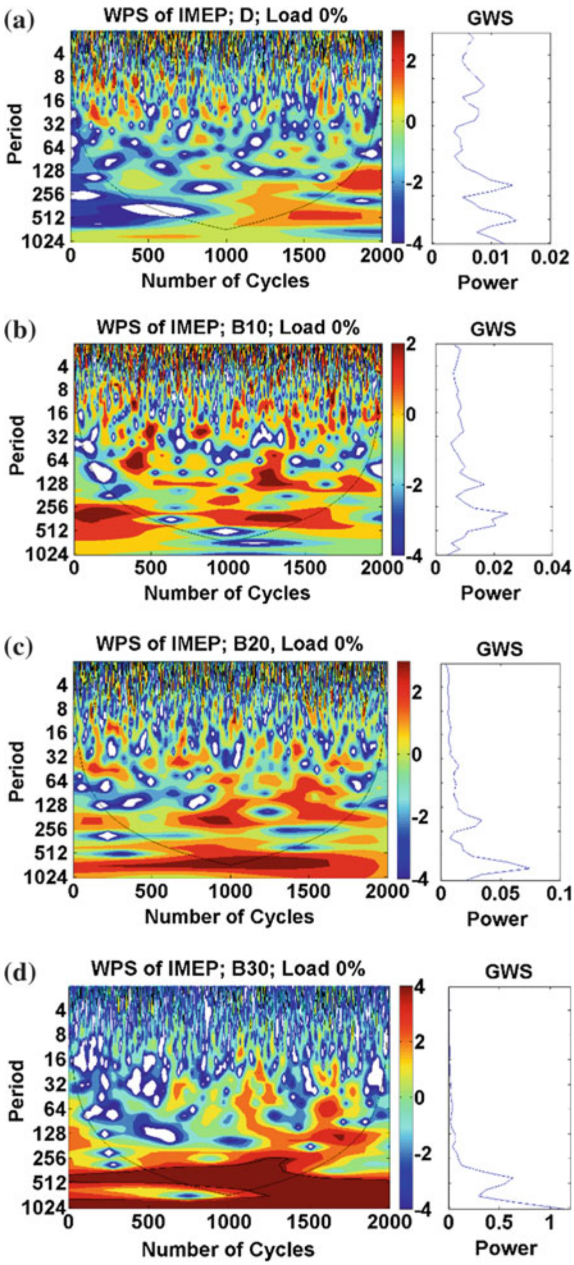

Fig. 11 WPS and GWS of IMEP for **a** D100; **b** B10; **c** B20; **d** B30 blended fuel at 0% load conditions in CI engine

304–479, 1168–1500, and 746–1622 cycles, respectively. Moderated intensity periodic bands also observed alternatingly throughout the cycles.

Similarly, in Fig. 11c, strong intensity periodic bands of 128–256, 64–256, and 512–1024 were observed during 672–1159, 1280–1752, and 845–1200 cycles, respectively. In case of 30% butanol/diesel blend, a strong intensity periodic band of 256–512 was observed during 494–1426 consecutive cycles (as shown in Fig. 11d).

In Fig. 11, GWS reveals that peak power in case of B10 and B20 blends is closer to the GWS peak power of neat diesel at 0% engine load condition. It represents that there was not too much difference in cyclic variation with 10 and 20% butanol blends as compared to neat diesel fuel. However, intense cyclic variations were obtained with B30 blended fuel. It might be because of the combined effect of lower cetane number and higher oxygen contents which retards the combustion phasing and results in unstable combustion.

4 Summary and Conclusion

This chapter discussed the characterization of cyclic variations in conventional diesel engine using statistical technique as well as wavelet technique. Combustion instability or cyclic variations in the engine cycle have significant deteriorating effect on the performance of the engine. Statistical and wavelet analysis results showed that cyclic variations are higher at lower load condition and decrease with increase in the engine load. Global wavelet spectrum (GWS) results indicate that with an increase in the engine operating load, peak power of GWS decreases. The decrease in GWS power suggests the lower cyclic variations. The GWS analysis also demonstrates the similar trend in cyclic variation with engine load as estimated by statistical methods. The WPS results also indicate that with an increase in the engine operating load, strong intensity variance shifts toward the higher frequencies from lower frequencies. At higher load conditions, fewer number of strong/moderated intensity periodic bands were found. It is also found that cyclic variability increases as compression ratio decreases. Butanol has a potential to reduce the cyclic variations in diesel engine. Statistical analysis of cyclic variations in IMEP indicates that at lower load condition, the cyclic variability is higher and it reduces with increase in the engine load. The results showed that up to 20% addition of butanol in the diesel fuel, cyclic variations in IMEP are close to the variation with neat diesel fuel. On further increasing the butanol fraction in the blended fuel, cyclic variations increase drastically. Finally, it can be summarized that wavelet analysis has a potential to analyze the cyclic variations in the combustion parameters and can provide additional information, which can be beneficial to control the cyclic variations. However, a more detailed exploration is required to utilize the full potential of wavelet analysis.

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