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Experimental investigation on cyclic variability in diesel engine fueled with ternary blends of diesel, methanol and 1-pentanol using wavelet method

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ABSTRACT
In this study, the cycle-to-cycle variation of peak cylinder pressure in single-cylinder four-stroke diesel engine was examined using wavelet transform. In this investigation, diesel and two other blends namely PM5 and PM10 were tested under different loading conditions. In-cylinder pressure data of 1000 consecutive cycles was used to measure the cyclic variation. The result indicated that cyclic variation in peak cylinder pressure decreased for PM5 and PM10 as compared to diesel because the global wavelet spectrum power which is an indicator of the cycle-to-cycle variation decreased for both the blends as compared to GWS power for diesel. Furthermore, the wavelet power spectrum results at 25% load indicated the strong variance at high frequencies for both the blends and diesel. Moreover, at 50% load WPS results depicted the high variation at high frequencies for diesel and PM10 but for PM5 the high-intensity variance shifted towards low frequencies.

***Keywords* -** Cycle to cycle variation, Diesel engine, Combustion, Wavelet transform Peak pressure

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I. INTRODUCTION

Improving the fuel economy and reducing emissions are two main challenges before the automotive researchers. Cyclic variation in the engine is one of the important parameters which affects the fuel economy and emission, is gaining the attention of most of the researchers. Cyclic variation can be defined as the variation of one combustion cycle to the next.[1]. In other words, cyclic variation is analogous to variation in human fingerprints as the two consecutive cycles are not similar to each other.[2]. Cyclic variation may occur in SI, CI and low-temperature combustion engines like HCCI or PCCI. Most of the researchers have studied combustion cyclic variation in SI engines and low-temperature combustion engines like HCCI or PCCI.[3–7]. Although CI engine offers very low cyclic variation due to very short ignition delay as compared to SI engine. But this ignition delay may increase while using alternative fuel blends in the diesel engine. So, it is essential to study the cyclic variation in CI engine while using alternative fuel blends. Various parameters have been used by different researchers to measure the cyclic variation, but the most prevalent parameter is peak pressure i.e., Pmax. Analysis of cyclic variation may be done by using Pmax per cycle data.[8]. Many researchers have adopted a statistical technique to study the cyclic variation in the engine [9–11]. But the major limitation of this technique is that only temporal variation present in data can be analyzed because it does not consider the frequency content of the data. Generally, the frequency content of the data can be analyzed by using the Fourier transform. However, it is not suitable for nonstationary signals in which frequency changes with time [12]. Hence to overcome the disadvantages of the above two techniques, wavelet technique is being used by several researchers. [13–16]. Ali et al.[17] studied the effect of alcohol on cycle to cycle variation in a diesel engine running on dieselbiodiesel blends using wavelet analysis. WPS (wavelet power spectrum) analysis of Pmax / cycle data showed the strong periodic oscillation and intermittent fluctuation for B-30 with and without alcohol respectively as compared to regular diesel. Furthermore, GWS (global wavelet spectrum) depicted that spectral power increased by using alcohol as an additive. Longwic et al.[18] studied the cyclic variation in a diesel engine fueled with three alternative fuels using mean indicated pressure (MIP) data. These three alternative fuels were the mixture of fatty acid methyl easter (FAME) and anhydrous ethanol, the mixture of FAME and ethyl tertiary-butyl ether (ETBT) and the mixture of diesel and ETBT. The cyclic variation in diesel engine was investigated for each alternative fuel and at three engine speeds of 1200, 1600 and 2000 rpm. The results indicated that strong periodicity was observed when the engine was fueled with alternative fuels at all three speeds. Moreover, long periodicity was ascertained in the engine running on regular diesel only at highest speed. But intermittent fluctuation appeared at all three speeds. Ali et al. [19] again investigated the effect of diethyl ether addition to biodiesel-diesel blend (B-30) on cyclic variation in a diesel engine using wavelet analysis. They reported an increment in spectral power with the increase in diethyl ether percentage in the diesel-biodiesel blend (B-30). Yusri et al. [20] studied the cyclic variation in diesel engine running on diesel-butanol blends namely DBu-5 (95% diesel+5% butanol), DBu-10 (90% diesel+10% butanol) and DBu-15 (85% diesel+15% butanol). They observed that DBu-15 exhibit high engine cyclic variation by using the wavelet power spectrum. From previous studies, it may be concluded that Wavelets can be used to determine the amplitude as well as periodicities of cycle-to-cycle variations in combustion engines because wavelet transform offers a good spectral and temporal resolution. But very few studies are available about cyclic variation in CI engine especially fueled with alternative fuel blends. Moreover, most of the studies were conducted on non-stationary engines. So, the main objective of present work is the application of wavelet to find out cyclic variations in conventional stationary diesel engine and its ability to represent the abrupt changes and functions which are not localized in space and time.

II. EXPERIMENTAL SETUP AND METHODOLOGY

A single-cylinder four-stroke conventional diesel engine with eddy current dynamometer was used as shown in Fig 1. The engine specifications are given in Table-1.

Table 1: Engine Specifications

Engine Characteristic	Specifications
Make/Model	Kirloskar TV1
Maximum Power	3.7 kW @1500 RPM
Injection type	Direct Injection
Number of cylinders	Single
Cylinder bore/Stroke	80 /110 mm
Compression ratio	16.5.:1
Fuel Injection timing	-24 CAD a TDC
Fuel Injection pressure	170 to 250 bar

An optical encoder of 1 CAD resolution was used to measure the crank position. A piezoelectric transducer was used to measure the in-cylinder pressure. A high-speed data acquisition (DAQ) (Manufacturer: National Instrument, USA) is used for recording the in-cylinder pressure data using LabVIEW based program. In-cylinder pressure data was recorded for 1000 cycles.

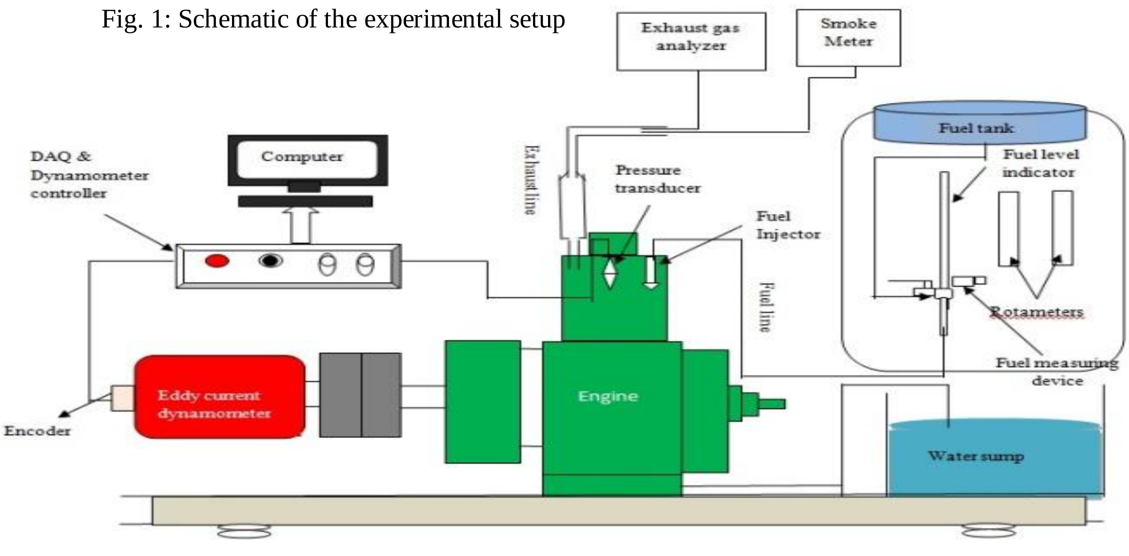
1.1 WAVELET ANALYSIS

A wavelet is a waveform of effectively limited duration that has an average value of zero. Mathematically it can be shown in Eq-(1)

$$\int_{-\infty}^{\infty}\psi(t)dt = 0; \quad \text{and} \int_{-\infty}^{\infty}|\psi(t)|^2\, dt < \infty \qquad (1)$$

Wavelet transform is an integral transform in which basis functions (localized in frequency and time domains) are used. Basis functions are the set of sine and cosine wave with unity amplitude. In wavelet transform the original signal decomposes into frequency bands (or scales) at various resolutions by scaling the basis functions. The original signal is projected on a set of basis functions

Fig. 1: Schematic of the experimental setup



called mother wavelets. The scale and translation parameters make the difference between various wavelet functions. Originally, Morlet thought the wavelets as a family of functions generated from translations and dilations of a single function (known as mother wavelet). Daughter wavelet in terms of mother wavelet is presented by Eq-(2) [21-22]

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\, \psi\left(\frac{t-b}{a}\right) \qquad a, b \in R \qquad (2)$$

Where, a= Dilation (scale) parameter,
b= Translational (position) parameter

Wavelet can be stretched or compressed and shift or translate along the time axis by using dilation 'a' and translational parameter 'b' respectively. The function $\psi_{a,b}(t)$ is multiplied by a factor $1/\sqrt{a}$ to get the same energy for all values of scale parameter 'a'. Scaling parameter is very similar to zoom lens as it decreases and increases the time width at higher frequencies and smaller frequencies in the signal respectively. [23]

2.2 SELECTION OF WAVELET TRANSFORM

Wavelet transform can be divided into two types: continuous wavelet transform (CWT) and discrete wavelet transform. Choosing an appropriate wavelet transform could be very challenging for the one who is new to wavelet analysis. Although very vast literature is available on a wavelet, unfortunately very few researchers or authors have given proper advice to select the suitable wavelet transform. Addison [24] reported that CWT can capture non-stationary signals because it gives a very high spectral and temporal resolution. Furthermore, Albarbar[25] observed that CWT is very sensitive to engine speed and load variations. Moreover, the injection process and lubrication related faults of an engine can be detected at early stages. In the present study, morlet wavelet was used to analyze time-series data or signal, because it is suitable to capture oscillatory behavior [1]. Torrence and Compo[26] reported that the shape of a wavelet should be chosen based on the types of the feature present in the time series data or signal to be analyzed. The continuous wavelet transform (CWT) divides the signal into a set of functions, called wavelets. Furthermore, for a given continuous signal $x(t)$ CWT can be written mathematically by Eq. 3:

$$CWT(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\, \psi\left(\frac{t-b}{a}\right) dt a, b\epsilon \qquad (3)$$

Where $\psi(t)$ is the mother wavelet and further dilated and translated form of mother wavelet is given by Eq-2. The outcomes of CWT are called wavelet coefficients which are the functions of time and scale. The similarity between the original signal and the wavelet function depends on wavelet coefficients. Higher the coefficient more would be the similarity between the original signal and the wavelet function [25].

In the present study, morlet wavelet is used because most of the mechanical signals and impulses are oftentimes leads to fault and morlet wavelet is almost similar to impulse component [27].

Wavelet power spectrum (WPS) is used to get information about the fluctuation of variances at different frequencies or scale. The squared modulus of CWT gives the magnitude of signal energy at a particular scale 'a' and certain position 'n'. This mathematical expression, shown in Eq-4, is called WPS or scalogram. Normalized WPS can be obtained by dividing it with σ2 to get power relative to white noise. Therefore, mathematical expression for WPS and normalized WPS are shown in Eq-4 and Eq-5 respectively.

$$WPS = |CWT_n|^2 \qquad (4)$$

$$NormalizedWPS = \frac{|CWT_n|^2}{\sigma^2} \qquad (5)$$

Where σ is the standard deviation and modulus of CWT represent the magnitude.

WPS can be obtained by plotting contours of the surface on the time-frequency plane. One can easily understand that how much each frequency band contributed to the energy of a given signal over a certain time interval by using WPS. In other words, it gives the information about the event with higher variances at certain frequencies and time duration. Furthermore, any system can be modified or controlled by using WPS. It also represents the distribution of energy in the signal or data.

Global wavelet spectrum is defined as a time average of WPS and can be calculated by using the Eq-6:

$$GWS = W_s = \frac{1}{N} \sum_{n=1}^{N} |CWT_n(a)|^2 \qquad (6)$$

Where, W_s is the global wavelet spectrum.

Dominant periodicities can be determined by using the global wavelet spectrum as peak location represents the highest periodicities. In this study, the wavelet power spectra (WPS) and global wavelet spectrum (GWS) of Pmax time series for different loads are plotted with the help of Morlet wavelet. For the calculation of WPS and GWS, a MATLAB code was used by taking reference.[28]

III. RESULTS AND DISCUSSION

Cyclic variation of Pmax in diesel engine for 1000 consecutive combustion cycles was used for combustion stability analysis. WPS and GWS of Pmax were calculated for different loads. WPS represents the intensity of variation in Pmax time series using contour plots. It has number of cycles on the x-axis and different period or frequency band on the y-axis. The dark red color in the contour plot signifies the highest variation whereas blue color shows the lowest variation or energy of the given signal or data. Logarithmic scale (log base 2) color bar is used to represent the intensity of variation i.e., value -2 is 2^{-2} which is equal to ¼. U-shaped thick curve is known as the cone of influence (COI). It is defined as the region where edge effect becomes imperative. It is observed to be lower and higher at high and low frequencies of a signal respectively. Because artifacts introduced by discontinuity at high frequencies vanished in no time while at lower frequencies time taken for the edge effect is longer i.e., one has to wait for quite some time before the wavelet is drawn into observation interval. Therefore, this thick line represents 5% level of significance i.e., area above which is significant. GWS depicts dominant periodicities and having power on the horizontal axis and period on the vertical axis.

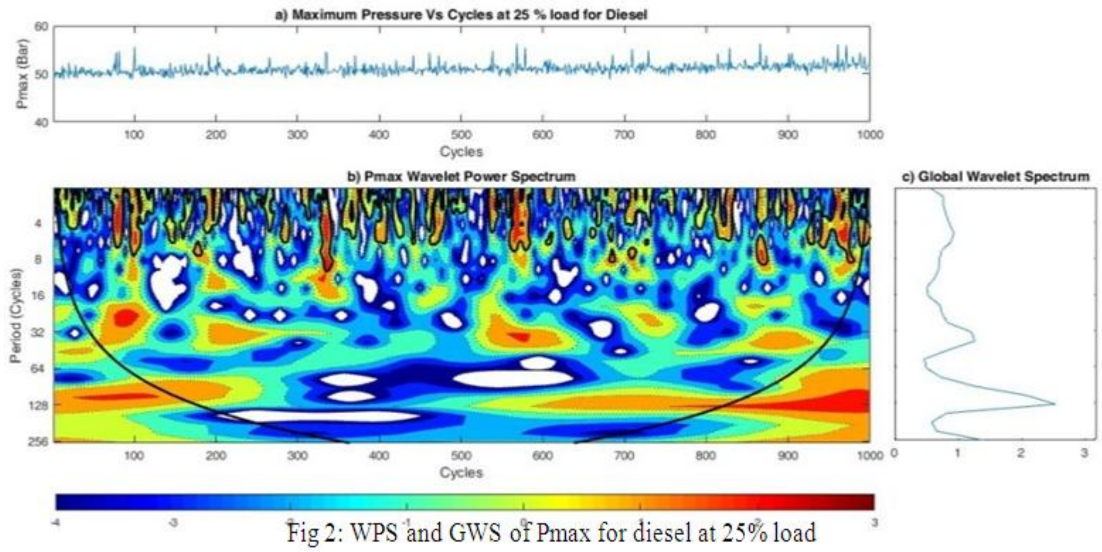


Fig 2: WPS and GWS of Pmax for diesel at 25% load

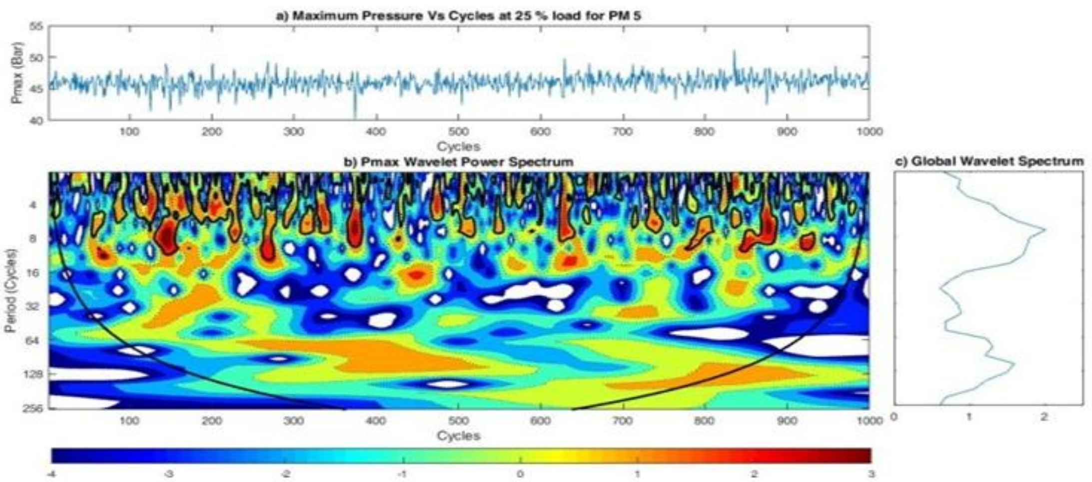


Fig 3: WPS and GWS of Pmax for PM5 at 25% load

Fig. 2 (a), 3(a) and 4(a) represent the variation of time series data of Pmax for diesel, PM5 and PM10 respectively at 25% engine load. And further Fig. 2 (b)-(c), 3(b) -(c) and 4(b) -(c) represent the WPS and GWS of the Pmax time series for diesel, PM5 and PM10 respectively at 25% engine load and an engine speed of 1500 rpm. From Fig 2(b), it was observed that period band with low intensity of period 4-8 and 8-16 have the strong

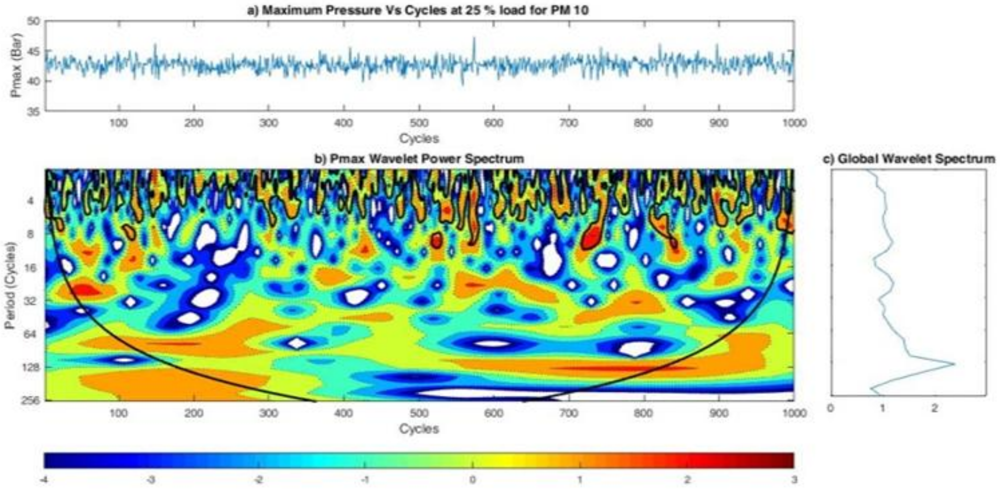


Fig 4: WPS and GWS of Pmax for PM10 at 25% load

intensity of variance during the cycle ranging from 326–342 and 558–587 respectively. Furthermore, Fig. 2(c) reveals that the power of GWS is lower at a lower intensity of periods.

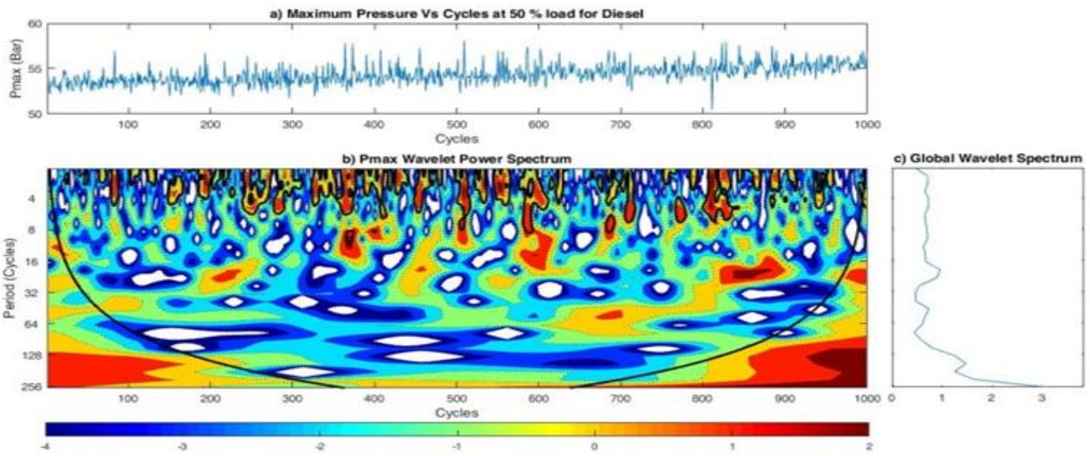


Fig 5: WPS and GWS of Pmax for diesel at 50% load

In fig 3 (b) WPS of Pmax of PM5 shows that periodic band with low intensity of period 4-8 and 8-16 have higher cyclic variation in cycle ranging from 361-383, 622-642, 842-888 and 129-157 respectively. In Fig.3(c), GWS power is found to be higher at lower intensity periods. This may be due to amplification of GWS power at higher period.

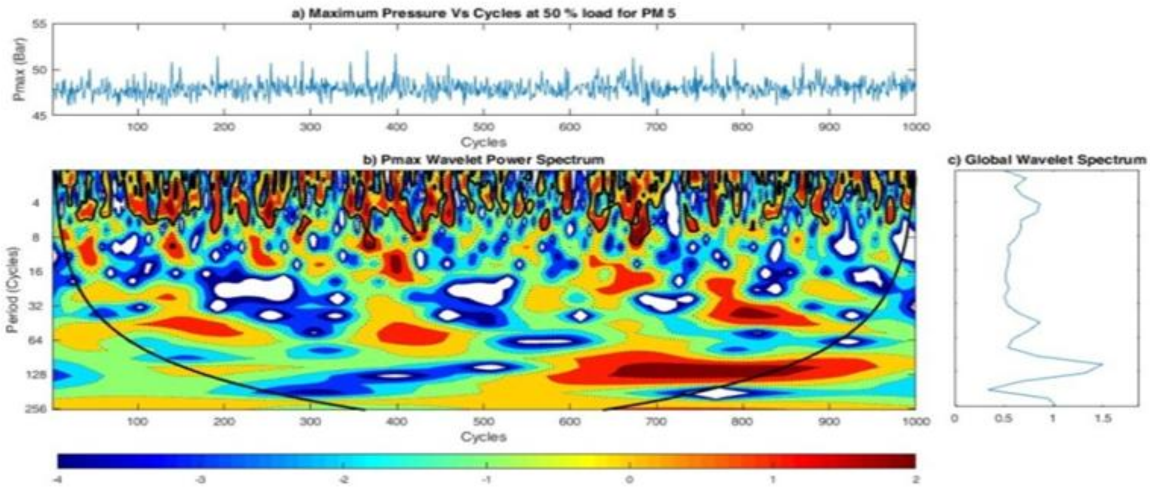


Fig 6: WPS and GWS of Pmax for PM5 at 50% load

Fig 4(b) reveals that periodic band with less intensity of period 4-8 and 8-16 have strong cyclic variation in cycle ranging from 524-546, 890-945 and 715-746 respectively. It is also observed in Fig 4(c) that the power of GWS is found to be higher at higher intensity periods.

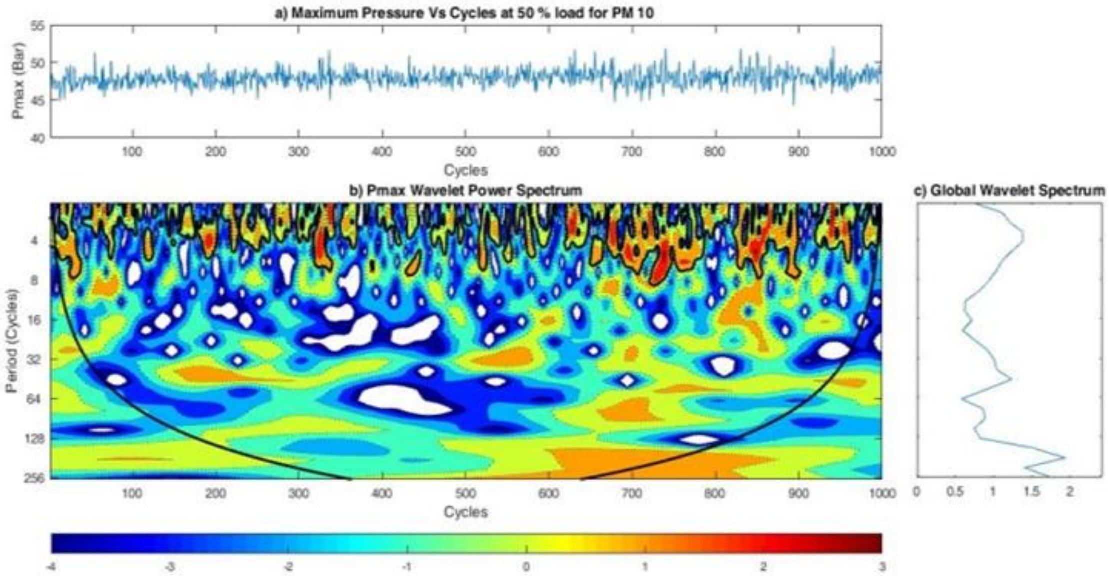


Fig 7: WPS and GWS of Pmax for PM10 at 50% load

Further, Fig. 5 (a), 6 (a) and 7 (a) depict the variation of time series data of Pmax for diesel, PM5 and PM10 respectively at 50% engine load and Fig. 5 (b)-(c), 6 (b)-(c) and 7 (b)-(c) represent the WPS and GWS of the Pmax time series for diesel, PM5 and PM10 respectively at 50 % engine load and an engine speed of 1500 rpm. It is clear from Fig. 5 (b) that periodic band with low intensity of period 4-8 and 8-16 have higher cyclic variation in cycle ranging from 578-610, 795-838 and 357-382 respectively. Furthermore periodic band with a moderate intensity of period 16-32 have a higher cycle to cycle variation in cycle ranging from 823-902. Fig. 5 (c) reveals that GWS power is increased with the increase of period intensity.

In fig 6 (b) lower intensity period band 4-8 depict strong cyclic variation in cycle ranging from 150-334, 669-697. Moderate intensity period band 32-64 shows the higher cyclic variation in cycle ranging from 379-457 and 783-842. Furthermore higher intensity period band 64-128 also shows strong cycle to cycle variation. Fig 6(c) again reveals that higher GWS power at the high-intensity periodic band.

Fig 7 (b) depicts that only lower intensity period band 4-8 have higher cyclic variation in cycle ranging from 179-203, 317-342, 670-785 and 824-900. There is no sign of strong or higher cyclic variation at moderate and high-intensity period bands. GWS power was also found to be higher at the low periodic band (Fig 7(c)).

IV. CONCLUSION

In order to get better performance and operation of an engine, the combustion inside the cylinder should be stable. In other words, the cycle-to-cycle variation has to be as low as possible. Therefore, the cycle-to-cycle variation in diesel engine was investigated in the present study by using the wavelet technique. Based on wavelet analysis results the following conclusions can be drawn-

1. The WPS results at 25% load indicated the strong intensity variance at high frequencies for both the bends i.e., PM-5 and PM-10 and neat diesel.
2. GWS results indicate that peak power of GWS for both the blends was slightly decreased as compared to diesel. However, the peak power of GWS for PM-10 was shifted towards the higher frequencies as compared to diesel and PM-5.
3.The WPS results at 50% load indicated, the higher variation at high frequencies for diesel and PM-10 while for PM-5 the high-intensity variance was get shifted towards the low frequencies.
4. GWS results at 50% load indicate that peak power was again decreased for both the blends as compared to diesel and peak power for both the blends have shown a similar trend as diesel.

By and large, it may be concluded that 1-pentanol and methanol have the potential to mitigate the cyclic variation or combustion instability. Furthermore, the wavelet technique is an effective tool to analyze cyclic variations in different combustion parameter and subsequently can be used to develop an effective engine control system.

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