617. Cycle-to-Cycle Variation of the Combustion Process in a Diesel Engine Powered by Different Fuels

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Abstract. We have studied the fluctuations in mean indicated pressure (MIP) in a diesel engine powered by different fuels. Three alternative fuels and the regular diesel oil (RD) were tested. The alternative fuels are: (1) mixture of fatty acid methyl esters (FAME) and anhydrous ethanol (ET), (2) mixture of FAME and ethyl tertiary-butyl ether (ETBE), and (3) mixture of RD and ETBE. Using statistical and wavelet analyses, we investigated the cycle-to-cycle MIP variations for each fuel, at three engine speeds of 1200, 1600 and 2000 rpm. The results for the alternative fuels were compared with those for RD. At all three speeds, the MIP variations for the alternative fuels were found to exhibit strong periodicities of 64-256 cycles, and these periodicities persist over many engine cycles, whereas shorter-term periodicities at 2-32 cycles appeared to be intermittent. In the case of RD, the MIP variations with longer periodicities appeared only at the highest engine speed but intermittent fluctuations of 2-32 cycles are present at all three speeds. Among the four fuels considered, the MIP variations for the RD were found to be closest to the Gaussian white noise.

Keywords: diesel engine dynamics, cycle-to-cycle pressure oscillations, wavelets, non-linear vibrations.

1. Introduction

The combustion process in spark-ignition and compression-ignition engines can develop cycle-to-cycle variations when operating conditions reach some fundamental limit such as lean flammability [1-3]. These variations may lead to both reduced output power and higher emissions; so there is a strong motivation to understand, diagnose, and control them. We have recently investigated the cycle-to-cycle variations of pressure in spark-ignition engines fueled by standard gasoline and natural gas, and compression-ignition engines fueled by regular diesel oil [4-8]. Such studies are important to gain a better understanding of the various factors that affect the overall combustion process and develop effective control strategies for efficient combustion. The most important factors influencing the average pressure level and its cycle-to-cycle variations include fuel-air ratio in the combustible mixture, amount of recycled gases supplied to the cylinder, and engine aerodynamics.

The tightening of emissions standards for toxic emissions and the nonstable situation on the petroleum fuels market forces to carry out the search for new types of fuels to power internal combustion engines. With respect to diesel engines these searches are conducted in three main directions: looking for a fuel not derived from petroleum; diesel fuel additives, which can be used in mixtures with diesel oil by volume; modifying the chemical composition and physicochemical properties of diesel fuel during its production. In the first group of fuel, the fuel oil plants deserves special attention. In European conditions it is canola oil. In other climatic regions soybean oil, palm oil, peanut oil are used. These oils with certain restrictions can be used as pure fuel or as additives to diesel fuel. Vegetable oils may also be subjected to a process of esterification to get a fuel (FAME) with physical and chemical properties similar to the regular diesel fuel. Work in this area in many countries is already on an industrial scale. Other types of fuel not derived from petroleum refining are gas and fermentation gas. These fuels are used in pure form or with a dose of test case of diesel. In the second group of fuel additives are particularly noteworthy alcohols or ethers to diesel - ET, ETBE. The use of these additives affects mainly on reducing emissions of particulates, nitrogen oxides and hydrocarbons. In the third group of components to produce diesel fuel with low sulfur content is based on reformed oil. When using FAME combustion process is unlike the case of RD. The main reason is the higher density of FAME in relation to RD while the calorific value is similar for both fuels. As a result, at the same dose volume of injected fuel quantity of energy in the fuel delivered in the case of FAME is greater than in the case of RD. Simultaneously, the greater the viscosity affects the caulked FAME injection equipment components and a slight increase in the dose volume. The whole phenomena described above, increases the temperature of combustion and engine power characteristics described in the external service points. Application of ET or ETBE in addition to the RD results in a reduction of density and calorific value of mixtures of RD with ETBE (ET) in relation to the result of decreases slightly RD in terms of the engine power measured on the external characteristics of the engine. At the same time simple molecular structures and ET ETBE affects the emission of particulates, nitrogen oxides and hydrocarbons.

In this paper, we examine the use of alternative fuels in a diesel engine. Clearly, due to different physico–chemical properties, the type of fuel affects the combustion process in the engine through its effect in subsequent cycles following the development of combustion in the previous cycles. We study the cycle-to-cycle variations in Mean Indicated Pressure (MIP) for three alternative fuels and compare the results with those for regular diesel oil. We use a continuous wavelet transform (CWT) to detect the various periodicities in MIP variations [10]. Using a variable-size window in the time-frequency plane, a CWT offers a spectral-temporal approach in which both the time and frequency resolutions can be adjusted in an adaptive fashion. It uses a window that narrows when focusing on small-scale or high-frequency components of a signal, and widens on large-scale or low-frequency features, analogous to a zoom lens [11].

Our presentation is organized as follows. In Section 2, we describe the pressure measurement procedure and present the statistical properties of the MIP time series. In Section 3, we apply and discuss the results of wavelet analysis. Finally, in Section 4, a few concluding remarks are given.

2. Experimental Procedure and Statistical Analysis

The experiments on the diesel engine were carried out at the Engine Laboratory in Radom University of Technology, Poland. A three-cylinder diesel engine was used and the in-cylinder pressure was measured in one of the three cylinders. The following fuels were used: a mixture of fatty acid methyl esters (FAME) and 30% anhydrous ethanol (ET), a mixture of FAME and 30% ethyl tertiary-butyl ether (ETBE), regular diesel oil (100% RD), and a mixture 40% ethyl tertiary-butyl ether (ETBE) and regular diesel oil (RD). The speed of the engine was maintained at 1200, 1600, and 2000 rpm, for each fuel.

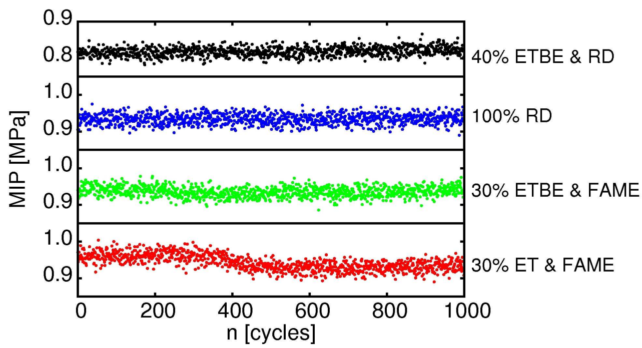
Table 1. Summary of statistical properties of the experimental time series presented in Fig. 1

Type of mixture	engine speed	average MIP <MIP>[MPa]	standard dev. σ_{MIP} [MPa]	skewness *skew*	kurtosis *kur*
30% ET & FAME	1200 1600 2000	0.943 0.958 0.923	0.021 0.012 0.014	-0.462 -0.060 0.330	2.537 2.993 3.330
30% ETBE & FAME	1200 1600 2000	0.936 0.977 0.953	0.014 0.013 0.013	0.025 0.032 -0.164	2.922 3.090 3.100
100% RD	1200 1600 2000	0.935 0.935 0.905	0.014 0.016 0.016	-0.067 -0.027 -0.002	2.606 2.973 3.203
40% ETBE &RD	1200 1600 2000	0.819 0.819 0.794	0.012 0.012 0.014	0.061 0.163 -0.166	3.101 3.092 3.158

The pressure measurements were made with a sampling frequency of 1024 times per crankshaft revolution and controlled by the crankshaft position sensor. The loading of the engine was controlled by an eddy-current brake coupled to the crankshaft. From the pressure measurements we estimated the cyclic MIP. It should be noted that MIP is defined as a constant alternative pressure which acting on the piston during the whole expansion stroke performs the same amount of work as the real variable pressure in the cylinder [1]. Consequently, the MIP can be expressed as

$$MIP = \frac{L_i}{V_s}, \tag{1}$$

where L_i is the amount work indicated in the cylinder, and V_s is the piston displacement volume of the cylinder. The work L_i is estimated numerically by integration of the measured pressure.



(a)

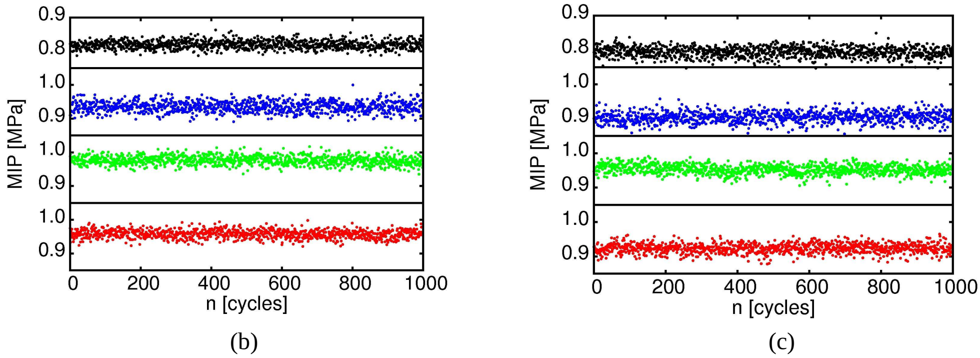


Fig. 1. MIP time series for different fuels: 30% ET & FAME, 30% ETBE & FAME, 100% RD, and 40% ETBE & RD for different engine speeds: (a) 1200, (b) 1600, and (c) 2000 rpm.

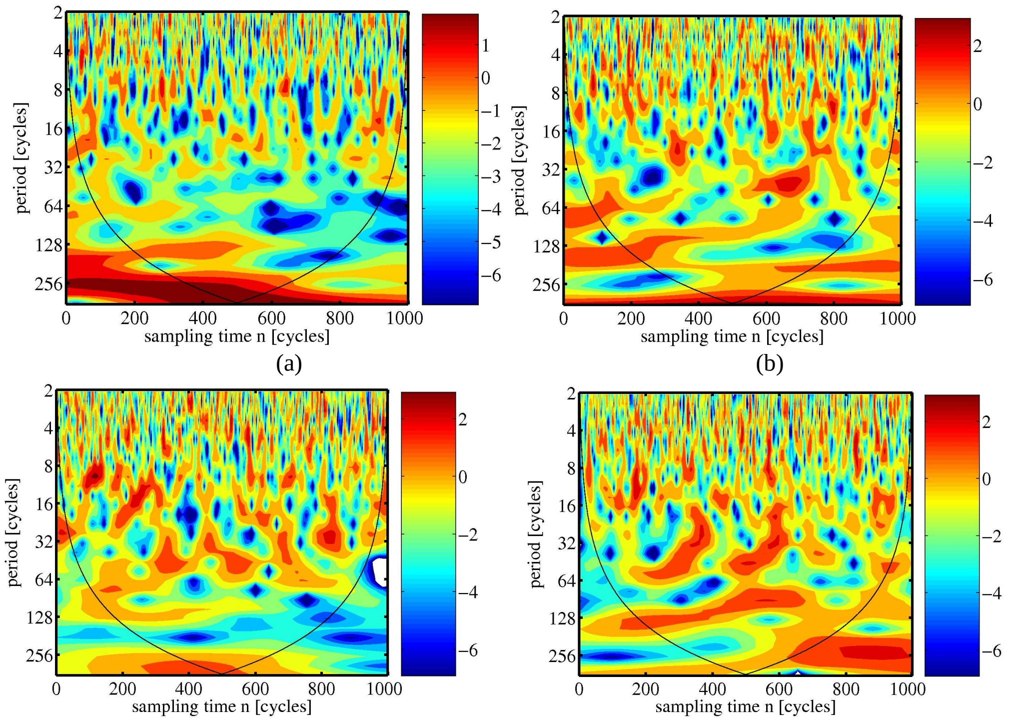


Fig. 2. Wavelet spectra of engine MIP time series for different fuels: (a) 30% ET & FAME, (b) 30% ETBE & FAME, (c) 100% RD, and (d) 40% ETBE & RD for the engine speed 1200 rpm. The colours are related to the magnitudes of $PW(s, n)$ (Eq. 3) according to the logarithmic scale $\log_2$ (see right panels marked with the corresponding scale exponents). The dark contour lines enclose regions of greater than 95 % confidence and the area below the thin U-shaped curve denotes the cone of influence (COI).

The time series of the mean indicated pressure (MIP) for the four fuels are presented in Figure 1. The statistical properties of these time series are listed in Table 1. Interestingly, the average indicated pressure level < MIP > is slightly higher for the alternative fuel mixtures ET & FAME and ETBE & FAME compared to RD. The only mixture, ETBE & RD, appears to have smaller values of < MIP > than RD at each speed. Note also that the standard deviations σ_{MIP} , are smaller for the alternative fuels. The exception is ET & FAME at the speed of 1200 rpm. But in that case (Fig. 1a) one can observe a trend in these fluctuations. Furthermore, the skewness and kurtosis (Table 1) are increasing with increasing engine speed. As far as the kurtosis is concerned, in the most cases, we observe an increase with higher engine speed. Thus MIP distributions change from more flat (*kur* < 3) to more concentrated (*kur* > 3). Note that the faster increase is observed for the mixture ET & FAME while in case of ETBE & RD, the tendency is not clear. It is also worth noting that the distribution of MIP for 100% RD is the closest to Gaussian (*kur* ≅ 3) for all speeds. By changing the engine speed we observe that skewness shows clear monotonical tendencies which are different for different mixtures. Here one can also note that the smaller range of skewness changes is observed for RD.

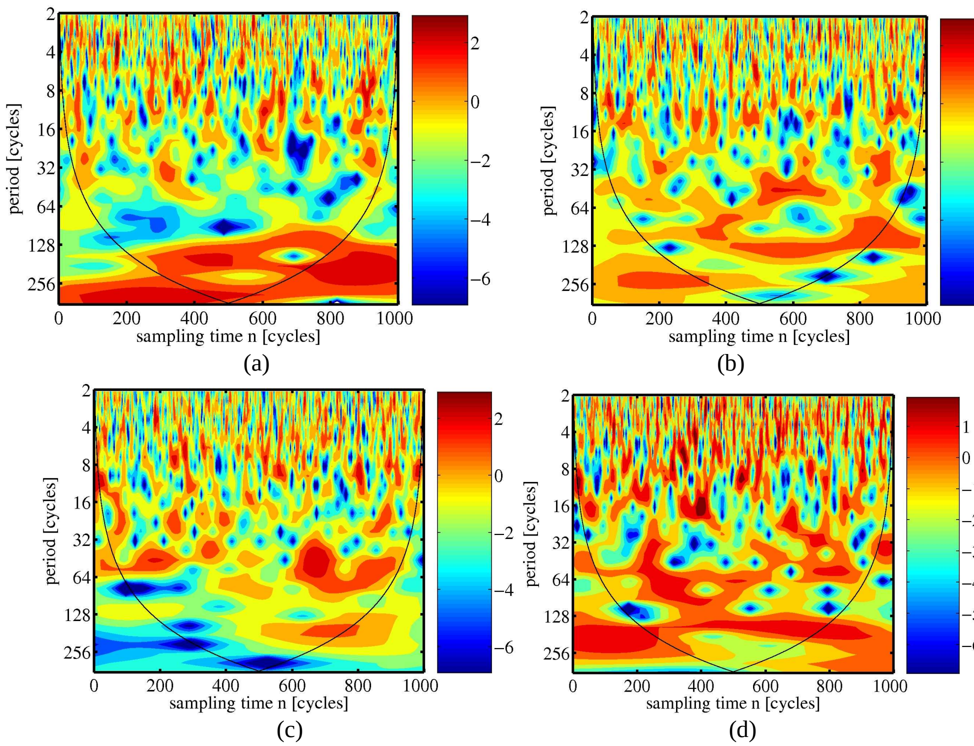


Fig. 3. Wavelet spectra of engine MIP time series for different fuels: (a) 30% ET & FAME, (b) 30% ETBE & FAME, (c) 100% RD, and (d) 40% ETBE & RD for the engine speed 1600 rpm. The colours are related to the magnitudes of $PW(s, n)$ (Eq. 3) according to the logarithmic scale $\log_2$ (see right panels marked with the corresponding scale exponents). The dark contour lines enclose regions of greater than 95 % confidence and the area below the thin U-shaped curve denotes the cone of influence (COI).

3. Wavelet Analysis

For the MIP time series given by $MIP(i)$, with i = 1, 2, 3,…, N, the continuous wavelet transform (CWT) with respect to a wavelet $\psi(t)$ is defined as follows:

$$W_{s,n}(MIP) = \sum_{i=1}^{N} \frac{1}{s} \psi\left(\frac{i-n}{s}\right) \frac{(MIP(i) - < MIP >)}{\sigma_{MIP}}, \qquad (2)$$

where < *MIP* > and σ_{MIP} are the averages and standard deviations (see Table 1). The wavelet $\psi(t)$ is referred to as the mother wavelet, and the letters s and n denote the scale and the time index, respectively. The wavelet power spectrum (WPS) of the MIP time series is defined as the square modulus of the CWT:

$$P_W(s,n) = \left| W_{s,n} \right|^2. \tag{3}$$

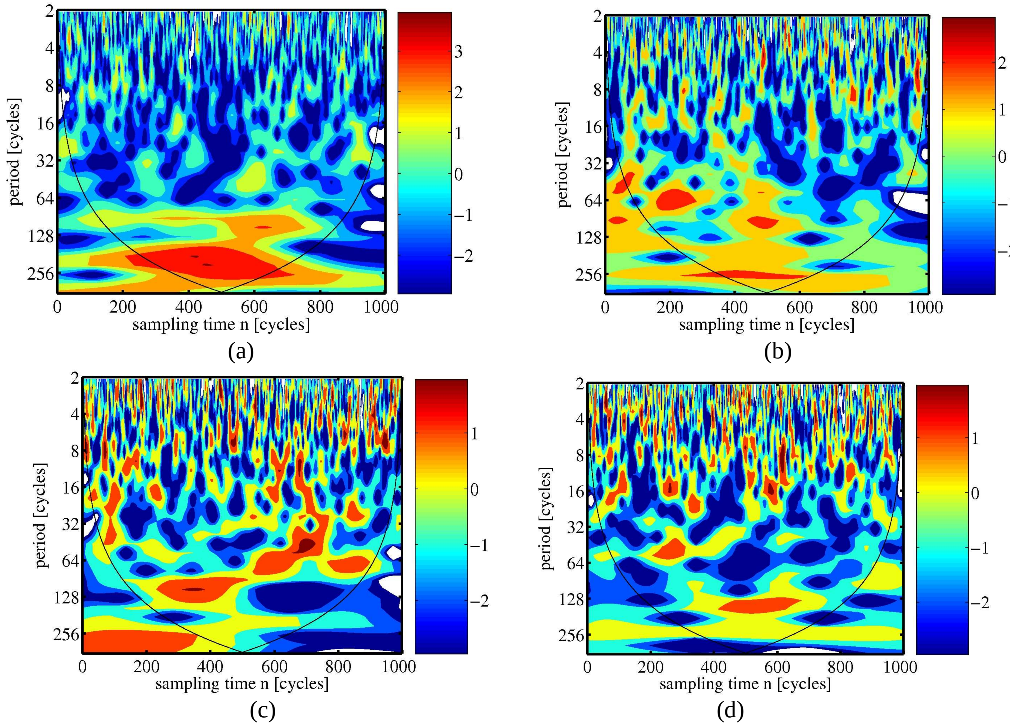


Fig. 4. Wavelet spectra of engine MIP time series for different fuels: (a) 30% ET & FAME, (b) 30% ETBE & FAME, (c) 100% RD, and (d) 40% ETBE & RD for the engine speed 2000 rpm. The colours are related to the magnitudes of $PW(s, n)$ (Eq. 3) according to the logarithmic scale $\log_2$ (see right panels marked with the corresponding scale exponents). The dark contour lines enclose regions of greater than 95 % confidence and the area below the thin U-shaped curve denotes the cone of influence (COI).

In our calculations, we have used a complex Morlet wavelet as the mother wavelet. A Morlet wavelet consists of a plane wave modulated by a Gaussian function and is described by

$$\psi(\eta) = \pi^{-1/4} e^{i\theta_0 \eta} e^{-\eta^2/2}, \tag{4}$$

where θ_o is the center frequency, also referred to as the order of the wavelet. The value of θ_o controls the number of oscillations in the wavelet and thus controls the time/frequency resolutions. In our analysis we used $\theta_o = 6$. This choice provides a good balance between the time and frequency resolutions. Also, for this choice, the scale is approximately equal to the period, and therefore the terms scale and period can be interchanged for interpreting the results. The reader is referred to [10] for further details on the wavelet analysis methodology.

The wavelet power spectra (WPS) of the MIP time series for the various fuels are depicted in Figs. 2-4. Note that ET & FAME and ETBE & FAME (Figs. 2a, 2b, 3a, 4a, 4b) exhibit strong periodicities of 64-256 cycles, and they persist over many engine cycles, whereas intermittency is present at shorter periods (2-32 cycles). In case of RD, the MIP fluctuations of longer periodicities appear only at the higher engine speed (Fig. 4d). These results may be summarized as follows. For all four fuels tested here, the MIP variations exhibit high-frequency intermittent behavior at the three engine speeds considered. In addition, for the alternative fuels, the MIP undergoes lower-frequency variations at all three speeds. For the standard diesel fuel, on the other hand, lower-frequency variations are observed only at the highest speed of 2000 rpm.

4. Concluding Remarks

Studies on new types of fuel for diesel engines are important for at least two reasons: (1) to improve combustion efficiency and increase power output, and (2) preserve the oil resources by using biofuels such as the mixture of ET & FAME, instead of regular diesel oil.

In this paper, we focused on analyzing the variations in the mean indicated pressure (MIP) in a diesel engine for three alternative fuels and regular diesel oil. Due to differences in physicochemical properties of the various fuels, such as density, viscosity, cetane number, calorimetric values etc, different patterns of MIP variations are to be expected, as observed in our analysis. Analysis of these variability patterns is essential in order to develop effective control strategies for efficient combustion [12-17]. To make further conclusions we are planing to perform more systematic tests on engine efficiency and confirm the above initial results using longer time series.

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