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Investigation of Diesel Engine Combustion Instability using a Dynamical Systems Approach

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Abstract

This study investigates the combustion instability of a compression ignition engine using dynamical system analysis in the form of a recurrence plot approach. In-cylinder combustion chamber pressure and crank angle are obtained from a six-cylinder, turbocharged diesel engine with a common-rail direct fuel injection system using a piezoelectric transducer and encoder, respectively. The common-rail system keeps the fuel pressure at a constant rate, which helps to minimise the effect of fuel pressure in this study. Constant speed and 4 loads are investigated. The engine emission and operation can be influenced by combustion instabilities and inter-cycle variability. Previous studies reported that ambient temperature, fuel pressure and injection timing, residual gases and fuel properties significantly alter the combustion instability. This study focus on the effect of biodiesel on this phenomena. Considering the CI engine as a dynamical system, the dynamic state of the combustion can indicate its stability. Typically, peak pressure, heat-release rate and indicated mean effective pressure in a range of consecutive cycles are utilised to represent the variability of combustion. The recurrence plot of these data is used to visually study the characteristics of combustion dynamics. Additionally, the recurrence quantitative analysis is used to present the characteristic dynamics of the system. The study finds that the combustion instability is higher for biodiesel compared with diesel, owing to the fuel properties. The results aid in developing our understanding of the complexity of biodiesel combustion in a modern engine and help to advance the combustion control strategy in order to improve the performance of biodiesel fuelled engines.

Introduction

Growing energy demands and decreasing fossil fuel energy resources, along with rising concerns over environmental and health issues, have promoted researches in the area of biodiesel. Biodiesels have the potential to be used directly in compression ignition engines or blended with diesel [1]. Many researchers have reported promising results regarding the engine performance and exhaust emission of CI engines fuelled by diesel-biodiesel blends [2], [3]. Fuel blending leads to a product with different physical and chemical properties compared with conventional diesel. Hence, investigating the combustion behaviour of theses fuels' use in modern engines is vital to assess their ability to be adapted for further utilisation.

One of the indicators of engine efficiency is combustion instability. High instability in combustion can result in poor performance and an increase in HC and CO emissions. According to the literature, ambient temperature, fuel pressure and injection timing, residual gases and fuel properties can affect combustion instability[4], [5]. Henein et al. investigated combustion instability of a single cylinder engine under a cold start condition [4]. They investigated the influence of different parameters, such as: in-cylinder pressure, fuel mass rate, exhaust temperature, etc. They reported that the combustion instability during cold start is not random. They showed that the combustion instability is also present when utilising fuels of various Cetane numbers. Another study reported that the combustion instability increases at lower ambient temperature [6]. One of the major reason for the instability is the combustion variability or cycle-to-cycle variation, which is caused by the failure of combustion in some cycles [4]. Inter-cycle variability in IC engines has been extensively studied [7], [8]. Some researchers reported that the combustion variability is deterministic while others reported irregular phenomena [9], [10]. Daily described the inter cycle variability as a chaotic behaviour caused by inherently nonlinear combustion [11]. Thus, nonlinear dynamic theory has been utilised to investigate this phenomenon. In order to investigate the nonlinearity of combustion, different nonlinear methods such as coarse-grained entropy, correlated integral and multifractal analysis have been used to analyse the peak pressure, heat release rate and indicated mean effective pressure (IMEP) [12]–[14]. Yang et al used IMEP to study the combustion instability in a natural gas engine using recurrence plots (RPs) and recurrence quantification analysis (RQAs) and revealed promising results regarding the combustion stability [15].

Most of studies involving nonlinear dynamics have been focused on spark ignition engines [14], [16]. This study focused on the effect of biodiesel on combustion instability in a modern diesel engine. Four different fuels were used, namely ultra-low-sulphur-diesel, 80% diesel blended with 20% biodiesel (B20), 50% diesel blended with 50% biodiesel (B50) and pure biodiesel (B100). The engine used in this investigation had a common-rail fuel injection system to keep the pressure of the fuel constant regardless of the fuel composition. The test was conducted when the engine was fully warmed up and the intake air temperature remained constant around 30^o Celsius. In this case, the effects of intake air temperature and the fuel pressure are negligible. Four engine loads (25%, 50%, 75% and 100%) at a constant engine speed 1500 RPM (peak torque) were used for each fuel. The analysis was done by means of non-linear embedding theory which includes recurrence plots and recurrence analysis of in-cylinder peak pressure.

Experimental Setup

This study was conducted in the Biofuel Engine Research Facility (BERF) at the Queensland University of Technology (QUT). A 6-cylinder diesel engine was employed in this research. The specifications of this engine are shown in Table 1. The engine was driven by a hydraulic break dynamometer. The engine had an in-cylinder pressure transducer along with a crank angle sensor. Other sensors were also mounted on this engine showing the fuel consumption, charge air flow, exhaust temperature, etc. The pressure signal, injection signal and crank angle signal were acquired by a National Instrument data acquisition board (DAQ).

Table 1 Engine Specification

Specifications	
Model	**Cummins ISBe220 31**
Number of Cylinders	6 in-line
Capacity (L)	5.9
Bore×Stroke (mm)	102 × 120
Max. power (kW/rpm)	162/2500
Max. torque (Nm/rpm)	820/1500
Compression ratio	17.3:1
Aspiration	Turbo-charged & after cooled
Fuel Injection	Common-Rail

The data rate in this study was one million samples per second to ensure the acquisition of the whole sensor frequency band. The pressure sensor was installed in the first cylinder of the engine. The transducer was a Kistler piezoelectric transducer (6053CC60) which has good stability at high temperatures and low thermal shock errors that make it suitable for working in the cylinder environment. The crank angle on the Cummins was measured by a Kistler crank angle encoder (type 2614) which has a resolution of 0.5 degrees. The data from the latter was digital data that is acquired synchronously with the pressure and injector signals. The setup schematic is shown in Figure 1.

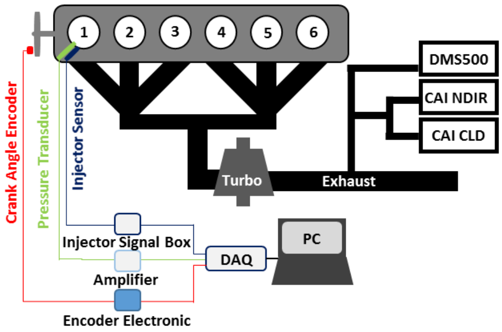


Figure 1 Experimental Setup

Analysis Method

The peak pressure (PP) of all engine testing cycles (400 consecutive cycles) was measured based on the in-cylinder pressure trace and crank angle. The data was represented in the phase space and, then, the corresponding RPs was constructed. Furthermore, RQAs were calculated based on RPs.

The attractor of a dynamic system can be reconstructed by phase space representation of a signal based on a finite time series [17]. The phase space represents the possible states of a system in our case the sequence of the peak pressure $x(i)$. The reconstruction is possible by applying a suitable time-delay embedding which needs to properly set two parameters: the time-delay τ and the embedding dimension m. However, the dynamical invariants are independent of the embedding [18], the RQA measures are determined by the embedding. There are a handful of approaches for calculating the optimum embedding parameters, such as mutual-information for time-delay, and false-nearest-neighbours for embedding dimension [19].

$$\mathbf{X}_i = [x(i), x(i+\tau), \dots, x(i+(m-1)\tau)]$$
$$i = 1, 2, \dots, N-(m-1)\tau \qquad (1)$$

where $\mathbf{X}_i$ is the corresponding vector of phase space and N is the number of samples.

The recurrence plot determines recurrence of a trajectory in d-dimensional phase space. It can visualise recurrences which is formally represented by the matrix $\mathbf{R}_{i,j}$

$$\mathbf{R}_{i,j} = \Theta\left(\varepsilon - \|\mathbf{X}_i - \mathbf{X}_j\|\right)$$
$$i, j = 1, 2, \dots, N-(m-1)\tau \qquad (2)$$

where $\mathbf{X}$ is the trajectory of the state space, ε is the threshold of the recurrence, ||.|| indicates the norm, and $\Theta(x)$ is the Heaviside function which is equal to zero for $x<0$ and one otherwise. The recurrence plot is formed by plotting the matrix $\mathbf{R}_{i,j}$ (usually in black and white)[15], [19].

The threshold ε is the vital parameter of the RP. Choosing ε too small results in no recurrence point, and too large shows all points in neighbours of all other points. Hence, several methods have been suggested in the literature such as 10% of the average of maximum of the phase space diameter or 5 times larger than the standard deviation of signal noise [17]. Since the recurrence plots from different signals are compared in this study, a fixed recurrence density is considered in the interest of equity.

In order to qualify the RP, several measurement techniques have been introduced to the recurrence quantification analysis (RQA). Most of these techniques use the diagonal and vertical lines of the RP to reveal the deterministic or chaotic behaviour of the signal. In this study the focus is on the recurrence rate (RR), determinism (DET), line length entropy (ENTR), and trapping time. The recurrence rate (RR) is a measure of the RP density and an estimation of the recurrence probability of the system [19].

$$RR = \frac{1}{N^2}\sum_{i,j}^{N} R_{i,j} \qquad (3)$$

In the RP, the diagonal line length indicates the time the system grows similar to another time. A large number of diagonal lines can be indicators of a deterministic system. On the other hand, RPs with single points show a system with independent values, such as white noise. Thus, measuring of recurrence points which create diagonal line can show the determinism in the data [17]. This can be calculated by

$$DET = \frac{\sum_{l \geq l_{min}} lP(l)}{\sum_{i,j} R_{i,j}} \qquad (4)$$

where l is the length of the diagonal line and $P(l)$ measures the histogram of the diagonal lines length. Entropy is another measure of RQA. This term is based on the Shannon entropy which is correspond to probability $p(l)=P(l)/N_l$. It can reveal the complexity of the system determinism [17]. For instance, random noise has a low ENTR value. ENTR is measured by

$$ENTR = -\sum_{l=l_{min}}^{N} p(l) \ln p(l) \qquad (5)$$

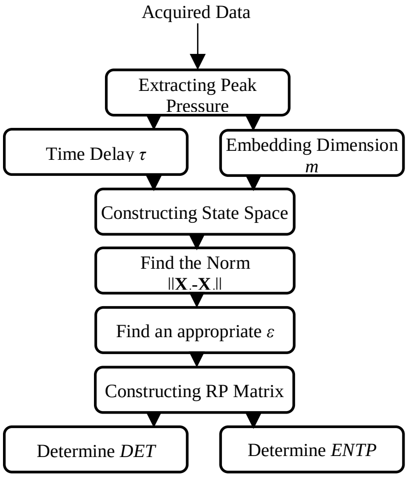


Figure 2 Data analysis procedure chart

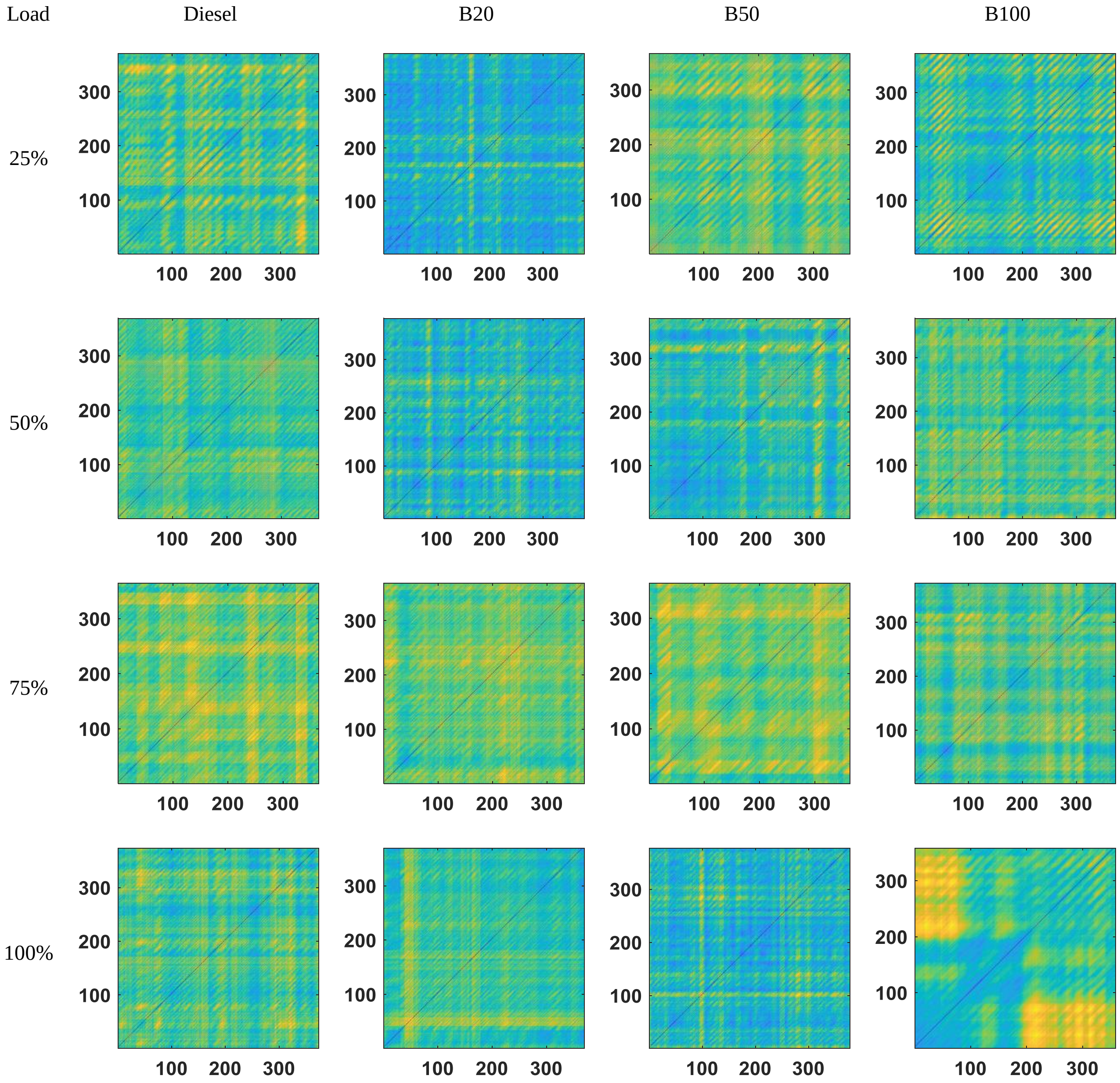
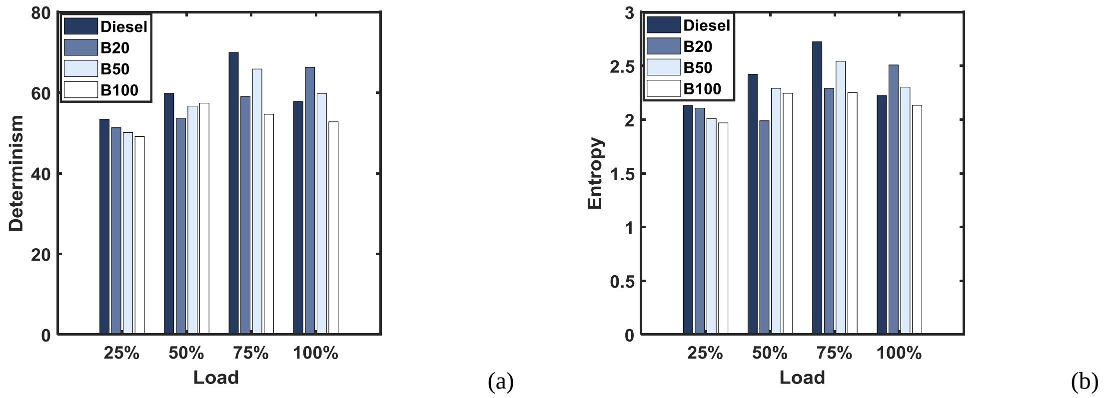


Figure 3 Recurrence plots of 400 consecutive cycles, showing in-cylinder peak pressure for each test. The plots in the same row have the same load and the plots in the columns used the same fuel.



(a)

(b)

Figure 4. RQAs of RPs: determinism percentage in the RPs (a) and entropy of diagonal lines in the RPs (b)

Results and Discussion

The recurrence plot of the peak pressure of 400 consecutive cycles has been plotted for each test. The phase space is constructed by considering $\tau=1$ and $m=5$. τ and m are determined based on the time delayed mutual information and false-nearest-neighbours, respectively. Selecting appropriate thresholds is critical in both RPs and RQAs for comparing different conditions. Hence, ε is selected in the way that the density of RPs (RR) remain constant (0.1) for each test.

The dynamics of the combustion with different fuels in the test engine can be identified based on relationships between the dynamic behaviour and the structures of the recurrence plot. The RPs at four loads and constant speed for testing fuels are illustrated in Figure 3 presenting the impression and texture of the RPs. As mentioned by Henein et al [4], [6], all of the fuels have some degree of instability. As apparent in Figure 3, there are vertical and diagonal lines and white bands, clearly different from each other. This shows the nonlinear behaviour of the combustion. However, these shapes indicates the stability of each test. The figures at 25% load for all the fuels shows lower determinism since they exhibit a more point like distribution rather than containing diagonal lines. By increasing the load to 75%, the system shows more stability but then drops at full load. This is owing to the injection strategy of the engine used in this study. As shown in Figure 4 (a) and (b), diesel has better stability at all loads compared with the other fuels, except at 100% load where B20 and B50 have higher determinism and entropy. B100 shows more instability compared with other fuels. Overall, the use of biodiesel can introduce more instability to the engine that is tuned for diesel. The reason for this can be the physical properties of fuel, such as viscosity and lubricity, which can change the spray characteristic and cylinder wall lubrication regime, or the chemical properties of fuel, such as cetane number or oxygen content.

Conclusions

This investigation showed the combustion instabilities of a modern CI engine fuelled by diesel, pure biodiesel and two blends of B20 and B50. This research can indicate the feasibility of using biodiesel in the CI engines with no modification. The engine performance and exhaust emissions can be influenced by combustion instabilities and inter-cycle variability. Considering the CI engine as a dynamical system, the dynamic state of the combustion can indicate its stability. The peak pressure of 400 consecutive cycles were utilised to represent the variability of combustion. Then recurrence plots of these data visualise the characteristics of combustion dynamics. Furthermore, the recurrence quantitative analysis represents the dynamic characteristics of combustion. The results illustrated greater instability of biodiesel blends for the first three loads when compared to diesel. Pure biodiesel showed a lower stability than diesel for all the loads. Given that this study was conducted on a diesel-tuned engine to study the feasibility of using biodiesel in a CI engine, calibration of the engine with each if the fuels in this study may lead to a different results. However, the results from this study are beneficial in developing understanding of biodiesel combustion in a modern engine and can be used with other methods of data analysis, such principle component analysis, to find the correlation between fuel and engine parameters with combustion instability.

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