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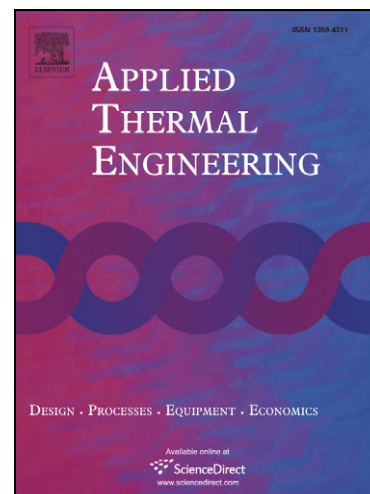
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Analysis of Repeatability of Diesel Engine Acceleration

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Abstract

The analysis of combustion non-repeatability in the dynamical working conditions of a Diesel engine is presented. In the frame of statistical analysis, applied to a number of acceleration trails, basic determinants such as standard square deviation, skewness, and kurtosis have been calculated for the mean indicated pressure (MIP). The methods of return maps, delay phase portrait reconstruction, recurrence plots and quantification recurrence analysis have been also used to analyze a single chosen course of the measured pressure starting from the idle run of engine, through its acceleration process and ending on a stable engine run with a certain velocity. The results show that recurrence techniques are able to identify various phases of the engine non-stationary work.

Key words: combustion, pressure oscillations, recurrence plots, recurrence quantification analysis

1 Introduction

The dynamical conditions of combustion are very important in any engine work. Usually, they apply to substantial time intervals of an engine working time [1]. The essential issue connected with the engine work is non-repeatability in combustion. This phenomenon is also present in a stationary combustion process as cycle-to-cycle fluctuations of combustion determinants including cyclic indicated mean effective pressure, or heat release [2–9]. In case of acceleration, such fluctuations are superimposed on its increasing trend [1].

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We focus on such a composition throughout this paper. The purpose of analysis is to show a new research methodology and consequently to improve the performance of a Diesel engine.

In the following sections we will show the experimental setup and data analysis for a number of experimental trials (Sec. 2). In Sec. 3 the standard statistical methods will be applied to the MIP. More detailed embedding methods are applied to the selected course of pressure in one of cylinder chambers (PCC). In the final section (Sec. 4) we provide summary and conclusions.

2 Experimental setup

In our experiment we have used three cylinder aspirated Diesel engine with a direct injection of 2502 cm³ full capacity. The schematic picture of the experimental standing with a suitable description is presented in Fig. 1.

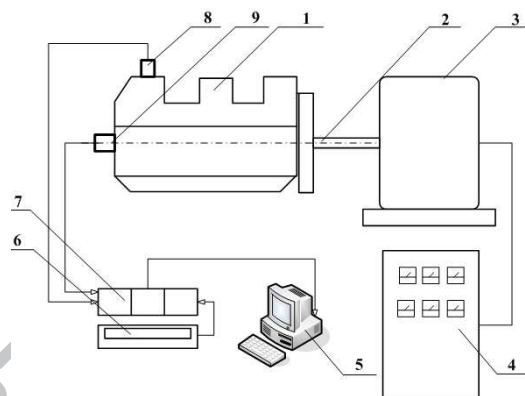


Fig. 1. Schematic plot of the experimental stand (1 - Engine, 2 - Crankshaft, 3 - Brake, 4 - Brake steering, 5 - Computer with data acquisition card, 6 - Signal generator, 7 - Amplifier, 8 - Piezoelectric pressure sensor, 9 - Position sensor of the crankshaft).

10 repeated accelerations result in 30 consecutive cycles of the engine work in each trail. An example of a single course of internal pressure, *PCC*, is shown in Fig. 2. All three phases of engine work can be observed. Namely, first 5 cycles of the pressure curve course show the idle work of engine without loading. In next 10 cycles the phase of sudden increase of pressure appears. It is caused by the shift of the fuel ratio control lever. In the end we have the engine work with constant rotational velocity controlled by the fuel injection pump rotational velocity controller. During the acceleration phase the thermal conditions of the piezoelectric pressure sensor are changing. These conditions influence the sensor response by additional downward shift in the pressure plot. The region of unstable temperature can be easily noticed in Fig. 2 for cycles 5 through

18.

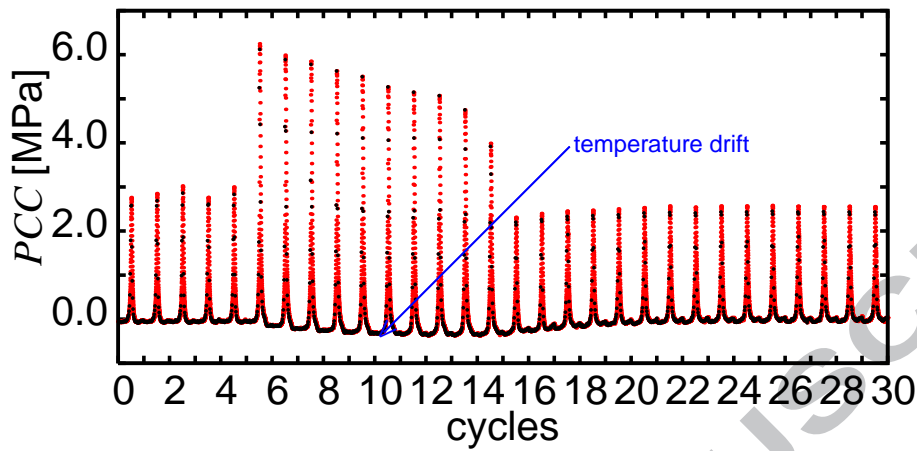


Fig. 2. Measured pressure in the chosen cylinder chamber PCC. Red points show all measurements (512) per cycle. Black points indicate each 8 measurement points (modulo 8). Note, the dip of the pressure for 5 through 18 cycles is associated with a piezoelectric sensor response in variable temperature conditions.

It is worth pointing out that combustion is started here by self-ignition as in any other Diesel engine. The absence the external ignition event can result in some additional cycle-to-cycle combustion fluctuation comparable to spark ignition engines. However, in spite of the above, the pressure curve (Fig. 2) seems to be highly deterministic. This effect is better visible in the corresponding return map presented in Fig. 3.

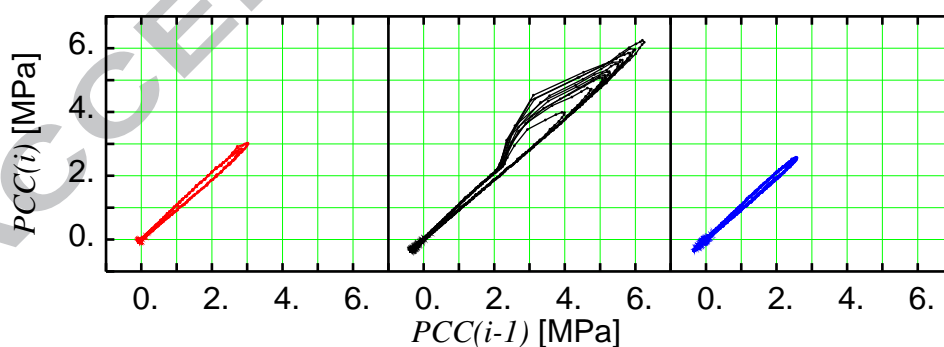


Fig. 3. Return maps corresponding to the pressure curve shown in Fig. 2 for all three phases of engine work: idle, acceleration and stable work with a constant velocity (reading from left to right).

3 Results and their analysis

In this section we will discuss the basic statistical properties of the MIP for a number of tests. Subsequently, we will return to the above example of a single trail pressure (Fig. 2) to examine cycle-to-cycle fluctuations patterns and recurrences.

3.1 Statistics of mean indicated pressure

In Fig. 4 we show average of MIP estimated from 10 consecutive combustion cycles pressures related to the acceleration phases of the engine work averaged over 10 parallel acceleration trails. Here, one can see that the largest value is reached in the middle cycle (see the corresponding cycle number - 6). This could be explained by larger fluctuations in the beginning and the end of examined acceleration trails. We have estimated the basic statistical properties to shed more light on the subject.

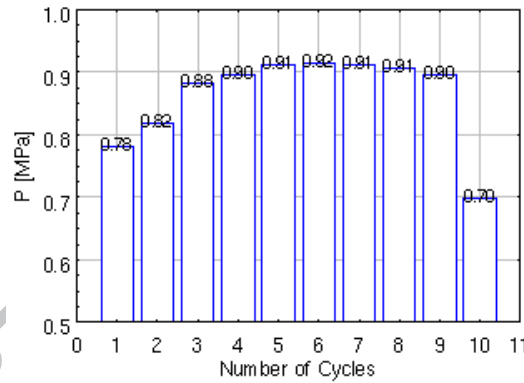


Fig. 4. MIP in 10 consecutive combustion cycles, related to the acceleration phase of the engine work, averaged over 10 parallel acceleration trails.

In the subsequent figures (Figs. 5a-c) we plotted standard square deviation, skewness and kurtosis related to different statistical moments of MIP (denoted by $P(i)$) for corresponding acceleration cycles (cycles 6–15 in Fig. 2). Specifically:

– the standard square deviation σ and the variance V_2 :

$$\sigma = \sqrt{V_2}, \quad V_2 = \frac{1}{N-1} \sum_{i=1}^N (P(i) - \bar{P})^2; \quad (1)$$

– the skewness V_3 :

$$V_3 = \frac{N}{(N-1)(N-2)} \sum_{i=1}^N \left(\frac{P(i) - \bar{P}}{\sigma} \right)^3; \quad (2)$$

– the kurtosis V_4 :

$$V_4 = \frac{N(N+1)}{(N-1)(N-2)(N-3)} \sum_{i=1}^N \left(\frac{P(i) - \bar{P}}{\sigma} \right)^4 - \frac{3(N-1)^3}{(N-2)(N-3)}, \quad (3)$$

where N is a number of trails ($N = 10$ in our case) and \bar{P} denotes MIP for given number of trails.

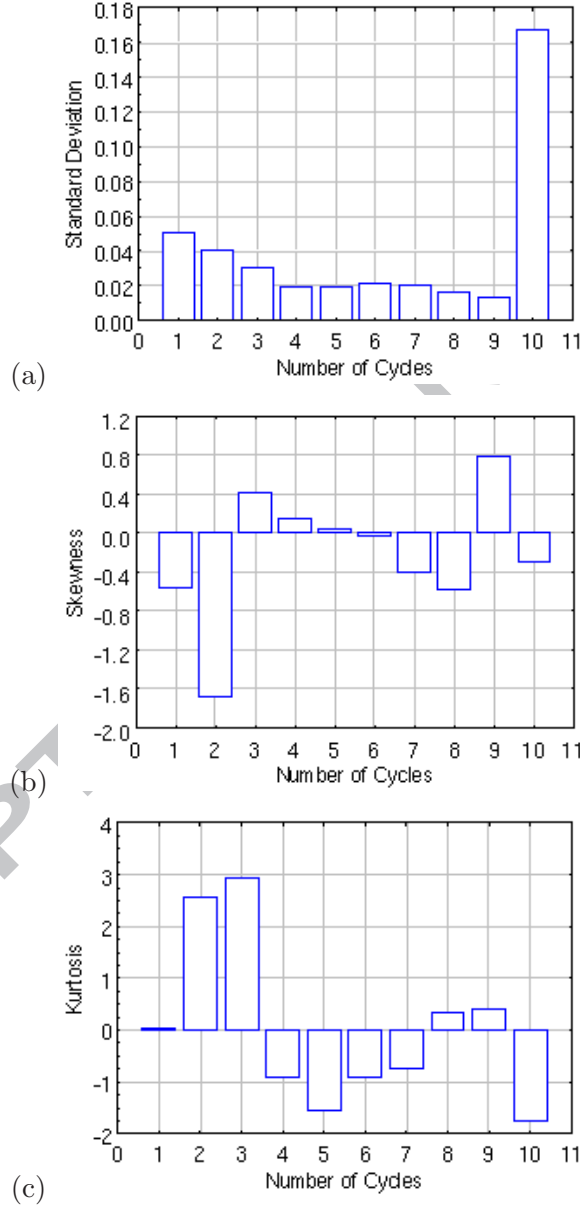


Fig. 5. Statistical properties of 10 parallel accelerations process consisting of 10 non-stationary succeeding cycles of combustion.

The calculated standard deviation, shown in Fig. 5a, indicates that the highest fluctuations of pressure $P(i)$ are present in the first and last cycles. The skewness (Fig. 5b) provides some information about asymmetry of the distribution

which is evidently highly inclined to the left in the beginning of the acceleration process. This could mean that for the second cycles the distribution is rather of the Poisson asymmetric type related to discrete events occurring in a the examined period of time than the Gauss symmetric one. Note, the Poisson distribution is frequently related to a description of some rare phenomena. We could interpret it as the sudden increase of $P(i)$ which, however, is not fully developed in most of trails. On the other hand, in the last cycle the situation could be physically similar. Technically, it is related with partial termination of combustion present in the end of acceleration process. The kurtosis plot (in Fig. 5c) shows the discrepancy between the distribution of measured quantities and the standard Gaussian one. Positive values (leptokurtic) indicate that the distribution is sharper than Gaussian, while negative values (platykurtic) show that the distribution is less condensed.

Interestingly, in the first cycles of the acceleration process the kurtosis of the distribution of $P(i)$ is roughly 0 showing consistency with the Gaussian result, while in the next two cycles the kurtosis grows rapidly to about 3 indicating much more concentrated distributions of acceleration. In the next cycles the distribution is evidently flatter around the average value. The fairly large negative kurtosis in the last cycle is related to the nature of the engine acceleration. If one looks back in Fig. 4 and 5a it is clear that the distributions have larger standard deviations and simultaneously flatter shape in respect to the Gaussian distribution.

3.2 Phase space reconstruction

A single scalar signal brings more information if it is nonlinear. Multiple dynamical scales can be reflected in higher embedding dimension which is usually defined by the delayed coordinates. The phase space of a nonlinear system initially described by a single measured coordinate $PCC(i)$ (Fig. 2) can be supplemented by the delayed coordinates after Takens [10]:

$$\mathbf{P}(i) = [P(i), P(i - \Delta i), P(i - 2\Delta i), \dots, P(i - (n - 1)\Delta i)] \quad (4)$$

where Δi is the characteristic time delay while n is the embedding dimension. Through further analysis we assume that $n = 3$ is enough to describe our system. As far as the time delay is concerned we notice that the characteristic period in the system is related to the two complete revolutions consisting of $M = 512$ measurement points. We assume that it is a quarter of M :

$$\Delta i = \frac{M}{4}. \quad (5)$$

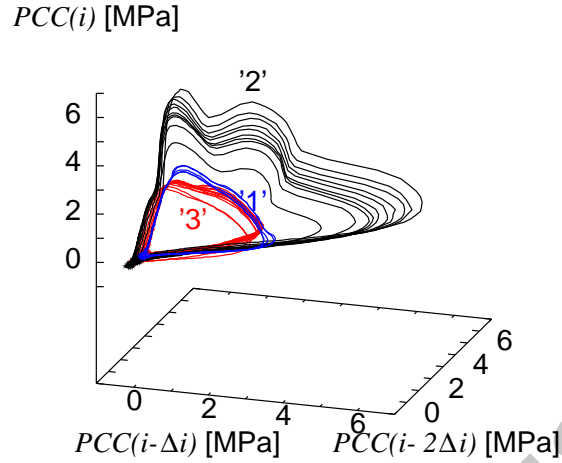


Fig. 6. Attractors for corresponding phases of engine work ('1' idle, '2' acceleration, and '3' stable work with constant velocity).

In Fig. 6 we have plotted the related attractors in using the above defined values, Δ_i and n .

3.3 Recurrence plots analysis

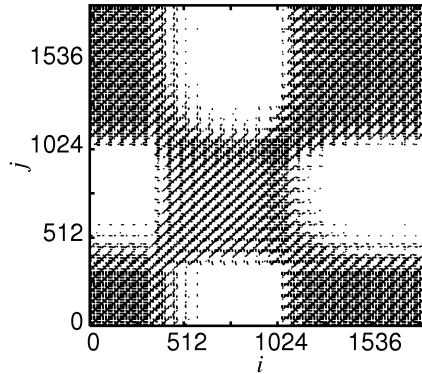


Fig. 7. Recurrence plot obtained for the 30 cycles time series shown in Fig. 2 (here $\epsilon = 0.22$, $\Delta i = 16$, $n = 3$, $M = 64$).

Recurrence plots have been introduced originally by Eckmann et al. [11] and used by Casdagli [12] as a graphical representation of examined time series and an approach to identify various nonlinear dynamical systems through two dimensional patterns. They are defined by the following matrix elements

$$\mathbf{R}_{ij}^{n,\epsilon} = \theta(\epsilon - |\mathbf{P}(i) - \mathbf{P}(j)|). \quad (6)$$

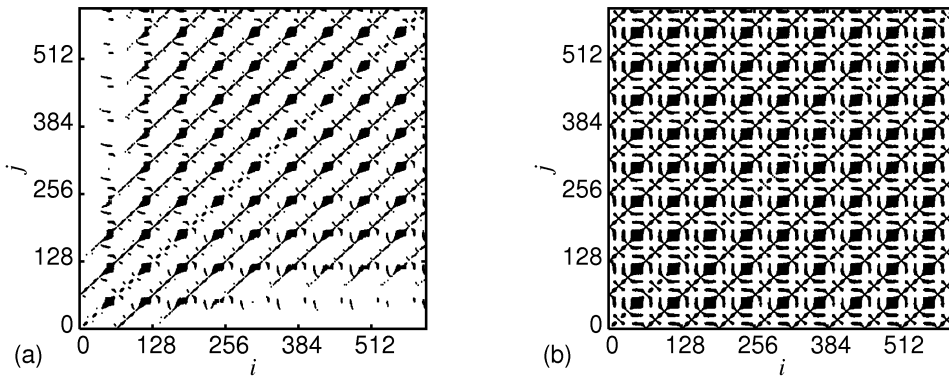


Fig. 8. Recurrence plots for the acceleration phase (a) and for the stationary work with higher rotational velocity (b) (here $\epsilon = 0.22$, $\Delta i = 16$, $n = 3$, examined cycles - 10).

Note that $\theta(x)$ denotes a step Heaviside function having 0 or 1 value for close and far values $(\mathbf{P}(i), \mathbf{P}(j))$ associated with i and j measurements points, respectively. 0 and 1 values are interpreted as white or black points in the corresponding recurrence plots. n denotes the dimension of the embedding space (Eq. 4) while ϵ is a small threshold value. This method has been also used to examine the dynamical states of engines [13–16].

In Fig. 7 we show the corresponding patterns for the examined time series (Fig. 2). Here, because of a large number of points per cycle we used only one eighth of all measured points marked in Fig. 2 (modulo 8). Interestingly, the recurrence plots can be used in both, stationary and non-stationary cases. The black points found in Fig. 7 indicate the highly correlated regions while the white area is associated with the non-correlated parts of $\mathbf{P}(i)$ and $\mathbf{P}(j)$ series. In addition to the initial and final part, where we had the steady states of engine work, one can also find some regularity in the acceleration phase (see in the middle part of Fig. 7).

The basic deterministic patterns of any recurrence plots consist of diagonal and horizontal lines and can be expressed by numbers using so called quantification recurrence analysis (QRA) introduced by Webber and Zbilut [17] and extended by Marwan and others [18–20]. In frame of QRA, it is possible to identify dynamics of the system [13]. In Fig. 8a and b we compare the acceleration and the constant developed velocity run of the examined engine, respectively.

The summary of the corresponding QRA analysis can be found in Tab. 1. Note that RR (recurrence rate) is the estimated ratio of black points in respect to all possible points. DET (determinism) and LAM (laminarity) are the cor-

Table 1

Summary of quantification recurrence analysis (corresponding to Figs. 8a and b patterns, here $\epsilon = 0.22$, $i = 16$, $n = 3$).

	RR	DET	LAM	L_{max}	V_{max}	L_{ENTR}	V_{ENTR}
a	0.075	0.893	0.893	160	18	2.489	2.356
b	0.213	0.949	0.957	386	22	2.113	2.207

responding ratios of points in diagonal and vertical lines, respectively. L_{MAX} and V_{MAX} correspond to longest diagonal and vertical lines, while L_{ENTR} and V_{ENTR} are entropies of diagonal and vertical lines length distributions (see in Marwan *et al.* [20] for further details). As expected RR is larger for a more stable work of an accelerated engine (Fig. 8b). The same can be applied to DET and LAM . These quantities are connected with a deterministic recurrence structure. The different situation can be observed for diagonal and vertical lines entropies L_{ENTR} and V_{ENTR} . They are larger for acceleration phase (Fig. 8a). Entropy, by definition, describes the disorder degree of the examined system. Here it is associated with non-periodic variations of the examined pressure. Maximal lengths of diagonal and vertical lines (L_{MAX} , V_{MAX}) are also longer for stabilized motion of engine (Fig. 8b).

4 Summary and conclusions

Initial cycles of free acceleration occur in engine non-stationary thermal conditions. In such conditions it is possible for the process of fresh air feeding to be effected as well. Consequently, the standard deviations of MIP are larger in the initial cycles of the engine acceleration process. On the other hand, the possible explanation for MIP large differences in the last cycle could be different time of the fuel injection pump rotational velocity controller. The fresh fuel amount could be terminated at slightly different time. This paper is a continuation of our previous investigations devoted to the dynamics of stationary Diesel engine conditions [13,14], where the recurrence plots technique and QRA were successfully used in to distinguish various states of the engine work. Here, these techniques have been applied to identify various phases of the engine non-stationary work. Note, the recurrence plots and RQA can be used to examine relatively short time series. Using this advantage of the presented above approach one can adopt this method to engine testing procedures. The efficient feedback control [21–23] also requires predictability of engine dynamics, at least in a short time range. The above examined QRA quantities, developed originally for bio-medical applications [19], provides important information about a transient engine response in the time domain. This approach can be easily extended and for any of the examined trails for

which one could estimate basic statistics. Such analysis is in progress and the results will be published in a separate report.

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