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# Chaotic combustion in spark ignition engines

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## Abstract

We analyse the combustion process in a spark ignition engine using the experimental data of an internal pressure during the combustion process and show that the system can be driven to chaotic behaviour. Our conclusion is based on the observation of unperiodicity in the time series, suitable stroboscopic maps and a complex structure of a reconstructed strange attractor. This analysis can explain that in some circumstances the level of noise in spark ignition engines increases considerably due to nonlinear dynamics of a combustion process.

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## 1. Introduction

It is known that the cyclic combustion variability is one of the main characteristics for spark ignition (SI) engines. If cyclic variability were eliminated, there would be even 10% increase in the power output of the engine [1]. Cyclic variations in the combustion process of SI engines have been a subject of an intensive research in last 40 years. Heywood [2] identified three main factors influencing cycle-to-cycle variations: aerodynamic in the cylinder during combustion, the amount of fuel, air and recycled exhaust gases supplied to the cylinder and a mixture composition near the spark plug.

Recently, in the context of engine control, there appeared a lot of papers on dynamic phenomenon identifications and predictions of engine behaviour [3–7]. Many of them discuss the problem of a high noise level which make the engine difficult to control. On this basis several stochastic models have been applied to pressure cyclic variation analyzing [4,5].

As the combustion of gases in the cylinder may be viewed as a nonlinear dynamical process [1,3], it may be studied by tools belonging to the theory of nonlinear systems. The variations might originate in nonlinear dependence of the peak cycle temperature and pressures on the initial conditions at the beginning of compression due to exhaust recirculation and a mixture preparation process. Such nonlinear approach has been already started by Daw et al. [3] where he suggested the possible chaotic nature of combustion. Our paper explanation is going in the same direction, however in our approach we adopted the novel measurement method basing on optical fibers and piezoelectric sensors to measure the pressure directly [8].

## 2. Chaotic oscillations of internal pressure

We start our analysis monitoring the measured time series for various spark advanced angles  $\Delta\alpha_2$ . The crankshaft frequency was chosen to be  $\Theta = 14.17$  Hz ( $\Theta = 850$  RPM) as an idle speed of the engine. In a combustion process only

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one of each two cycles of crankshaft rotation are coincided with combustion leading to pressure oscillation with a period  $2/\Theta = 0.141$  s. Note that depending on ignition timing ( $\Delta\alpha_z$ ) the system behaves differently. Starting with  $\Delta\alpha_z = 5^\circ$  (Fig. 1a) we observe initial periodic oscillation. Increasing  $\Delta\alpha_z$  to  $20^\circ$  the situation does not change very much nevertheless, one can note that in the background of a periodic motion some singular instabilities occur (i.e. at  $t = 2.8$  s at Fig. 1b) after a long interval of a stable motion (Fig. 1b). Interestingly, going further to a larger value of the spark advanced angle  $\Delta\alpha_z = 30^\circ$  changes the system behaviour completely. The corresponding time history is plotted in Fig. 1c. In this case the system has lost its initial periodic nature undergoing to a more complicated type of motion. In the last panel (Fig. 1d) we show the power spectrum for this interesting case. The continuous spectrum indicates that system can be in a chaotic state.

To clarify our conjecture about chaotic combustion we decided to present results on the stroboscopic map. In this aim we prepared Fig. 2 where we plotted the internal pressure coincided with the position of the crankshaft rotation angle. For enough long time history we see a kind of collection of Poincare maps plotted simultaneously for large number of performed measurements. Namely, our crankshaft was divided into 512 angles. These gives 1024 measurement points per two cycles of a crankshaft rotation corresponding to one cycle of combustion. One can see that initially seen periodic motion (Fig. 1a) has already some modulation of combustion slope. The critical region of modulation was however located behind the maximum pressure peak leaving its value  $p_{\max}(\phi)$  practically unaffected. Obviously, this modulation, rather difficult to observe in Fig. 1a, introduces another time scale with longer period. Note that for larger value of  $\Delta\alpha_z$  ( $\Delta\alpha_z = 20^\circ$ ) that critical region has moved towards the maximum pressure peak giving rise to observable changes of the maximum pressure value (Fig. 2a). These changes become the most dramatic for  $\Delta\alpha_z = 30^\circ$  where the the modulations of pressure exceeds its average value (Fig. 2c). To illustrate the final effect of pressure instabilities we show, in Fig. 2d maxima of pressure  $p_{\max}$  in sequential cycles  $n$ . In this figure squares correspond to  $\Delta\alpha_z = 20^\circ$  and circles to  $30^\circ$ , respectively. Note that the maximum value of pressure  $p_{\max}$  for  $\Delta\alpha_z = 5^\circ$  would be a constant line in the scale of Fig. 2d.

To this end we plot in Fig. 3 the reconstruction of the chaotic attractor. Changing the parameter  $\Delta\alpha_z$  which can be regarded as a bifurcation parameter we see that the attractor which was in principle two dimensional enlarge its dimensionality with increasing  $\Delta\alpha_z$ . The expected minimal embedding dimension was chosen arbitrary to be equal to 3 as on the basis that it is the smallest dimensionality enabling chaotic solutions. The characteristic time delay value  $\tau = 0.138$  s was chosen simply as a number smaller than the characteristic period in the system  $2/\Theta = 0.141$  s (Fig. 1a–c). Note  $2/\Theta$  as a period of a parametric excitation is unaffected by changes of the bifurcation parameter  $\Delta\alpha_z$ . Starting

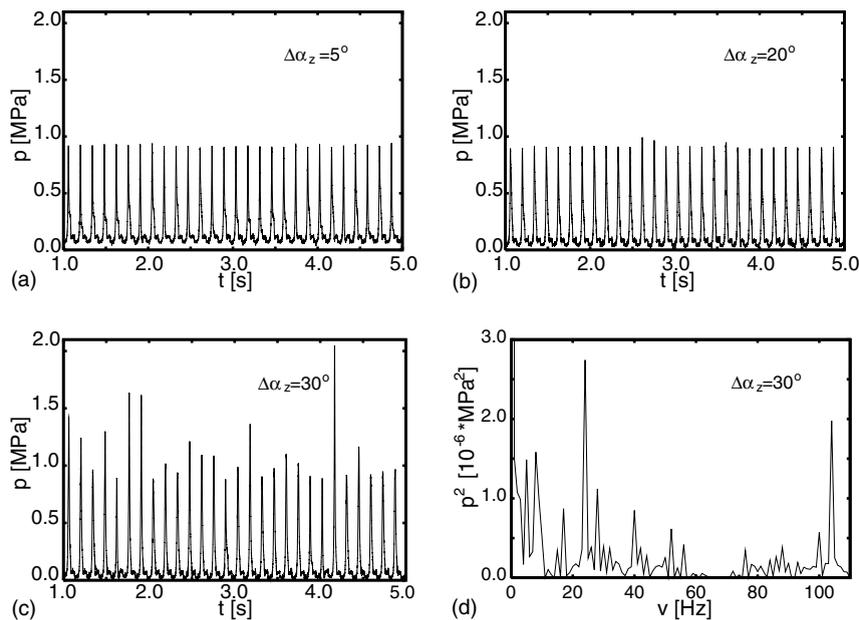


Fig. 1. Time series of pressure  $p(t)$  in a combustion process the crankshaft frequency  $\Theta = 850$  RPM (a)–(c) for various spark advance angles  $\Delta\alpha_z$ . The power spectrum for  $\Delta\alpha_z = 30^\circ$  (d).

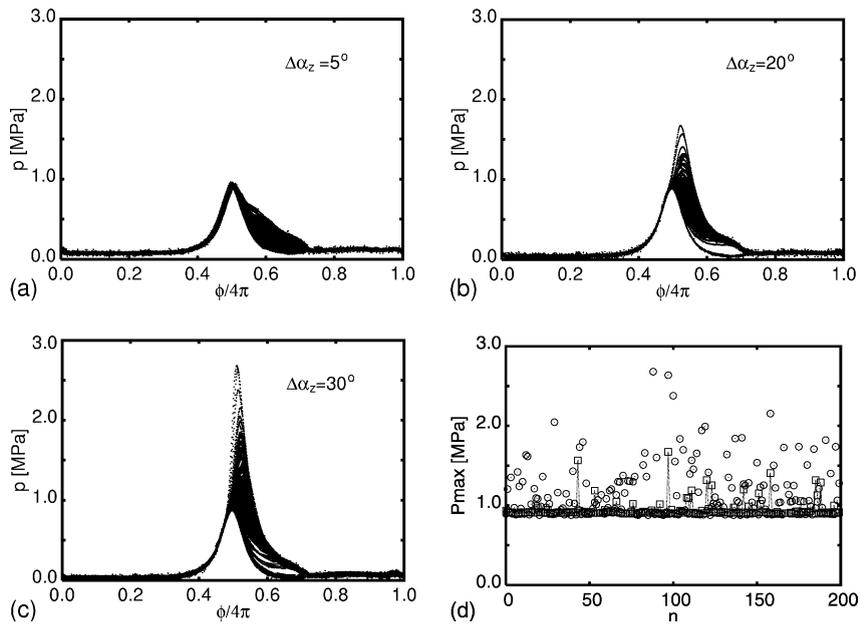


Fig. 2. Stroboscopic projection of internal pressure  $p(t)$  on a relative position of a crankshaft in a combustion process  $\phi$  for various  $\Delta\alpha_z$  (a)–(c). Maxima of pressure  $p_{\max}$  in sequential pressure cycles  $n$  where squares correspond to  $\Delta\alpha_z = 20^\circ$  and circles to  $30^\circ$ , respectively (d) (squares are connected by a dotted line for better clarity).

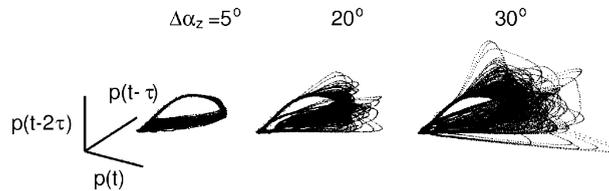


Fig. 3. Reconstruction of the attractor for a combustion process in a SI engine. Characteristic time delay was assumed to be  $\tau = 0.138$  s.

with basically 2-d structure of the attractor in three dimensions (Fig. 3a) one can follow small changes of it for  $\Delta\alpha_z = 20^\circ$  (in Fig. 3b) and a large qualitative change in Fig. 3c for  $\Delta\alpha_z = 30^\circ$ .

### 3. Conclusions

In this paper we examined the oscillations of combustion internal pressure. It appeared that, in some conditions, intermittency is capable to drive the system into chaotic region. We have shown that the change of a spark advance angle  $\Delta\alpha_z$  is making a significant effect on the combustion dynamics. It is clear that it influences directly the flame initiation phase which occurs on a larger time-rate for an increasing spark advance. In this way the cyclic variations become an inherent phenomenon in time and in space. Chaotic nature of combustion in SI engines appears in strong sensitivity on such conditions. It is worth to note that Fig. 1c and d, for  $\Delta\alpha_z = 30^\circ$  can be easily associated with a chaotic process, but Figs. 1b and 2b show that even for the advance angle  $\Delta\alpha_z = 20^\circ$  main instabilities appear. This fact leads us to conclusion that the mechanism of transition to chaos should be based on the intermittency phenomenon [9–11].

Our preliminary results indicate that the noise SI engines ought to be connected with nonlinear dynamics. Moreover analysing the combustion process for different system parameters we observed similar behaviour. It should be noted, however that in parametric systems with an additional self-excitation the problem of distinguishing between chaotic and multi-frequency quasi-periodic motions is not an easy task [12]. To tell more about dynamics of that particular

combustion method one have to use more sophisticated nonlinear methods [13]. We plan to conduct such analysis in a future report [14].

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