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ANALYSIS OF INFORMATION CONTENT OF IN-CYLINDER PRESSURE SIGNAL DEVIATIONS FROM THE MEAN VALUES

ANALIZA ZAWARTOŚCI INFORMACYJNEJ SYGNAŁU ODCHYLEK CIŚNIENIA OD ICH WARTOŚCI ŚREDNICH W CYLINDRZE SILNIKA

Abstract

This paper analyses the option of using pressure signal new descriptors for controlling a selected object. Pressure signal deviations from the pressure mean values were selected to be the example descriptors. Diesel fuelled with mineral- and bio-fuels was chosen to be the reference object. The in-cylinder pressure signal (p_c) was recorded during the combustion process.

Keywords: signal descriptors, diesel, control, combustion, biofuel

Streszczenie

W pracy przeanalizowano możliwość wykorzystania nowych deskryptorów sygnału ciśnienia do sterowania wybranym obiektem. Odchylenia wartości sygnału ciśnienia od ich wartości średnich zostały wybrane jako przykładowy deskryptor. Jako obiekt referencyjny wybrano silnik Diesla zasilany olejem napędowym lub biopaliwami. Sygnał ciśnienia w cylindrze (p_c) rejestrowano podczas procesu spalania.

Słowa kluczowe: deskryptory sygnałów, silnik Diesla, sterowanie, spalanie, biopaliwa

1. Introduction

An in-cylinder pressure signal can be used to control the fuelling process of combustion engine cylinders [3]. The purpose of this system is to optimise combustion in each cylinder in terms of performance, fuel consumption and emissions [5]. The pressure signal values are used to determine the descriptors directly involved in the control process, such as the mean indicated pressure, maximum pressure, or the crank angle for which half dose of fuel has been burnt. To calculate the values of these parameters with appropriate uncertainty, complicated algorithms and thermodynamic models have to be developed, along with the use of high processing power microcontrollers. Hence, the need to look for easy and fast methods of computing combustion process descriptors: the start of combustion angle or the angle corresponding to the maximum heat release rate. Some of the combustion parameters can be evaluated based on the mean value and the standard deviation of the measured in-cylinder pressure [6]. These estimates are easy to calculate, but are useful only when the values of the parameters are Gaussian distributed. The review of the literature [1] shows that the signal of pressure deviations from the mean is also easy to determine and that it can have a significant informational load. This is what the authors of this paper decided to investigate. The researchers in [2] proposed a new method of determining characteristic points of the diesel operation, based on signal deviations from their mean values and presented the results of preliminary investigations. This paper analyses the potential for the application of this method to various operating conditions of an engine powered with mineral fuel and biofuel. Calculations of the measurement results were performed using the R statistical package.

2. Experimental facilities and same test results

The experimental study was carried out on a three-cylinder diesel Perkins AD3.152 UR [4]. The measuring system consists of four measurement chains: in-cylinder-, in-injection pipe-pressure, injector needle lift and the crankshaft angle. Pressure was measured by quartz piezoelectric transducers and injector needle lift was measured by an inductive displacement sensor. The in-cylinder pressure was measured using a piezoelectric sensor AVL QC34D mounted directly in the cylinder head and cooled with a water. Piezoelectric properties of materials decline along with the rising temperature. A rapid decrease in piezoelectric properties of quartz is observed at a temperature of 523 K while at 846 K the piezoelectric properties disappear. Cooling with a liquid prevents the transducer from overheating, reduces thermal drift, and enables installation of the transducer directly in the combustion chamber. It is important that the cooling system of the engine provide a constant temperature, and the pulse-free flow of the coolant. Very high temperatures of the combustion process impose high thermal loads on pressure sensors. When the cooling system operates properly, the temperatures in the front zone reach 373 K and the temperatures of the measuring element are about 20 K higher than that of the liquid [7]. Large variations in pressure and temperature values cause the sensor sensitivity to change up to 1%. The pressure in the injection pipe

near the injector was measured using a piezoelectric sensor CL31 ZEPWN Marki, which prevented the need to cool it with water to minimize the effects of thermal shock. Table 1 summarizes the parameters of the piezoelectric transducers used for pressure measurements.

Table 1. Specification of the piezoelectric transducers used in the study

Parameter	Transducer AVL QC34D	Transducer CL31 ZEPWN Marki
Measurement range	0÷25 MPa	0÷100 MPa
Sensitivity	190 pC/Mpa	126 pC/MPa
Non-linearity	≤ 0.2%	≤ 0.5%
Overload capacity	20%	10%
Resonant frequency	69 kHz	50 kHz
Eigencapacity	10 pF	8 pF
Working temperature	293÷353 K	253÷323 K

Analysis of the data from Table 1 indicates that both transducers vary primarily in sensitivity, non-linearity and resonant frequency. In pressure measurements, the CL111 ZEPWN Marki charge amplifier was also used. Analog voltage signals from the amplifiers were converted into digital values using a 12-bit analog-to-digital converter KPCI-3110 manufactured by Keithley Instruments Inc. In each experiment, the values of the parameters measured were recorded as a function of the crank angle, with a resolution of 1.4°, which gave 512 measurement points for one working cycle of the engine. This was possible owing to the PFI60 shaft rotation-to-impulse converter produced by INTROL included in the measurement system, and the unit for sensing and synchronizing the crankshaft position, manufactured by ZEPWN Marki. The values obtained from fifty full working cycles were recorded for all the working conditions [4].

The scope of the tests covered the work of the engine under full- and part- load condition for loads from 4 to 20 kW, at speeds from $n = 1000$ to 2000 rpm. In both cases the engine was fuelled with diesel or biofuel FAME (methyl esters of fatty acids). Examples of pressure trace recorded during the measurements were presented in [2]. From the results of the p_c signal analysis conducted using the fast Fourier transform (FFT) is evident that the 13.3 Hz component is dominant, which results from the cyclic manner of the engine operation at the crankshaft speed of 1600 rpm. The analysis shows the component of a frequency of about 50 Hz and low amplitude which is not related to the processes taking place in the combustion chamber. The value of frequency of this component suggests interference coming from the electromagnetic field. A similar component was noticed for all the loads in the engine operating at 1600 rpm.

To see whether the analysed signal includes the components of other frequencies and low amplitudes, the authors deprived the signal of constant components related to particular crank angles. The resultant signal is represented by the deviations of p_c from the mean values, determined according to equation (1). Considering the location of maximum values of p_c

relative to the crank angle, and the fact that the registered signal is related to the process cycles, this signal can be regarded as close to the periodic signal with period $T = 120/n$. Based on the investigations [1], this signal can also be regarded as stationary due to the mean value and standard deviation. Verification of the agreement between the maximum p_c values distribution and the normal distribution indicated that for all cases, no grounds were found to reject the null hypothesis (the investigated variable is normally distributed) at the 5% level of significance. Since signal p_c can be regarded as close to the periodic signal, it can be represented in the form of a matrix with dimensions $[i j] = [512 50]$, where the columns show pressure values for consecutive working cycles, and the rows show the values related to the crank angles for which p_c was recorded. Deviations of p_c from their mean values can be calculated from [2]

$$\Delta p_c(i, j) = p_c(i, j) - \bar{p}_c(i) \tag{1}$$

where index i can take values from $i = 1$ to $I = 512$. The mean pressure values related to this i -th crank angle can be calculated using the following algorithm

$$\bar{p}_c(i, j) = p_c(i, j) - \bar{p}_c(i) \tag{2}$$

The deviations determined using equation (1) can be represented in the form of vector $\Delta p_c(k)$, in which they are arranged chronologically, where index $k = 512 \cdot (j - 1) + i$. Figure 1 shows the plot of consecutive deviation values computed in this way for the engine working under load conditions.

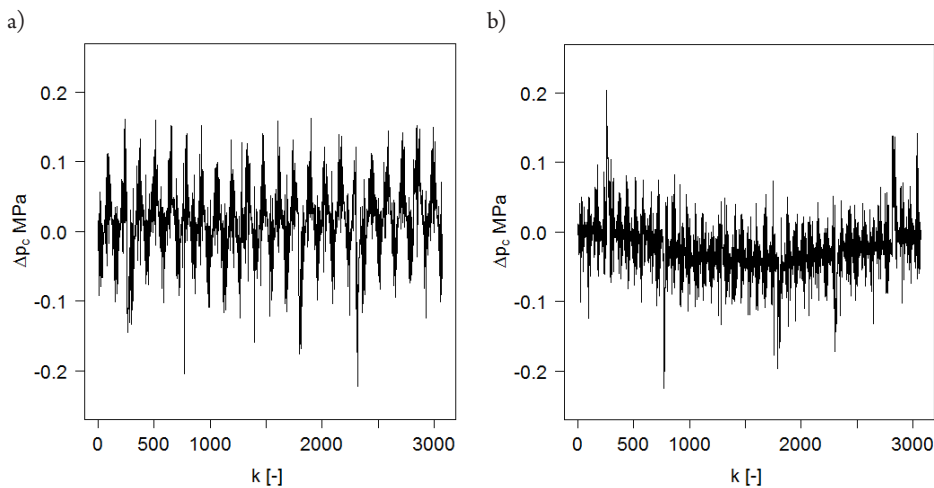


Fig. 1. In-cylinder pressure deviations from the mean values for the engine working under part- load conditions at a speed of 1600 rpm and load $N_e = 20$ kW: a) diesel- powered engine, b) FAME – powered engine – for the first six measurement cycles

The results from the FFT analysis of pressure deviations from their mean values. confirms the presence of the disturbing component with the frequency of about 50 Hz [2]. For further calculations, the original signal was filtrated and the component with the frequency of about 50 Hz was removed. The filtered signals were used in all further calculations.

3. The descriptors of the in-cylinder pressure signal

Determining the location of the points that characterize the p_c changes in real time can be useful for the engine working cycle control. The authors decided to calculate the start of combustion angles α_{ps} and the angles for which heat release rate reaches the maximum $\alpha_{\dot{Q}_{\max}}$ using the $\Delta p_c(i, j)$ signal. For this purpose, the squared deviations (Δp_c^2) were determined for individual crank angles. Analysis of the results in the spatial distribution leads to the conclusion that the highest values of the module occur in the angular interval for which the combustion takes place. To calculate the sought values of α_p and $\alpha_{\dot{Q}_{\max}}$ the authors determined the sum of the squared deviations $\sum \Delta p_c^2$ for the particular crank angles. Figure 2 shows the plot of this signal. The analysis of this plot leads to the assumption that it can be used for determining the start of combustion angles (α_p) and the angles for which the heat release rate reaches the maximum ($\alpha_{\dot{Q}_{\max}}$). The authors of this paper claim that the position of the maximum value of signal $\sum \Delta p_c^2$ (Fig. 2) corresponds to angle $\alpha_{\dot{Q}_{\max}}$, while the angle from which a rapid increase of $\sum \Delta p_c^2$ starts shows the start of combustion point.

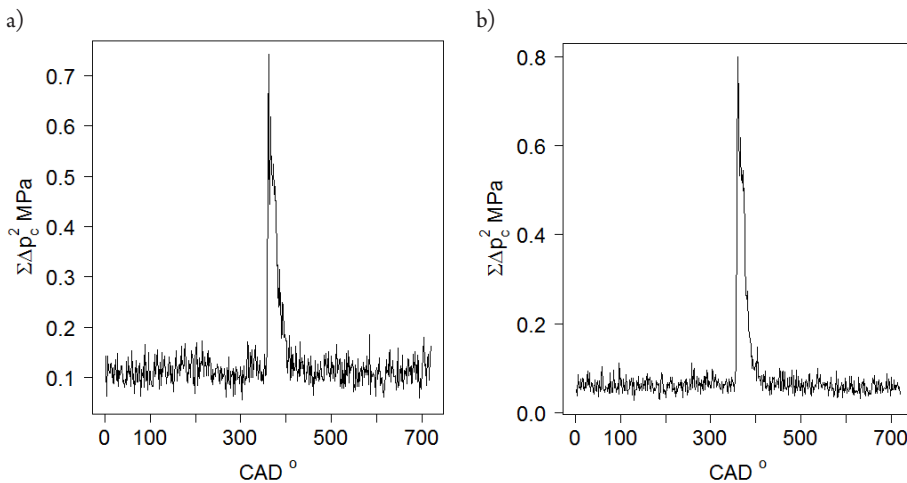


Fig. 2. The sum of the squared for the engine operating under part-load ($N_e = 20$ kW) conditions at a speed of 1600 rpm a) diesel-powered b) FAME-powered

Script 1 written in the R application language helps determine and graphically represent the values of $\sum \Delta p_c^2$.

Script 1. Determining the sums of the pressure squared deviations from the mean values.

```
%script1.R
rm(list = ls())
pc <- read.table("c:/on/1600/20/pc", header=FALSE, sep=";", na.strings="NA",
dec=".", strip.white=TRUE)
pc<-data.matrix(pc)
owk <- read.table("c:/on/1600/20/owk", header=FALSE, sep=";",
na.strings="NA", dec=".", strip.white=TRUE)
owk<-data.matrix(owk)
sredpc<-0
for (i in 1:512)
{
sredpc[i] <- mean(pc[i,])
}
od<-pc-sredpc
sum2od<-0
for (i in 1:512)
{
sum2od[i] <- sum((od[i,])^2)
}
par(family="Arial", font=2, ps=18, mar=c(4.2, 5.5, 1, 1))
plot(owk, sum2od, xlab=expression(paste(CAD, '
'^o)), ylab=expression(paste(Sigma, Delta, p[c]^2, "
MPa")), main="", pch=19, type="l", las=1)
```

The crank angles α_{ps} and $\alpha_{Q_{max}}$ values calculated based on the analysis of for engine operating under part-load conditions agreed satisfactorily with the values of angles reported in the literature [4]. The differences between obtained values were within the range $\pm 1.4^\circ$ [2].

Table 2. Comparison of angles determined based on the analysis of $\alpha_{Q_{max}}$ and on the values reported in the literature [4]; DIESEL/FAME powered engine operating under full-load conditions in the rotational speed range of $n = 1000 - 2000$ rpm

n [rpm]	α_{ps}	α_{ps} Lit.	$\alpha_{Q_{max}}$	$\alpha_{Q_{max}}$ Lit.
DIESEL				
1000	351,6	349,6	355,8	355,8
1200	351,6	349,2	355,8	357,2
1400	353,0	351,2	357,2	357,2
1600	350,2	352,4	357,2	358,4
1800	355,8	353,8	358,6	360,0

2000	357,2	354,4	361,4	360,0
FAME				
1000	348,8	350,1	353,0	353,0
1200	350,2	351,6	354,4	354,4
1400	350,2	353,0	355,8	355,8
1600	353,0	354,4	357,2	355,8
1800	354,4	354,4	358,6	357,2
2000	355,8	355,8	360,0	358,6

In order to verify the method proposed for determining the position of α_{ps} and $\alpha_{\dot{Q}_{max}}$, the calculations were made according to the same procedure but for the case of a diesel or FAME powered engine working under full-load conditions at speeds ranging from 1000 to 2000 rpm/min. Table 2 summarizes the results of these calculations.

The values of angles α_{ps} and $\alpha_{\dot{Q}_{max}}$ calculated based on the analysis of $\sum \Delta p_c^2$ and shown in table 2 agreed satisfactory with the values of angles reported in the literature.

4. Concluding remarks

The Pearson, Lilliefors and Shapiro-Wilk tests conducted for all the crank angles, for which deviations $\Delta p_c(i, j)$ were determined, in 90% of cases did not provide sufficient evidence to reject H0 about deviations from the mean values being normally distributed. It follows from the above that the sum of the squared pressure deviations $\sum \Delta p_c^2$, computed for each crank angle can be used for real-time determination of combustion process characteristic angles α_{ps} and $\alpha_{\dot{Q}_{max}}$, which can be used to control the engine working cycle.

To find and represent the $\sum \Delta p_c^2$ values graphically, Script 1 was written in the Rapplication language. This script can be implemented on a simple type ATmega microcontroller. The maximum of signal $\sum \Delta p_c^2$ corresponds to $\alpha_{\dot{Q}_{max}}$ angle, whereas the angle of the rapid $\sum \Delta p_c^2$ increase defines the start of combustion point. Good agreement was demonstrated between the results obtained for various engine operating conditions and those reported in the literature. To validate this method, the values of the sought angles were additionally determined by analysing the FFT module for signal p_c related to individual crank angles. The results obtained from each case analysed here were identical. The FFT procedure, however, extended the time necessary to make the calculations by about 50%.

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