A STUDY OF SHOCK WAVE PROCESSES IN THE COMBUSTION CHAMBER AND THE ESTIMATION METHOD OF THE KNOCK INTENSITY BASED ON ION CURRENT SIGNAL ANALYSIS

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ABSTRACT

The article is focused on the study of shock-wave processes in the combustion chamber on the basis of the ion current signal analysis. The possibility of detecting shock waves and estimating their intensity in the combustion chamber from the ion current signal is theoretically substantiated and experimentally proved. A criterion of the non-knock combustion process is given. It is based on spectral power density function analysis of the detected ion current signal. The proposed method for calculating the perturbations of the ion current signal in the shock wave processes is based on calculation of the fundamental and multiple harmonics of the standing wave packet arising in the combustion chamber during knock. The calculation of harmonics for standing waves which is based on the calculation of the conditions for the existence of standing waves and it takes into account the geometric dimensions of the combustion chamber and the velocity of propagation of shock waves. The spectral power density function of the detected ion current signal is calculated to study shock-wave processes. The obtained function of test signal calculation is approximated by a polynomial of the second degree. To estimate the energy of the shock wave packet, the function of the approximating polynomial is subtracted from the spectral power density function of the detected ion current signal. The energy of shock waves is estimated as the sum of the difference in areas under the test and calculated functions in the range of frequencies of standing waves existence calculated for a given combustion chamber. The results of an estimate of the knock intensity of four-stroke internal combustion engine with a combustion chamber diameter of 82 mm are given as an example.

Keywords: internal combustion engine, ion current, spectral analysis, knocks detection.

INTRODUCTION

A knock is one of the main factors limiting the power of the internal combustion engine (ICE) [1-19]. The knock is a result of self-ignition of the fuel-air mixture (hereinafter, FAM). It occurs in the region in front of the turbulent flame, leading to a rapid release of energy. An emergence of high local pressure leads to compression waves propagation within ICE. Shock waves encountered in knock combustion process, result in damage effects of ICE, deterioration of engine values and increasing of harmful substances in the exhaust gases.

To date, indirect methods for detection of knock combustion are widespread. These methods are based on the fact that vibrations and noise generated during knocking are excited by compression waves at certain frequencies corresponding to the resonant modes of the combustion chamber [1-21].

It is known that a group of waves with different velocities and energy arise upon knock combustion [1-19]. The influence of various waves and their harmonics on the processes upon knock combustion could be estimated using spectral analysis methods.

Figure-1 shows the plots of its power spectral density (PSD) for knock combustion obtained by engineers from General Motors [7, 8].

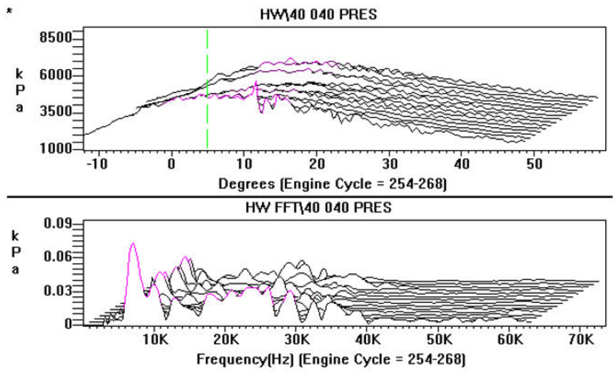

Figure-1. The PSD plots upon knocking in ICE.

The knock detection is available by filtering the sensor signals of pressure, combustion, vibration, sound, ion current, accelerometers and using other band-pass filters at the frequency of the main shock wave harmonics.

Narrow- and wideband knock sensors (hereinafter KS) based on the piezoelectric effect, track the vibration occurring at the desired frequency. The problem of this method is a strong noisy signal, caused by the vibrations of the running engine. A lot of moving parts and details of the internal combustion engine produce oscillations with a frequency lying within the target range. These noises reduce the reliability of the result.

The method of direct pressure measurement in the ICE cylinder gives more reliable and accurate results of knock detection, since vibrations and noises emitted by the engine parts have no significant effect on combustion pressure sensor. The method is highly sensitive, allows detecting knock of varying intensity, including at its initial stage. However, the use of knock signal sensors often is limited to the stages of research, calibration and diagnosis of ICE, because of small resource and a high cost.

The problem of signal noise in the target frequency range, low sensitivity, low resource and high cost of devices and components of the knock combustion detection system could be solved by the method of the ion current signal (ICS) recording. Since the measurements, as in the case of the combustion pressure sensor, are carried out directly in the combustion chamber, they have high reliability, and the noise and vibration of the ICE parts do not affect the ICS. This highly sensitive method does not require the use of expensive materials, sensors and electronic components.

The objective of the work is to study the effect of wave propagation in the combustion chamber on ICS and to develop estimation method of energy shock wave packet arising from knock combustion in the ICE.

The study of the effect of combustion parameters on the spectrum of the ion current signal and the development of a method for estimating the detonation intensity

The experiment was carried out for normal and knock combustion. The plots of ICS and the estimated power spectral density (PSD) are shown in Figure 2. All the plots provided in this article were obtained using MATLAB. Experimental data were obtained for a combustion chamber with a diameter of 82 mm. The main resonant frequency for this diameter is approximately 7000 Hz [2, 19].

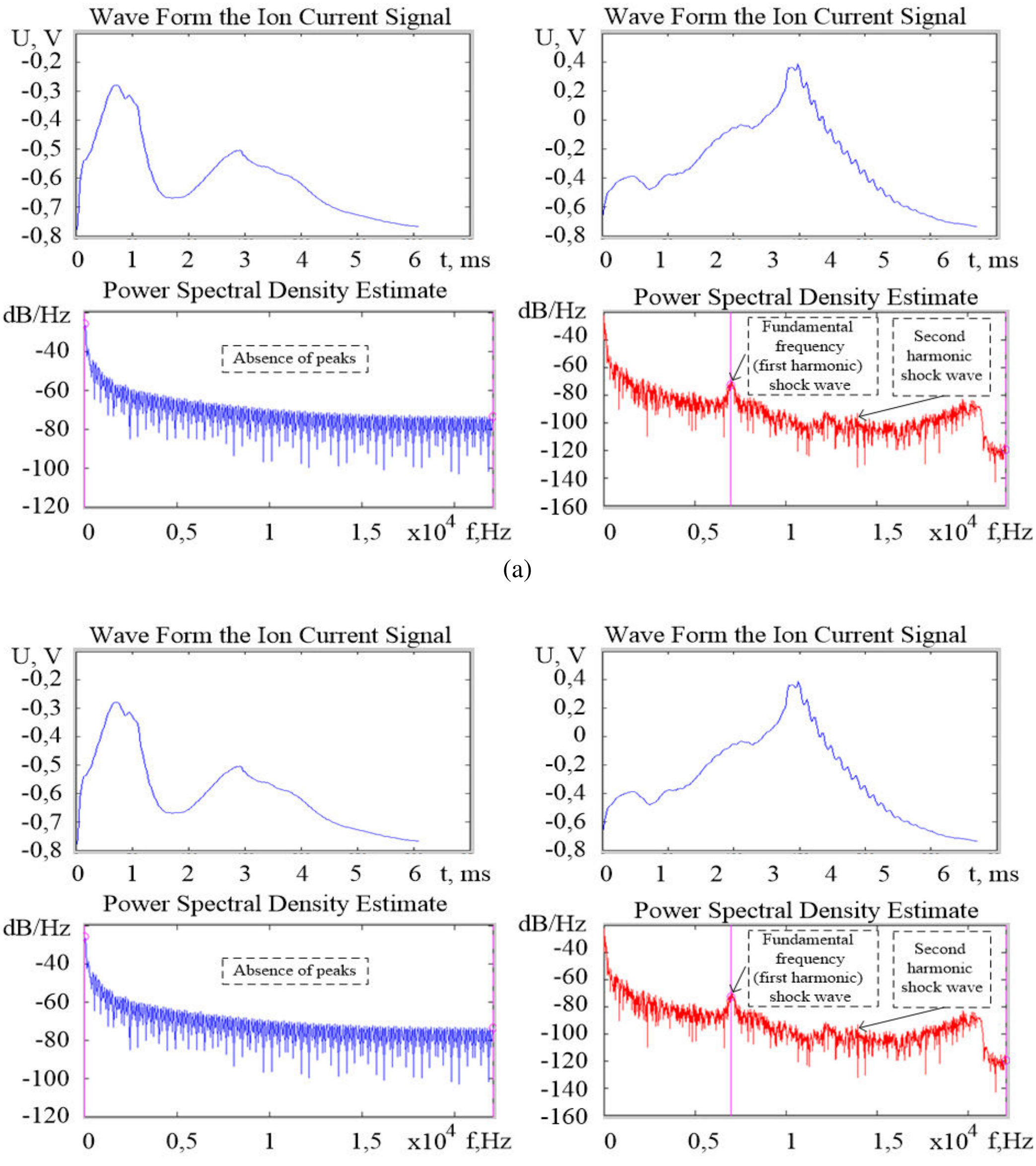

Figure-2. ICS and PSD of (a) - normal combustion, (b) - high knock combustion.

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The plots of estimated power spectral density ICS for knock combustion (see Figure-1 (b)) shows different spikes. The frequency of a standing wave depends on the speed of sound in the environment, the wavelength and the geometry of the combustion chamber [2, 19]. The assumption that the standing wave in the combustion chamber is flat allows us to calculate the frequencies of the harmonics according to equations (1):

$$\begin{cases} f_1 = \frac{V}{\lambda_1} = \frac{V}{2d}; \\ f_2 = \frac{V}{\lambda_2} = \frac{2V}{2d} = 2f_1; \\ f_3 = \frac{V}{\lambda_3} = \frac{3V}{2d} = 3f_1; \\ \dots \\ f_n = \frac{V}{\lambda_n} = \frac{nV}{2d} = nf_1, \end{cases} \quad (1)$$

where $f_1, f_2, f_3, \dots, f_n$ – are the frequencies of the fundamental and higher harmonics respectively, $\lambda_1, \lambda_2, \lambda_3, \dots, \lambda_n$ – are the wavelengths of the fundamental and higher harmonics, respectively, V - is the wave velocity, d – is the cylinder diameter.

Calculation of the power spectral density of the detected ion current signal produced by the algorithm computing the discrete fast Fourier transformation (DFT) by (2) when k=0, 1,…, (N-1) [20].

$$P(k) = 10\lg\left(\left|\frac{1}{NF_S}|X(k)|^2\right|\right), \quad (2)$$

where F_S is the sampling frequency, N – is the DFT dimension, $X(k)$ –is the N-point DFT of the N-point sequence $x(n)$, k - is the discrete normalized frequency, $P(k)$ - is the power spectral density.

The calculation of the PSD function of the normal combustion is performed by approximating the envelope of the PSD function for the recorded signal curve in sections between the frequencies $f_1, f_2, f_3, \dots, f_n$ This technique is based on the spectrogram analysis for normal combustion of FAM (Figure-1 (a)), which shows that the envelope of the PSD function has a smooth character without pronounced spikes on the frequency bands of the waves arising from knock combustion.

Approximation of ICE PSD function can be a polynomial of the second degree (3):

$$s(f) = p_1 f^2 + p_2 f + p_3, \quad (3)$$

where s – is the amplitude of the signal envelope; p_1, p_2, p_3 – are the polynomial coefficients; f – is the frequency.

To find the values of the function $s(f)$ the average amplitudes of the PSD function are calculated at sites between the frequencies f_1, f_2, f_3 in accordance with the expressions (4):

$$\begin{cases} s_1 = \frac{1}{2f_{dov}} \sum_{i=1}^{2f_{dov}} P_i \text{ , где } P_i \in [0{:}\, f_1 - f_{dov}]; \\ s_2 = \frac{1}{2f_{dov}} \sum_{i=1}^{2f_{dov}} P_i \text{ , где } P_i \in [f_1 + f_{dov}{:}\, f_2 - f_{dov}]; \\ s_3 = \frac{1}{2f_{dov}} \sum_{i=1}^{2f_{dov}} P_i \text{ , где } P_i \in [f_2 + f_{dov}{:}\, f_3 - f_{dov}], \end{cases} \quad (4)$$

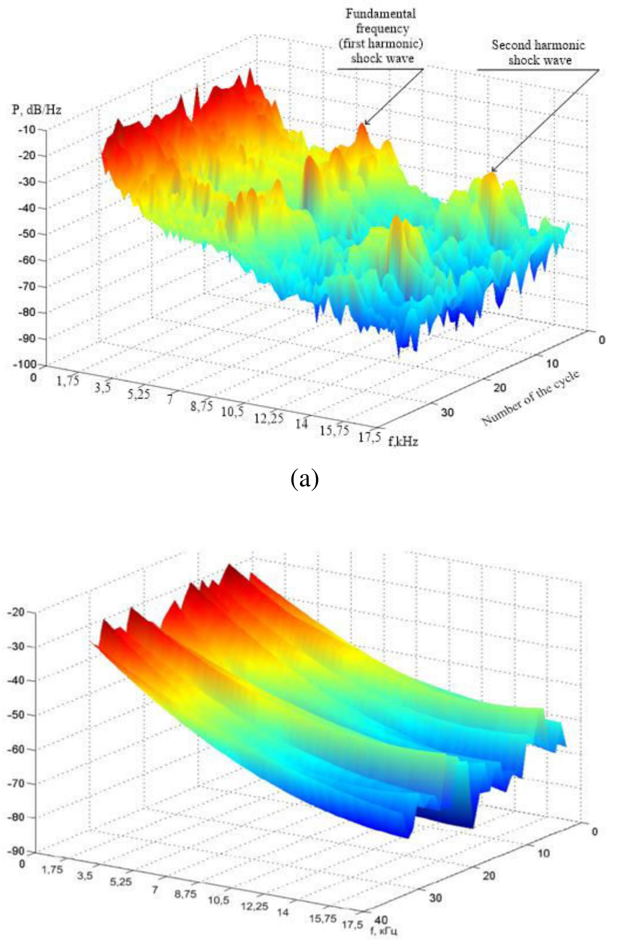
where, f_{dov} - confidence interval of recorded wave frequency determined experimentally.

The system of equations (5) for finding the coefficients p_1, p_2, p_3 of the polynomial (3) is based the calculated values of s_1, s_2, s_3 :

$$\begin{cases} s_1 = p_1 f_{s1}^2 + p_2 f_{s1} + p_3; \\ s_2 = p_1 f_{s2}^2 + p_2 f_{s2} + p_3; \\ s_3 = p_1 f_{s2}^2 + p_2 f_{s2} + p_3, \end{cases} \quad (5)$$

Where f_{s1}, f_{s2}, f_{s3} - are the frequencies corresponding to the s_1, s_2, s_3 calculated by expression (4)

Figure-3 shows the result of calculation using (1) ... (5) for 30 consecutive cycles of knock combustion in one of the ICE cylinders.



(a)

(b)

Figure-3. PSD function: upon knock (a); a calculated value of normal combustion (b).

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The energy of the shock waves is estimated as the difference between the integral values of the PSD function for recorded signal and for calculated values for normal combustion in frequencies domain f_1, f_2, f_3 in accordance with (6):

$$\begin{cases} P_{vf_1} = \int_{f_1-f_{dov}}^{f_1+f_{dov}} P(f)\,df - \int_{f_1-f_{dov}}^{f_1+f_{dov}} s(f)\,df; \\ P_{vf_2} = \int_{f_2-f_{dov}}^{f_2+f_{dov}} P(f)\,df - \int_{f_2-f_{dov}}^{f_2+f_{dov}} s(f)\,df; \\ P_{vf_3} = \int_{f_3-f_{dov}}^{f_3+f_{dov}} P(f)\,df - \int_{f_3-f_{dov}}^{f_3+f_{dov}} s(f)\,df; \end{cases} \quad (6)$$

where $P_{vf_1}, P_{vf_2}, P_{vf_3}$ - is the estimated energy of the shock wave harmonics.

The expression for total energy of the shock waves calculation is given (7):

$$P_{det} = \sum_{i=1}^{n} P_{f_n} \quad (7)$$

The knock intensity I_{det} is estimated by (8):

$$I_{det} = {P_{det}} \Big/ {\sum_{i=1}^{n} P_{Sf_n}}, \quad (8)$$

where P_{Sf_n} - are the integral values of the PSD function for normal combustion, which are on the right-hand side of expression (6).

An example of knock intensity using proposed method

Figure-4 (a) shows an example of the calculation for a shock wave in a four-stroke internal combustion engine with a cylinder diameter of 82 mm using expressions (1) ... (7). For other components of the shock wave, the calculations are similar.

In the graphical representation, the energy of the shock waves is equal to the difference in the areas under the experimental and PSD functions calculated for the target frequency band.

The total energy of the waves is equal to the sum of the areas calculated for all the target ranges determined by the frequencies f_1, f_2, f_3 and the confidence interval f_{dov}. Figure-4 (b) shows examples of PSD function plots of the recorded signal and calculated by (3) for normal combustion.

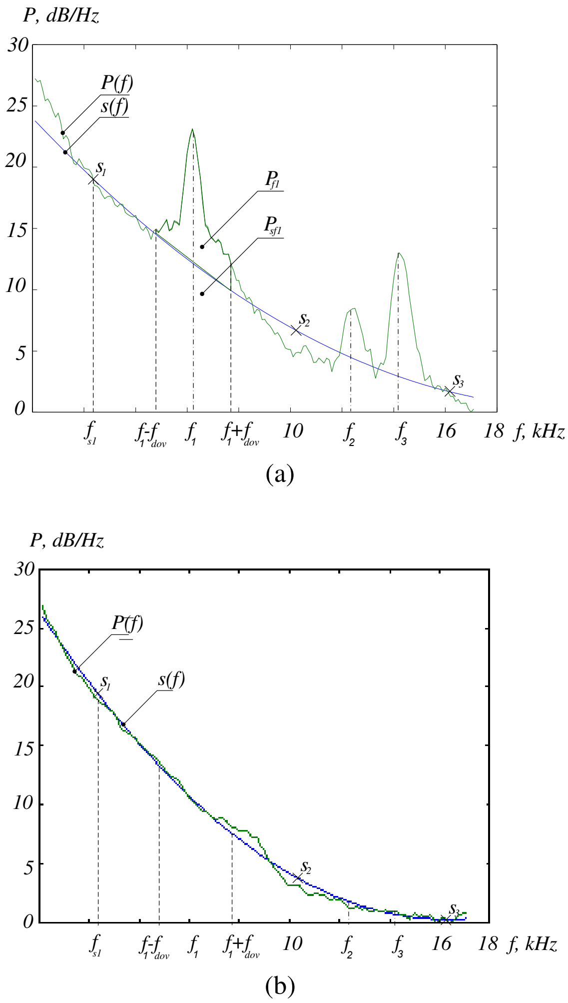

Figure-4. The experimental (green line) and the calculated (blue line) PSD of the ion current signal for knock (a) and normal (b) combustion of FAM.

Table-1 shows the results of the calculations made using the proposed method for the PSD functions, presented in Figure-4.

Table-1. Results.

Parameter	Knock combustion	Normal combustion
Total sum of estimated energy of shock-waves P_{det}	251,035	13,511
Estimated intensity of knock I_{det}	0,4857	0,0294

The results in Table-1 show high resolving power of the proposed method, since the shock wave energy calculated for normal and detonation combustion differ by an order of magnitude.

For 330 successive cycles of knock combustion, the degree of reliability of detection of detonation by the proposed method turned out to be 8% higher than the methods based on bandpass filtration of ICS.

CONCLUSIONS

The paper presents the results of an experimental study of the ion current signal under various combustion conditions.

As a result of the analysis of the spectra of recorded ICS for various combustion modes of FAM the following conclusions have been drawn: the frequencies at which resonance phenomena occur could be calculated using equations of plane wave; under normal combustion, the ICS spectrum has a smooth character without pronounced spikes, including in the frequency range with resonant phenomena; in knock it has been observed increasing amplitude of the waves in the frequency range with resonance phenomena, as shown by spikes on the spectrogram; the nature of the spectrum is common and unified for different combustion modes of FAM for the single combustion cycle signal and statistical ICS samples. The developed method for estimating the detonation intensity in ICS is based on the calculated frequencies of the harmonics of shock waves. It allows taking into account the energies of waves for different velocities and frequencies. An estimation of the energy of detonation waves occurs over the area of the PSD function in the region of the calculated frequencies of standing waves. The paper presents calculation results of knock wave energy using proposed method for normal and knock combustion in a four-stroke ICE with a cylinder diameter of 82 mm, the results show high resolving power of the proposed method, since the shock wave energy calculated for normal and detonation combustion differ by an order of magnitude.

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