Analysis of Ion Current Integral Characteristics for Estimation of Combustion Process Parameters in Internal Combustion Engines

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***Abstract*—An approach of peak pressure position and maximum pressure estimation in the chambers of internal combustion engine (ICE) is proposed in the paper. The approach is based on analysis of integral characteristic of ion current and has potentials due to robustness of estimation results to cycle-by-cycle parameters variations of combustion process and variations of measuring probe parameters. Besides, the use of integral characteristic does not require the knowledge of noise sensitive ion current profile. The proposed idea is validated via experiments and compared with analogous method of peak pressure angle calculation using thermal ionization of ion current. The final result of estimation can be applied in spark ignition or diesel engine control, wherein the proposed estimation mechanism can be applied in feedback instead of the use of expensive high pressure sensors or analog lambda sensors.**

***Index Terms*— ion current signal, peak pressure position, maximum pressure estimation, engine**

I. Introduction

A. Ion Current Signal

Methods of ion current signal (ICS) analysis have the potentials for estimation of different parameters and characteristics of the combustion process inside combustion chamber of ICE. [1]. Successful results of the analysis allow to estimate peak pressure inside cylinders, knocking, emission quantities and the rate of cylinders/pistons wearing [1]-[17]. Moreover, the possibility exists to substitute a number of expensive sensors for the relatively cheap ion sensors with well designed estimators.

The results of ICS analysis can be applied in design of ICE with structure optimization of cylinders and manifolds geometry [11], [12] as well as for design of ICE control systems with high performance and relatively cheap feedback measurement [3]-[7], [10].

Nowadays, despite the theoretical potentials, methods of ICS analysis are not widely applicable in practice due to the high sensitivity of ion current to cycle-by-cycle variations of combustion process parameters. As a consequence high sensitivity makes it difficult to define actual operating conditions of the engine. Moreover, ICE is affected by disturbance and primarily operates under transient conditions. Therefore, methods of signal analysis do not give acceptable results in a real engine system (even, if they demonstrate appropriate behavior in the lab).

Thus, the contribution of the paper is in proposition of approach for estimation of combustion process parameters - peak pressure position (PPP) and maximum pressure of cycle (MPC). The approach is based on analysis of ion current integral characteristics (ICIC) and potentially allows to broaden the use of ion current signal by significant reduction of sensitivity to noise and cycle-by-cycle variations of combustion process parameters.

Finally the proposed idea is compared with the method of PPP estimation using thermal ionization of ion current.

Manuscript received January 1, 2017; revised April 1, 2017.

doi: 10.18178/ijmerr.6.3.188-193

B. Survey of Methods of Ion Current Signal Analysis

As far as is known, the majority of methods of ICS analysis is based on search of informative features of the signal. These features are specific to different dominating mechanisms of ionization and combustion phases of fuel charge. All the methods of analysis can be formally divided into two groups. First group called parametrical analysis involves the estimation of such ICS parameters as number, amplitude of signal peaks together with time instants, signal durations (length) and spark angles corresponding to these peaks (see illustration in Fig. 1).

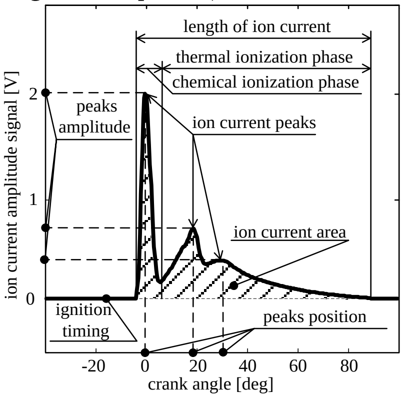

Figure 1. The parametric analysis of the ion current.

The second group called structural analysis implies the division of the entire signal into several simpler curves. Each curve approximates a distinguishable part of signal. For example, structural analysis for estimation of PPP from the angle of peak thermal ionization of ion current is proposed by Lars Eriksson [4] and Z. Gao [14]. The estimation of the thermal-ionization peak angle is the accomplished by selection of the following approximating function of time:

$$\delta_1(t) = a_1 e^{\left(-\left(\frac{x-b_1}{c_1}\right)^2\right)} + a_2 e^{\left(-\left(\frac{x-b_2}{c_2}\right)^2\right)} \qquad (1)$$

where a is the specifies the maximum amplitude, b is the location of the maximum, c is the width of the Gaussian curve.

Equation (1) describes the sum of two overlapping Gaussian curves corresponding to the first and second peaks of the ICS (see Fig. 2).

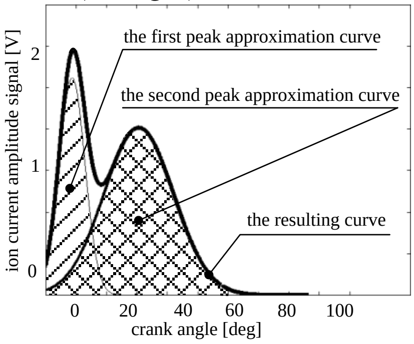

Figure 2. Structural analysis of the ion current signal.

Methods of parametric and structural analysis works well for engine operating at steady state, when it is possible to average the signal over several cycles of a homogeneous sample. Note, that it is difficult to apply aforementioned approaches at transients. Unfortunately all the trials to obtain homogeneous samples under transients lead to accumulation of errors. Moreover, ICS phases may overlap, what makes difficult to distinguish the phases of the signal by dominant ionization mechanism. Since the ICE operate under transients, and ICS is to be used in real-time control systems, methods of parametric and structural analysis cannot provide suitable feedback. Therefore, we propose another idea to use the ICIC.

Calculation of the area under ICS curve (found as definite integral) does not impose the restrictions on the parameters and wave form. It was experimentally demonstrated (see Kaiadi et al. 2008 [15], Zheng et al. 2014 [16]) that this area can be potentially used for further interpretation, estimation and use as feedback measurement in closed-loop ICE control systems.

Thus, time or angle domain analysis of ICIC parameters allows to estimate power characteristics of combustion process. The use of integral quantities leads to reduction of cycle-by-cycle variations and consequently the error of estimation

The remaining of the paper is organized as follows. In subsection 2a a method of evaluation of ICIC is presented, and the correlation between 80% angle ICIC and peak pressure is shown. In subsection 2b the advantages of ICIC use are demonstrated. In subsection 2c the results of experimental validation of the evaluation method are presented and compared with measurements of Kistler pressure sensor. Possibilities of the estimation of peak pressure, PPP and air-fuel ratio are shown. Finally, the conclusion is made in section 3.

II. Investigation of Ion Current Integral Characteristics

A. Calculation Procedure and Criteria for Analysis of ICIC

ICIC can be calculated with the method of step-by-step integration over crank angle. The limits of integration for one cycle can be selected according to the duration of the signal beginning from the ignition point:

$$I_{ion} = \int_{\theta_1}^{\theta_2} U_{ion}(\theta) d\theta \qquad (2)$$

where I_{ion} is the integral signal characteristic of the ion current; θ is the crank angle; θ_1 and θ_2 are the integration limits; $U_{ion}(\theta)$ is the voltage output of ionization sensor.

Practically, for ICIC estimation we apply method of trapezoidal numerical integration:

$$\tilde{I}_{ion}(n) = \tilde{I}_{ion}(n-1) + \frac{T}{2}[U_{ion}(n-1) + U_{ion}(n)] \qquad (3)$$

where $\tilde{I}_{ion}$ is the estimate of the I_{ion}; T is the sampling time (in time or crank angle domain); n is the number of sample.

If signal is measured with high sampling frequency, cumulative sum of values ICS $U_{ion}(n)$ can be used.

Examples of the ICS and its ICIC are shown in Fig. 3, where the maximum value of the integral characteristic I_{max} corresponds to the total area under the curve of the ICS. This parameter together with the shape of the curve ICIC and its step by step value are of the most interest.

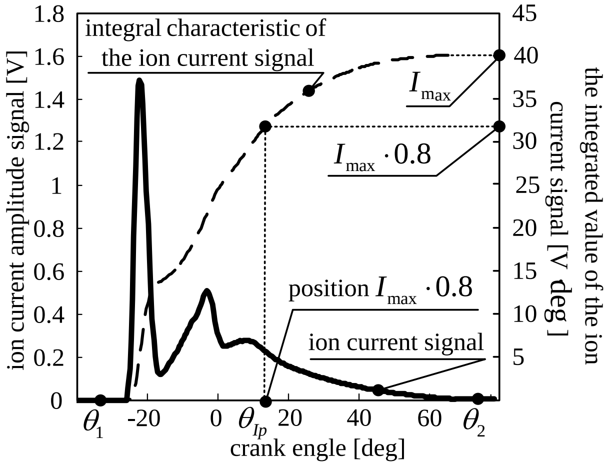

Figure 3. The ion current signal and its integral characteristics.

Duration of ion current signal $\theta_{ion}=\theta_2-\theta_1$ corresponds to the duration of the combustion process and $I_{ion}(\theta)$ corresponds to energy of the combustion process. Comprehensive analysis of ICS in relation to I_{max} allows to determine the typical phases of the combustion process. For example, if θ_{Ip} (see Fig. 3) achieves 80-90% of I_{max}, the main combustion phase is ended and peak cylinder pressure is achieved.

B. The Advantages of ICIC Use

The analysis of ICIC does not require the knowledge of shape and parameters of measured ICS what relaxes restrictions on transients of engine operating. Moreover, the estimation mechanism using ICIC is robust to variations of probe electrode parameters during engine operating what illustrated in Fig. 4 (taken from Wu X. et al. paper [17]). Wu X. et al. investigated the influence of probe electrode size on engine operating at steady state.

Analysis results of the data presented in Fig. 4 show that the geometrical parameters of the electrode affect the shape of the ICS. At the same time the values θ_{Ip} at the end of the main combustion phase almost does not change. The results of data analysis are presented in Table I.

TABLE I. ANALYSIS RESULTS OF ICIC FOR DIFFERENT PROBE SIZES

The area of the probe, [mm2]	I_{max}, [mA]	I_{max} *0.8, [mA·deg]	θ_{Ip} , [deg]
218	158	4302	20
148	146	3953	20
92	100	2826	19
56	90	2449	19
26	83	2094	19
12	52	1367	19

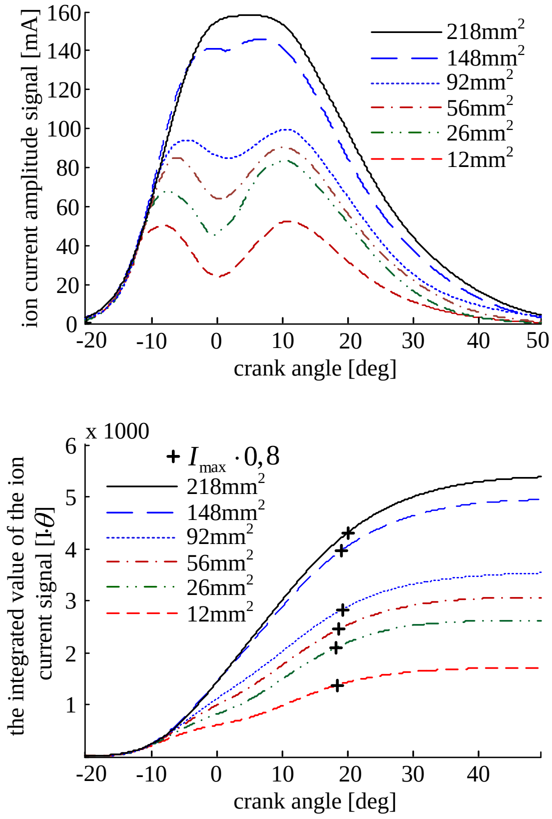

Figure 4. The current in the probe (upper plot) and the calculation result of the end of the combustion main phase for different surface of the probe (lower plot).

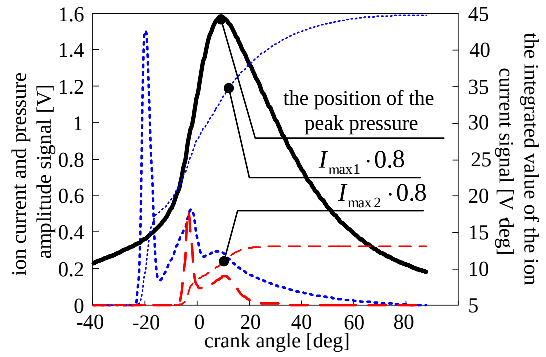

Figure 5. Ion current and the parameters calculated in the end of the main combustion phase: ▬▬ pressure signal, ----- probe to close of the spark plug, — — probe to remote of the spark plug.

Analysis results presented in Table I shows that the increase of probe area in 18.2 times leads to small changes of θ_{Ip}.

The diameter of the electrode of the standard spark plugs changes from 0.7 mm (platinum or iridium) to 2.5 mm (nickel). The electrodes have length 2.5-3.5 mm and area about 7-55 mm^2. This corresponds to change of I_{max} in no more than 1.5 times. For a given type of spark plugs change of the electrode area after burnout can be neglected. For example if electrode is wear out in 60% , I_{max} will be changed just in 20%.

Therefore, the change of geometry of probe electrode does not influent on specific points of ICIC. The corresponding stable values of points can be used for estimation of other physical characteristics of combustion process.

Probe position does not affect PPP what is demonstrated in Fig. 5. Figure shows the results of calculations for the two probes. One probe is mounted in the vicinity of the spark plug, and the other one located at some distance from the spark plug.

C. *Verification Results*

During the experiments the ion current signal, combustion pressure, the crankshaft and the mass flow of air and fuel at steady state have been measured.

In the first series of experiments we defined the influence of the ignition timing (IT) on ICIC. IT was changed during the experiments. The other variables stayed quasi constant. Figure 6 shows the results of the experiments — the averaged ion current and combustion pressure wave-forms versus IT.

In the second series we conducted analogical experiments, where we defined the influence of air-fuel ratio on ICIC by changing air-fuel ratio, while the other variables stayed quasi constant.

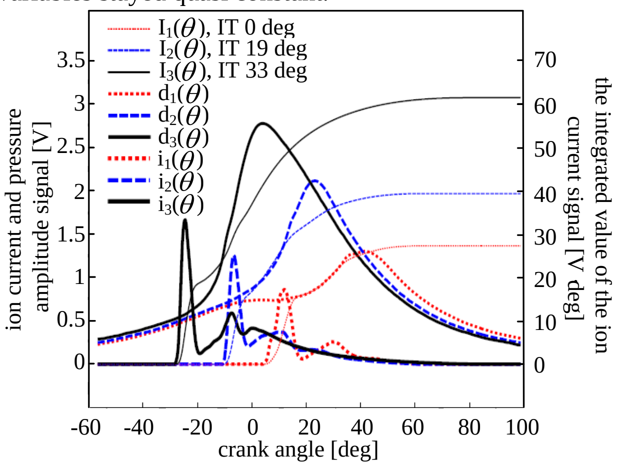

Figure 6. Effect of ignition timing (0, 19, 33 deg) on: the pressure form (d_1-d_3), the ion current (i_1- i_3) and its integral characteristics ((I_1- I_3))

In the third series we conducted analogical experiments defining dependence of ICIC from peak pressure for different IT. Fig. 7 demonstrate the results of experiment.

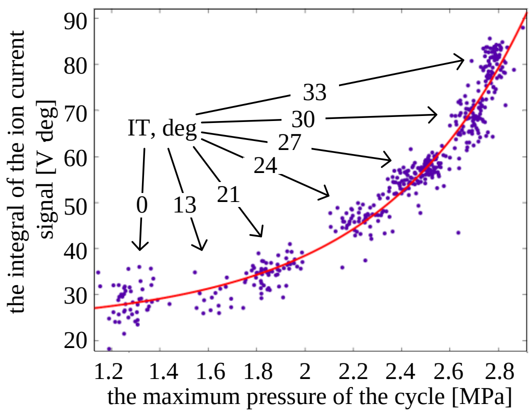

Figure 7. Effect of ignition timing on: the maximum cylinder pressure, the ion current and its integral characteristics.

Analysis results of the data presented in Fig. 7 show the possibility of estimation of maximum pressure in cylinders using ICIC.

In the forth series of experiments we compared ICIC based estimation of peak pressure and measured PPP. The results of comparison are presented in Fig. 8.

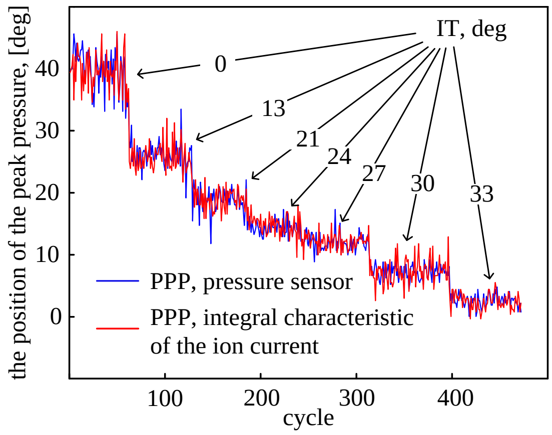

Figure 8. Measured and estimated the PPP versus IT.

As a result of experiments we found dependence of cycle mean peak pressure $P_{max}(\theta)$ and the $I_{max}(\theta)$ from the different air-fuel ratio (depicted in Figure 9).

The Figure 9 shows maximums $I_{max}(\theta)$ and $P_{max}(\theta)$ for θ = 0.8-0.9 versus to air-fuel ratio. These currents and pressures correspond to maximum energy of the combustion process (the maximum combustion pressure and the highest speed of flame spread). This allows to use I_{max} as a criterion for the evaluation and optimization of the control of the air-fuel ratio. Moreover, the dependence can be potentially used as feedback in the emission control.

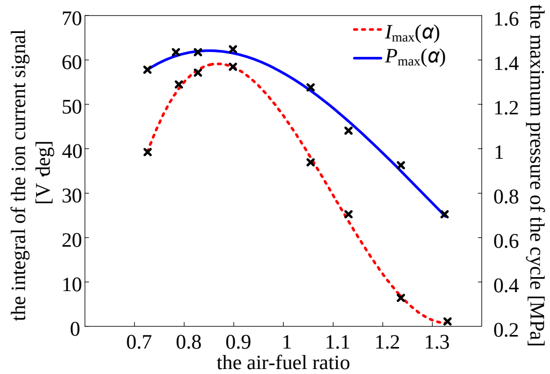

Figure 9. Dependence of mean peak pressure and ICIC on air-fuel ratio.

The comparison results of the methods efficiencies for estimation PPP by ICIC and by the peak thermal ionization of ion current is shown on Fig. 10.

The results of analysis presented in Figure 10 demonstrate insignificant differences between ICIC based estimation of PPP and measurements of pressure sensor. The results also show small susceptibility of ICIC to the effects of cycle-by-cycle variations of combustion process. The worse results are demonstrated for method of thermal ionization.

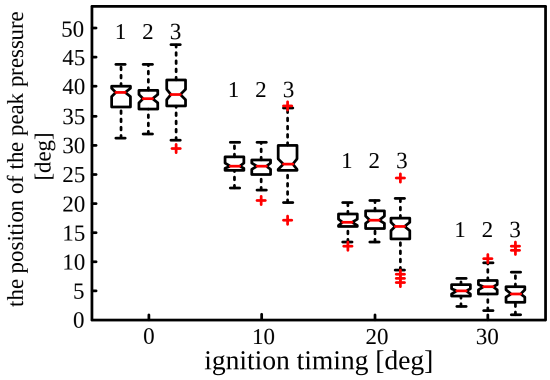

Figure 10. Box plot of the PPP for difference IT: 1 - pressure sensor, 2 - an integral characteristic of the ion current signal, 3 - peak thermal ionization.

III. Conclusions

The potentials of ICIC for analysis of combustion process parameters – peak pressure and air-fuel ratio are considered in the paper. It is showed that ICIC stores the information about combustion process that can estimated online and can be used in the future as feedback in ICE control systems for power and emission control. The main advantage of ICIC use in control is in substitution of expensive cylinder pressure sensors and lambda sensors for relatively cheap probe electrodes integrated into spark plugs.

Acknowledgment

This work was partially financially supported by Russian Foundation for Basic Research (RFBR) (Project № 16-38-00025 "New methods of the analysis of ion currents as a tool for research and optimize of the operation of the internal combustion engine"), Government of Russian Federation (Grant 074-U01) and the Ministry of Education and Science of Russian Federation (Project 14.Z50.31.0031) and Russia's Southern Federal University grant: "Theory and methods of energy-saving control for distributed generation, transportation and electricity consumption systems".

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