EVALUATION OF KNOCK INTENSITY USING WIDE-BAND OPTICAL SIGNAL FROM THE COMBUSTION CHAMBER

Dariusz Piernikarski

Lublin University of Technology
Department of Internal Combustion Engines and Transportation
Poland, 20-618 Lublin, 36 Nadbystrzycka Str.
fax: +81 53 81 258, e-mail: d.piernikarski@pollub.pl

Abstract

The paper evaluates the possibility of detection and evaluation of knock intensity using wide-band optical signal obtained from the combustion chamber of the gasoline engine. Preliminary data analysis confirmed existence of strong, statistically significant correlations between signals of indicated pressure and intensity of optical emission, and it is expected that optical signal can be successfully used for detection of knocking combustion.

As knocking combustion is associated with certain frequencies of successive modes of acoustic vibrations in the combustion chamber, detection of knock and evaluation of its intensity required filtration of optical signal eliminating constant components and high-frequency noise.

Knock intensity was characterized by "peak intensity of optical radiation" – defined as positive value of first derivative obtained for the filtered signal. This parameter gives useful quantitative information regarding the intensity of knocking combustion. Data analysis has shown, that occurrence of knock resulted in rapid changes in peak-to-peak amplitudes of the filtered optical signal. Further evaluation of signal properties allows for more precise description of knocking phenomena and of its intensity.

Keywords: *knock, optical radiation, knock intensity, optical combustion sensor, waveguides*

1. Detection of knock – general remarks

Knock is one of the most frequently investigated and yet not completely understood phenomena accompanying combustion in spark-ignition gasoline engines. Although a huge effort was done to understand knocking combustion, there are still many unexplained problems or explained unequivocally. Self-ignition in the combustion chamber can lead to the engine damage. It is the reason, why engine manufacturers have introduced many countermeasures aimed at elimination of the knocking phenomena, as soon as it appears. Knock is also one of main barriers in improvement of thermal efficiency and unit performance indicators of spark ignition engines, and therefore it should be consistently eliminated. Detection and control of knocking combustion have become essential components of control systems in modern engines. Nowadays all contemporary SI engines are controlled on the border of knock limit in case of full load or higher partial load operation, what allows for reaching maximum fuel efficiency. In this context, precise recognition of knock occurrence and definition of its intensity are of great importance.

Knock detection is based mainly on the analysis of time or frequency representations of the accompanying processes. In the series engines the most commonly used method is based on the application of vibration sensors (accelerometers), which transmit vibration of engine components (cylinder head, engine block) [1, 3]. The most significant weakness of this method is very low signal-to-noise ratio, especially at higher engine speeds, resulting from high background noise level. Therefore, on the basis of frequency analysis of the engine block vibrations and/or acoustic signals only rough estimation of knock intensity is possible. Objective evaluation of knock intensity is possible, but it requires precise separation of knock signal from the primary signal of engine operation using band-pass filtering. It creates the problem of exact separation of knock signal from the primary signal and its frequency properties, according to the engine operating conditions. In consequence, close-loop engine control is either impossible or retarded ignition decreases engine efficiency and power [5].

Knock identification using pressure transducers, also meets a recognition barrier, e.g. in extreme situations pressure sensor cannot record any oscillations, as it can be located directly in the vibration's node. Misinterpretations of the self-ignition phenomena on the basis of the pressure signal arise from the fact, that self-ignition has cyclic variability, even with the same pressures existing in the combustion chamber.

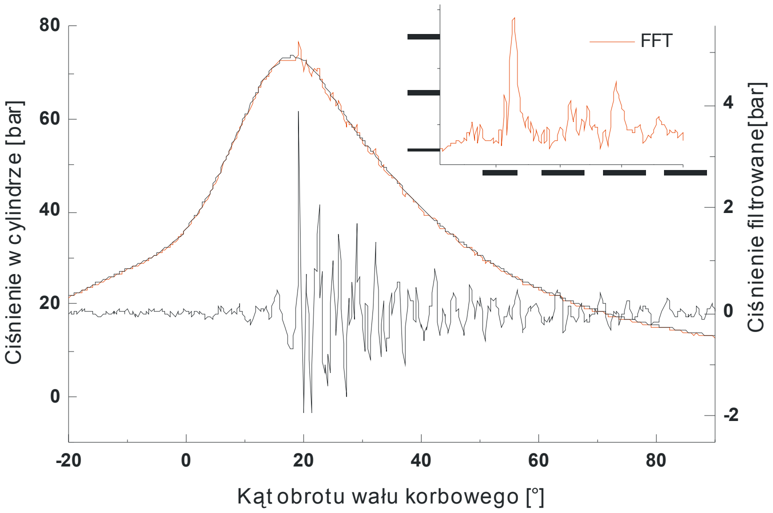

Fig. 1. Example of knocking cycle. In upper right corner – spectrum of the pressure signal filtered with high-pass filter. Highest amplitude corresponds to the frequency of 6.5 kHz (engine run at 3500 rpm, BMEP 1.25 MPa) [10]

Fig. 2 presents knocking combustion cycle – both primary and filtered pressure signal are shown. Below pressure curve a high-pass filtered signal is overlaid, with cut-off frequency of 3 kHz. This signal was later used for the evaluation of knock intensity. Frequency spectrum is shown in upper right corner. It is clearly visible, that pressure signal contains frequencies close to the calculated in [10] knock frequencies.

3. Knock detection using optical methods

In general, knock detection using optical combustion sensor is based on the measurement of intensity of optical radiation during mixture combustion, converting it to the electrical signal, and then analysis by the knock control system. Identification of knocking combustion can be done on the basis of peak values of the radiation intensity, mean value of total optical radiation or changes in radiation intensity during combustion. Knock detection algorithms usually use the fact, that occurrence of knock creates significant changes in the intensity of optical radiation – measured either in certain bands of radiation or as a resultant wide-band signal, and increase of peak values and increasing output voltage of the detector. Application of optical combustion sensors for the knock detection was proposed by many researchers [4, 7]. Optical signals were used to detect start and duration of combustion and then, used as feedback signal in control of injection timing, fueling and EGR level. The authors calculated knock intensity indexes on the basis of optical radiation signal and compared them to the corresponding indexes calculated from the reference pressure signal. Therefore it is expected that optical signal can be successfully used for detection of knocking combustion using similar methods of frequency analysis as it is done in the case of widely used knock-sensors or pressure sensors.

4. Experimental research

The main aim of the presented research was to verify usability of the designed optical combustion sensors and signal processing methods for combustion diagnostics. Described scope of investigation included qualitative and quantitative analysis of combustion on the basis of optical radiation signal, aimed at more comprehensive understanding of unwanted phenomena like knock occurrence. Research should also settle the question, whether it is possible to use the same signal processing procedures which are used in knock detection algorithms based on the pressure analysis in relation to the signal of optical radiation.

Research was done using modified Honda GX390 one-cylinder, air-cooled SI engine. Engine was equipped with fully controllable electronic ignition and fuel injection. Main technical parameters of the modified Honda GX390 engine are presented in table 1. Details of the test stand were presented in [8]

Tab. 1. Modified Honda GX390 test engine – main technical characteristics

Engine displacement	$V_s = 0.390\ dm^3$
Cylinder diameter x piston stroke	D x S = 88 x 64 mm
Compression ratio	$\varepsilon = 8.0$
Maximum power	$N_e = 8.7$ kW (11.8 KM) at 3600 rpm
Maximum torque	$M_o = 26$ Nm at 2500 rpm

Measurement system for the investigation of the combustion process was based on the set of optical combustion sensors recording intensity of optical radiation emitted from the combustion chamber. Sensors were mounted in the different locations of the cylinder head, and varied with the diameter of their optical window. This enabled observation of various regions of the combustion chamber. Indicated pressure was measured using miniature pressure transducer integrated with the spark-plug. The basic combustion sensor mounted in the cylinder head (G4 – fig. 2) has a core diameter of 8 mm and plane mirror surface. Signal-to-noise ratio remained on satisfactory level even with increasing contamination of sensor's tip [8, 9].

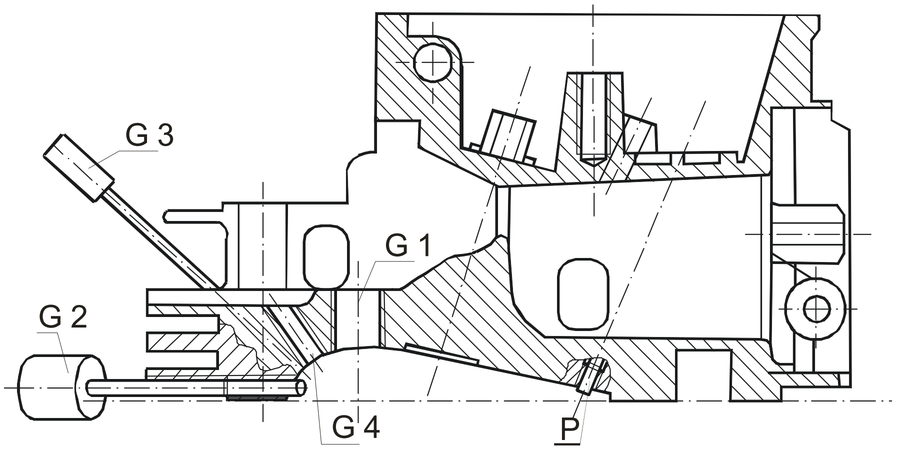

Fig. 2. Cylinder head of the GX390 test engine with marked locations of the combustion sensors: G1 – sensor integrated with the spark-plug, G2, G3, G4 – sensors mounted directly in the cylinder head, P – pressure sensor

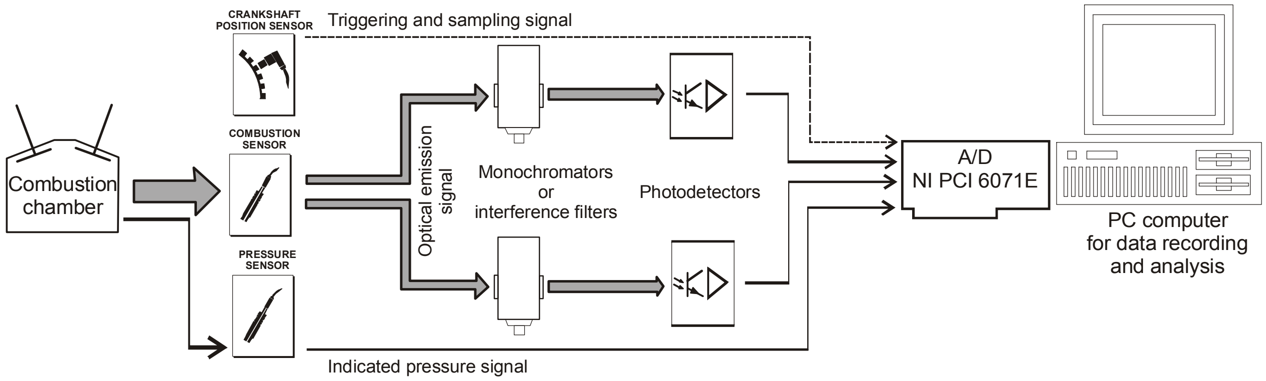

Fig. 3. General scheme of measurement system used for recording optical radiation from the combustion chamber

Optical signal was transmitted using elastic bundle of waveguides to filtering and detecting components. Resultant panchromatic optical radiation was recorded using optical two-channel transducer based on photodiodes (transmission band from 200 to 800 nm, with peak sensitivity at 750 nm), then amplified. Both indicated pressure and optical signal were recorded with resolution of 0.1 °ca. Triggering and sampling signals were supplied by crankshaft position sensor. Signals were digitized using 12-bit, 64-channel a-d converter card with maximum sampling rate 1.25 MS/s. General scheme of optical measurement system is shown on fig. 3.

Research was done for different engine operating conditions: engine speed (*n*): 1600, 2500, 3500 rpm; throttle positions (*ap*): 30, 60, 90%, ignition advance (*kwz*): 25–65 °ca BTDC. Mixture composition was always set to stoichiometric on the basis of readouts from wide-band lambda probe and exhaust gas analyzer.

5. Signal filtration

Analysis of the literature (see [6, 10]) indicates that knocking combustion occurs with certain frequencies generated by consecutive modes of acoustic oscillations in the combustion chamber, excited by high rates of energy release at the self-ignition of the charge. Vibration modes can be both of circumferential and radial type, and their frequencies are located typically within the range of 6-20 kHz. Consecutive vibration modes can be calculated analytically for the typical disc-shaped combustion chambers. Good understanding of acoustic oscillations is highly desirable during measurements and analysis of the knocking combustion, especially with relation to the problem of data filtration and optimum localization of measurement sensors.

Evaluation of knock intensity in the research engine required digital filtration of recorded signals, so as to eliminate constant components and high-frequency noise. In the first stage it was necessary to determine theoretical frequencies of vibrations accompanying knocking combustion in the combustion chamber of the GX390 engine. It was done using the equation describing vibration frequency of acoustic pressure wave in the disc-shaped combustion chamber [2]:

$$f_{m,n} = \frac{C \cdot \rho_{m,n}}{\pi \cdot B} \tag{1}$$

where:
$f_{m,n}$ – vibration frequencies for the modes *m*, *n*, [Hz];
C – speed of sound at knocking conditions, [m/s], $C = 950$ m/s;
$\rho_{m,n}$ – coefficient of vibration modes;
B – cylinder bore, [m], $B = 0.088$ m;
m – mode index of circumferential oscillations;
n – mode index of radial oscillations.

Above equation ignores axial vibrations, as height of the combustion chamber at TDC of the piston is relatively small in comparison to the piston diameter. Table 2 presents calculated frequencies for the consecutive circumferential and radial vibration modes. The most important is the first circumferential mode, according to the considerations presented in [2, 6, 10].

Tab. 2. Frequencies of acoustic oscillations of the pressure wave during knocking combustion in the combustion chamber of the GX390 engine

m – n	1 – 0	2 – 0	0 – 1	3 – 0	1 – 1
$\rho_{m,n}$	1,841	3,054	3,832	4,201	5,332
$f_{m,n}$ [kHz]	6,36	10,56	–	14,44	–

Sampling frequency is a very important parameter, which has to be considered during the research and analysis of knock. In general, the higher sampling frequency, the better. Required minimum is imposed by the Nyquist criterion: it should be at least the doubled value of the analyzed frequency. Of course, introduction of digital filters or FFT algorithms requires application of even higher sampling frequencies. As knocking frequencies for different vibration modes were approximated on the theoretical basis, it was possible to check Nyquist criterion for the sampling frequencies used during experimental research. Comparison of frequencies is presented in table 3.

Tab. 3. Comparison of sampling frequencies used during experiments with theoretical values

Engine speed [rpm]	Sampling frequency [kHz]	Theoretical frequency of pressure wave for the consecutive vibration modes [kHz]	Minimum sampling frequency acc. to Nyquist criterion [kHz]
1600	1600*60 = **96**	1 – 0: 6,36 2 – 0: 10,56 3 – 0: 14,44	1 – 0: 12,72 2 – 0: 21,12 3 – 0: **28,88**
2500	2500*60 = 150		
3500	3500*60 = 210		

It can be seen, that used minimum sampling frequency (96 kHz) is 3.32 times higher than maximum limiting sampling frequency determined for the analyzed vibration modes (28.88 kHz). Therefore, it can be assumed, that recorded signals are free from frequency masking and resonances and high-frequency vibration are not present.

Recorded signals of pressure and intensity of optical radiation were digitally filtered using low-pass and high-pass Chebyshev's filter with infinite impulse response IIR. In such a way high-frequency vibrations (noise) were eliminated and it was possible to separate oscillations of the pressure signal and intensity of optical radiation which were present during knocking combustion.

6. Results

Following figures (fig. 4a, 4b and fig. 5a and 5b) present filtered and averaged courses – correspondingly of indicated pressure and intensity of optical radiation, for the individual engine cycles. Charts show normal combustion (fig. 4a and fig. 5a) and knocking combustion (fig. 4b and 5b) recorded for the same engine speed. Occurrence of knock in case of intensity of optical radiation was associated with high increase in signal amplitude, with signal dynamics of approx. 16.0 dB, whereas for the pressure signal it was only 4.2 dB.

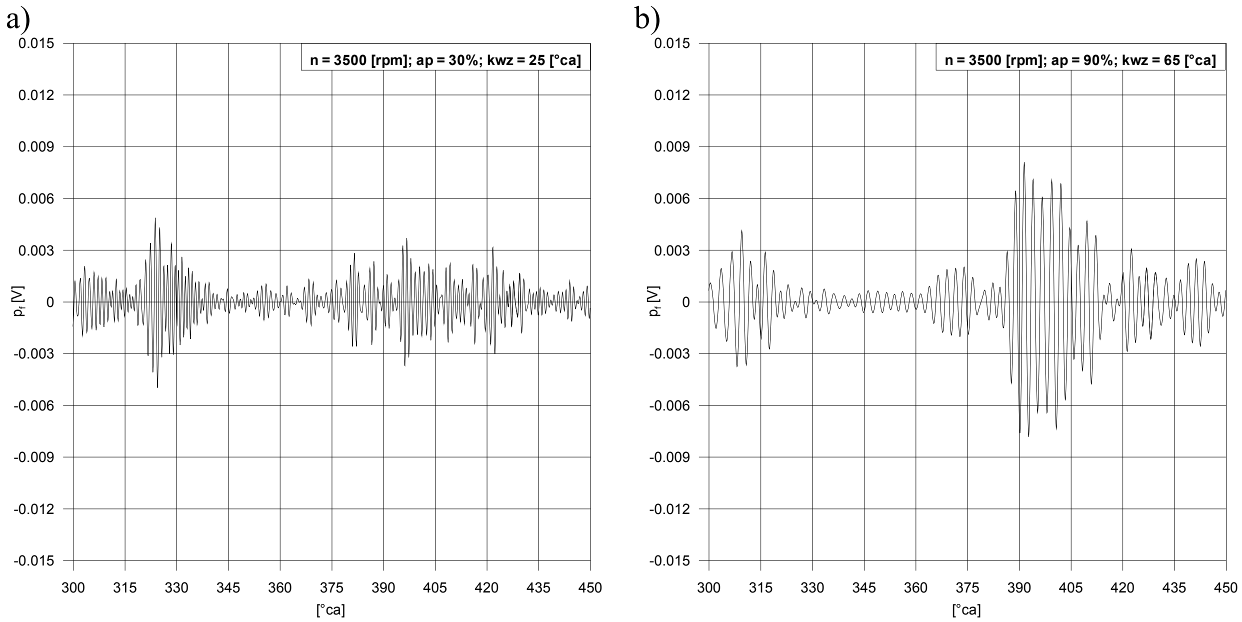

Fig. 5. Filtered courses of indicated pressure for various engine operating conditions – average from 100 consecutive engine cycles: a) normal combustion; b) knock

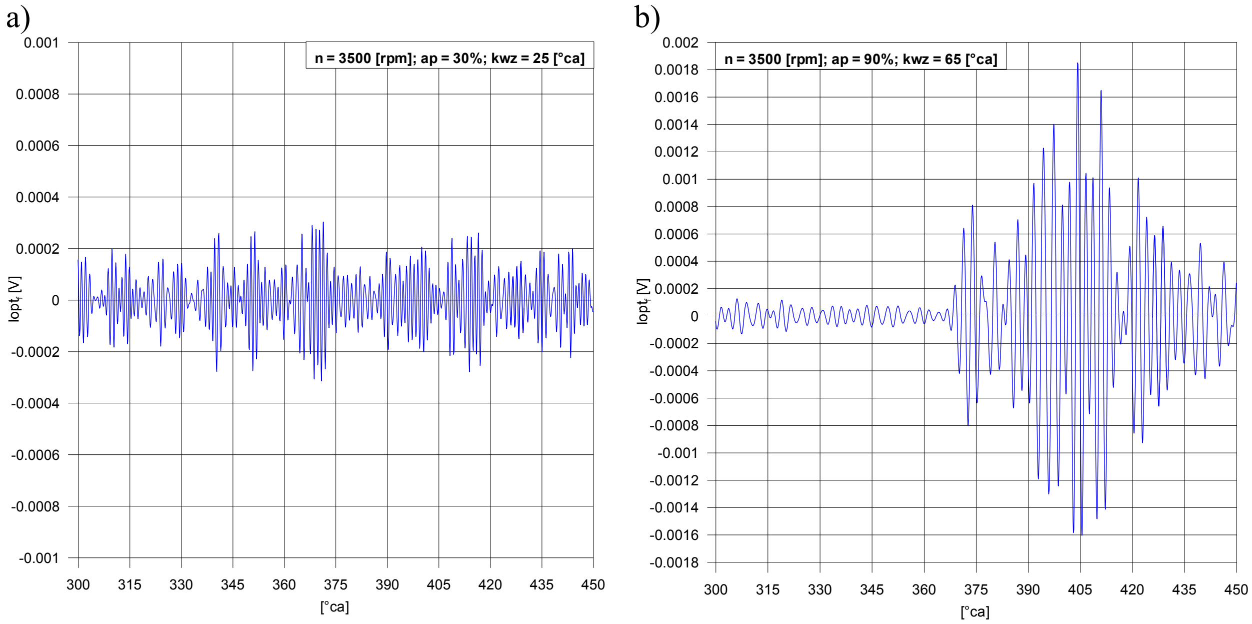

Fig. 6. Filtered courses of intensity of optical radiation for various engine operating conditions – average from 100 consecutive engine cycles: a) normal combustion; b) knock

Knock occurrence is usually characterized by the intensity of the phenomena and the corresponding crankshaft position. The basic metric of the knock intensity is the “peak knock pressure”, defined as maximum positive value of the first derivative calculated for the high-frequency component of the pressure signal. This parameter supplies valuable quantitative information about knock intensity and is connected with piston loads and possible damages. The same evaluation can be done with regard to the signal of intensity of optical radiation.

Fig. 6 presents average speed of pressure growth ration (average from 100 consecutive cycles), and fig. 7 shows average growth ration calculated for the signal of intensity of optical radiation. Again courses for the normal (a) and knocking combustion (b) were compared. Similarity with filtered signals is clearly visible (figs. 4 and 5), however occurrence of knock creates change of maximal amplitudes of the pressure derivative of about 3.1 dB, and in case of optical signal – 10.1 dB. This confirms previous observations about higher dynamics of the intensity of optical radiation and its sensitivity to the knock.

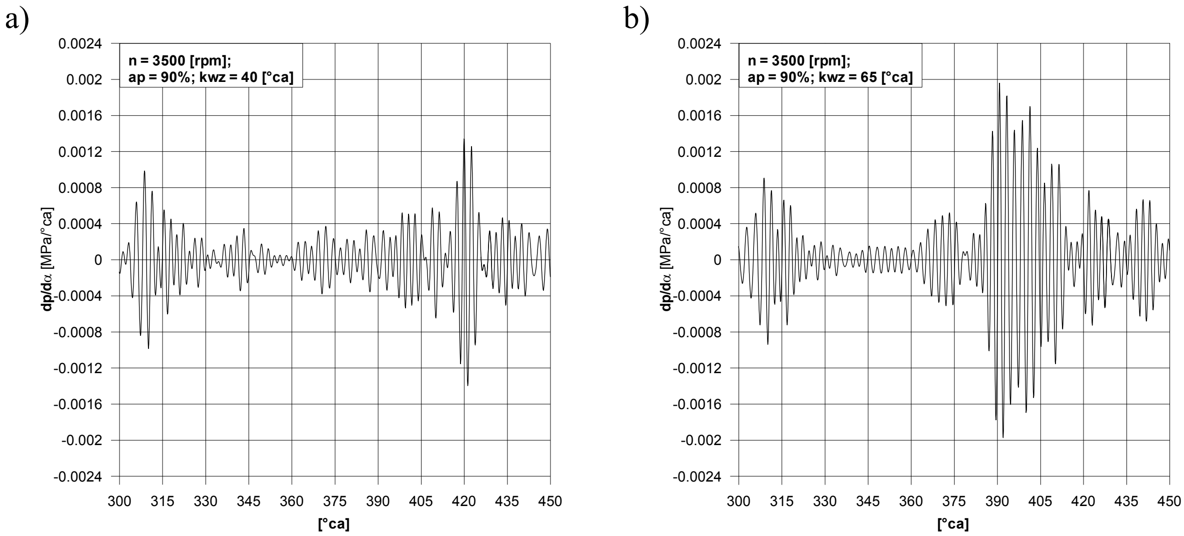

Fig. 6. Average (100 cycles) pressure growth ratio $dp/d\alpha$*:*
a) normal combustion, b) knock

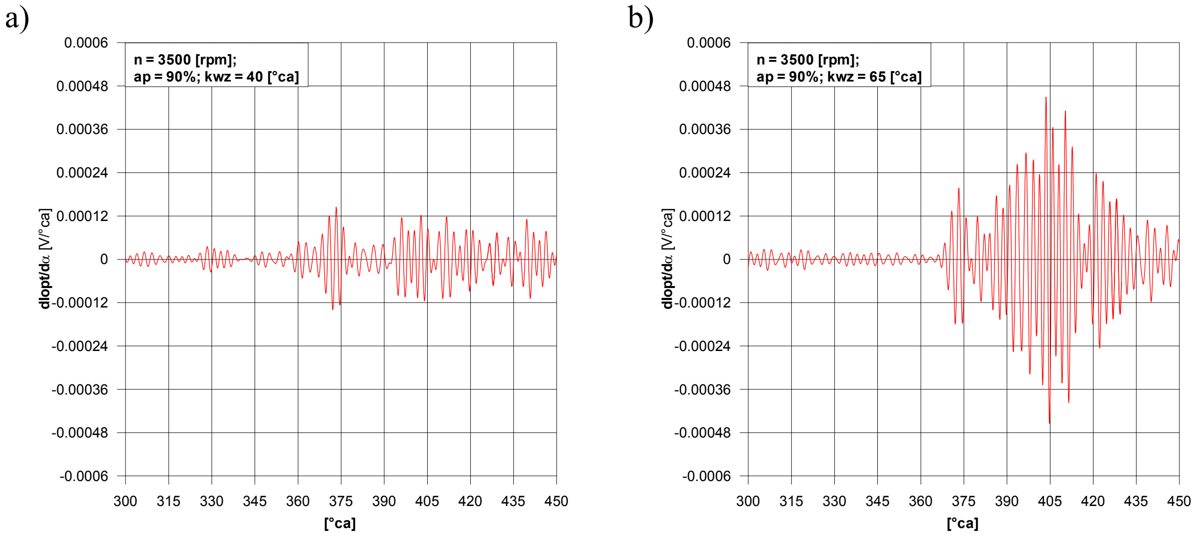

Fig. 7. Average (100 cycles) growth ratio of the intensity of optical emission $dI_{opt}/d\alpha$*:*
a) normal combustion, b) knock

However, proper evaluation of knock intensity using averaged metric described above can lead to some misleading conclusions. This is illustrated on figs. 9 and 10, which show growth ratio of filtered signals $dp/d\alpha$ and $dI_{opt}/d\alpha$ for 10 consecutive engine cycles with knocking combustion. As can be seen, only three of them can be described as heavy knock. Presented data was recorded within the angular window between 330-480 °ca.

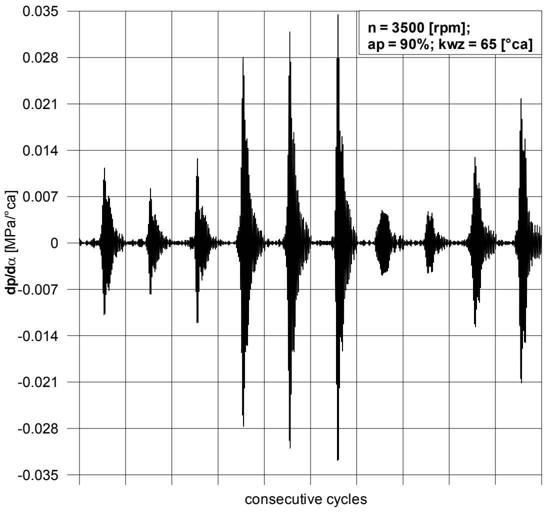

Fig. 9. Pressure changes ratio dp/dα for 10 consecutive cycles

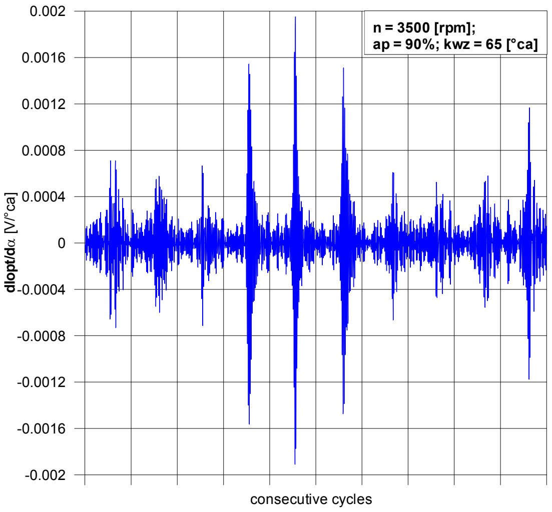

Fig. 10. Optical radiation intensity changes ratio $dI_{opt}/d\alpha$ *for 10 consecutive cycles*

7. Conclusions

1. Confirmed strong correlation between intensity of optical radiation from the combustion chamber and indicated pressure allows for the assumption, that wide-band optical radiation can be reliably used in the further research as a basis for knock detection. It will be also possible to use the same signal processing procedures which are used in knock detection algorithms based on the pressure analysis in relation to the signal of optical radiation.
2. Analysis of the results shows, that resultant wide-band optical radiation is more sensitive to the changing engine operating conditions in a wide-band region and less susceptible to the external interferences. Therefore it can be assumed, that optical knock detection is possible using such simple signal properties like peak values of the radiation intensity, mean value of total optical radiation or changes in radiation intensity during combustion.
3. Considering remarks included in the data analysis, it is necessary to use more qualitative description of knock intensity using so called knock intensity index (KI) defined as maximum peak-to-peak amplitude of the filtered signal [11] – both for the pressure and intensity of optical radiation. It is also possible to use second parameter describing knock intensity, defined as rms (root-mean-square) calculated for the amplitude of filtered in the angular range, where signals were analyzed (i.e. 330-480 °ca). Results of such an approach to evaluation of knock intensity will be presented in the future publications of the author.

8. References

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