# COMBUSTION PRESSURE APPRAISAL IN MARINE DIESEL ENGINE

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***Abstract***

*The practical design of the marine engine multi in-cylinder pressure acquisition system has been presented. The system operational properties and measurement methodology is aimed the online marine diesel engine applications. The design of engine combustion pressure recording system is based on piezoelectric sensors set that comprises quartz pressure element and charge amplifier, mounted on the indicator pipes, equipped with valves. The required crank degree signal is obtained from shaft encoder that is installed on the test bed engine shaft-line (free end of the hydraulic break). The encoder's TDC dedicated reference pulse is able generate simultaneously at the cylinder 1 and 6 in TDC position.*

*The accuracy of the static crankshaft position calibration was evaluated. Additionally, a complex timing system was developed for individual cylinder TDC and crankshaft positioning definition. Before real time data acquisition starts, the number of engine cycles is defined for recording and the first pulse of each crankshaft revolution is used as trigger signal, so that all instantaneous pressure and crank angle signals acquisition can be started at the identical crankshaft position. The method provides required numbers of combustion cycles to be measured for time domain averaging and offline processing.*

***Keywords:*** *marine diesel engine, in-cylinder pressure analysis, combustion pressure measurement*

## 1. Introduction

The reliable calculation of mean indicated pressure and other cylinder performance data requires accurate simultaneous measurement of cylinder pressures and detection of the engine crankshaft position. The cylinder combustion pressure data can be used for evaluating engine indicated mean effective pressure and other properties. Combustion process data has also been used as a secondary means of engine component degradation, such as: cylinder liner, piston rings, injector and valves condition. Engine combustion signatures, coupled with component level and phase-marked vibration can be used to assess the general condition of slow speed engines. Each combustion pressure component exhibits typical distinctive characteristics regarding timing (in crank angle), magnitude, and shape. Degraded component condition will result in altered or missing characteristics elements, which are different from the baseline. The usual way to measure cylinder pressure is to use an indicator pipe with indicator valve for transient measurement. This specific, for large bore diesel engine gas passage, in turn has an influence on the accuracy of the pressure measurement at the location where the sensor is mounted [1, 2]. Basically, the pressure transducer is mounted on the indicator valve for measurement and then moved from one cylinder to another, in order to complete the pressure measurement on all cylinders. Accurate determination of cylinder pressure requires application of transducers with wide measuring range, usually within 0-200 bar and more. Simultaneously, due to the high dynamic pressure changes, they must be characterized by fast response time for output signal. Nowadays, the most common are transducers based on: piezoelectric, optoelectronic or combined strain gauge sensor. There are transducers that generate the response signal solely as a result of dynamic pressure alteration. However, with a constant pressure there is no response signal generated. If cylinder pressure is measured, then only variation of pressure will be determined, but not its absolute value. To obtain absolute value of cylinder pressure there is essential to match the actual pressure signal with a known absolute pressure value [3, 4].There is a scavenging phase characterized by the lowest variation of pressure, during the work cycle of a reciprocating internal combustion engine. The mean static scavenging pressure is usually measured and it can be used for an absolute cylinder pressure determination. A multitude of commercial equipment and software packages is available to facilitate the cylinder combustion pressure data.

In principle, is to measure the individual, single in-cylinder pressure which can be used in almost all marine engine types. There are also available extended measurement systems, where number of the pressure sensors corresponds to the number of engine cylinders [5]. Such systems are very expensive and the results of measurements still questionable. An attempt is made to design and manufacture a high performance cylinder pressure measurement system. Essential system functional assumption is formed, that would be briefly expressed as the ability to measure simultaneously all engine cylinders pressure. The experimental in-cylinder measurement pressure system, for marine diesel engine was designed and manufactured. Subsequently, paper describes the application of an engine combustion analysis tool for diagnostic purpose.

## 2. In-cylinder pressure measurement conditions

### 2.1. The engine crankshaft speed evaluation

The incremental encoders have an advantage in application in diesel engine systems as rotational speed measurement methods. The modern marine engines manufacturers take of them as a crankshaft angle position transmitter for electronically controlled engines and there are a number of a measurement instruments utilizing signals from incremental encoders [1, 2, 5]. However, an accuracy problem of an angle measurement precision arose consequently and no calibration certificate provided by encoder manufacturers could be expected. The precision class of the instrument is not expressed, either. During the experiment planning phase a suitable angle measurement standard had to be selected. The encoder used subsequently in designed system is characterized by 1024 pulses per revolution. The most adequate standard should be considered as a high precision at a very small nominal value of the angle. Acquiring of such a standard of the encoder might be as difficult as costly. Finally, it was decided to utilize a direct measurement and a statistical procedure to evaluate the measurement uncertainty. The incremental encoders, manufactured in TTL standard, generate voltage pulses of 0 and 5.0VDC, alternatively. Those two voltage levels refer to the logic states of 0 and 1 respectively. When the signal, measured at the output of the encoder, is presented on the diagram it forms a square waveform pattern. In the presented experiment the time between the consecutive rising edges of the square waveform was adopted as a period $T_i$ which reflects the angle $\alpha_i$.

### 2.2. The cylinder pressure assessment

To obtain absolute value of pressure there is essential to match obtained cylinder pressure signal with a signal of a known absolute value [6]. In the entire work cycle of internal combustion piston engine, there is a scavenging phase characterized by the lowest variation of pressure. As the mean static scavenging pressure is usually known, it can be used as a base value for a cylinder pressure determination. In such a case the scavenging pressure value is assign to certain value of cylinder pressure value. In four stroke engines, the scavenging phase takes a period of 400-450 degrees of crankshaft revolution. An example of a cylinder pressure signal that enclosing the scavenging process is presented in Fig. 1.From the diagram substantial variation of pressure range, reaching 8-10 bar can be observed. Additionally, the signal is distorted with high frequency noise which may have meaningful effect. However, the disturbance decreases with rising of the cylinder pressure.

The target of the following analysis is a qualitative specification of a signal variation, in two characteristic scavenging events. There were selected samples of signal measured when piston comes through the bottom dead centre (later called BDC) and just before the inlet valve closing (IVC).

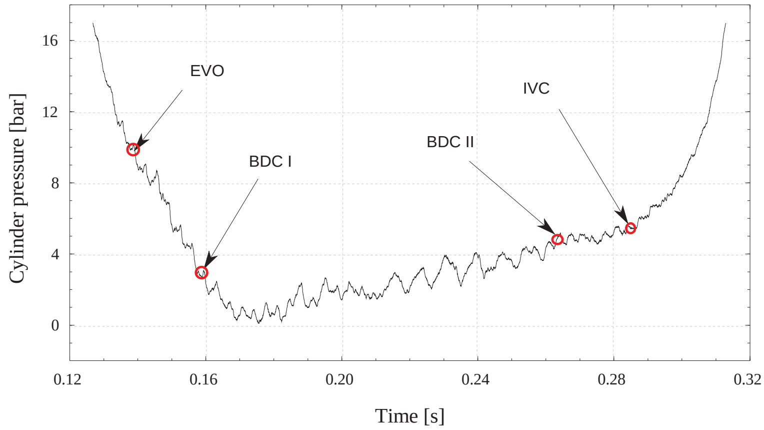


*Fig. 1. Course of cylinder pressure in a scavenging phase EVO – exhaust valve opening, BDC I – bottom dead centre after expansion stroke, BDC II - bottom dead centre before compression stroke, IVC – inlet valve closing*

The pressure transducer's signal analysis was conducted in voltage to avoid additional, unnecessary inaccuracies and digitalization of the pressure signal was done with a sampling rate of 48 kHz. The representative samples number achieved by means of extraction the independent data sets, incorporating 10° of crankshaft revolution phase. The engine scavenge phase is controlled according to crankshaft position given in Tab. 1.

*Tab. 1. Inlet and exhaust valves timing*

| Valve | opening | closing |
|---|---|---|
| Inlet | 50° before TDC | 26° after BDC II |
| Exhaust | 53° before BDC I | 44°after TDC |

Because there was no basis to use the statistic tests based on the normality assumption, the following parameters were chosen to describe the statistical properties of the sets: arithmetic mean value, variance and standard deviation. Comparing the values from the statistical analysis it can be found that the data sets extracted before IVC have higher means and medians, then those from BDC phase. Such performance is compatible with the cylinder refilling phenomenon. In Tab. 2 some statistical values, recalculated into the pressure units presented. Their analysis leads to conclusion that means value of the pressure before IVC is 63-64 kPa higher, than in BDC region.

*Tab. 2. Mean values of the selected scavenge pressures phase*

| | $\bar{x}$ | Median | Range | $\sigma$ |
|---|---|---|---|---|
| BDC region | 0.49150 | 0.49137 | 0.00751 | 0.00224 |
| before IVC | 0.49931 | 0.49934 | 0.00689 | 0.00201 |
| difference [V] | 0.00781 | 0.00796 | 0.00062 | 0.00023 |
| difference [kPa] | 63.35 | 64.62 | 5.07 | 1.90 |

The statistical tests proved, with confidential level of α=0.05, that data samples sets in BDC region and before IVC have different distributions. Analysis of the arithmetic means and medians indicates that the signal level recorded before IVC is about 7.8-7.9 mV higher and when recalculated into pressure unit gives the 63-64 kPa difference. The scattering parameters indicate that the sets recorded in BDC region have lower concentration. Their mean range is 0.62 mV higher which corresponds to the 5.07 kPa pressure. On the basis of the determined statistical analysis results it have been found that error committing risk, when choosing the base size for cylinder pressure, is lower for the IVC region than for BDC.

## 3. The experimental multi-cylinder pressure measurement system description

The experimental engine multi-cylinder pressure measurements system was developed for marine diesel engine – Fig. 2. The essential combustion pressure piezoelectric transducers are installed on the indicator pipes equipped with valves.

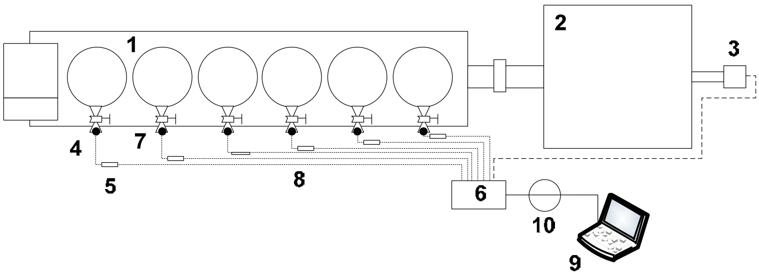


*Fig. 2. The multi-cylinder pressure measurement system layout: 1 –marine diesel engine; 2 – water break; 3 – incremental encoder; 4 – piezoelectric sensors 2200C5; 5 – in-line charge amplifier 4705M5; 6 – NI9233 module; 7 – low noise cable; 8 – BNC signal cable; 9 – PC with measurement application; 10 – USB connection*

The piezoelectric transducer system which typically comprises the quartz pressure element and charge amplifier was built in a rigid assembly and is shown in Fig. 3. The cylinder pressures are scanned by means of piezoelectric sensors Dytran type 2200C5, connected to an in-line charge amplifiers type 4705M5, IEPE standard output. Specification of cylinder pressure system transducers and charge amplifiers is presented in Tab. 3.

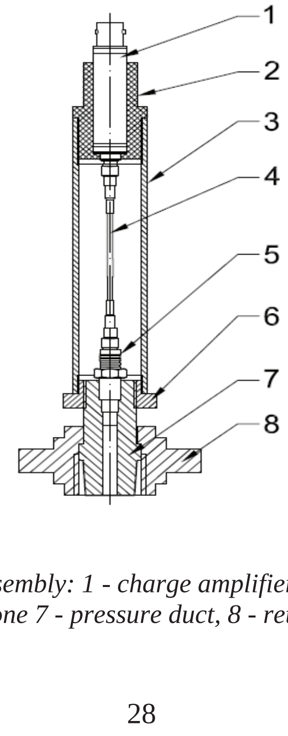


*Fig. 3. Pressure transducer and amplifier assembly: 1 - charge amplifier, 2 - holder, 3 – cooling sleeve, 4 - low-noise cable, 5 - pressure sensor, 6 – base cone 7 - pressure duct, 8 - retaining nut*

The voltage signals of pressure transducers were scaled into pressure unit [bar] according to the formula:

$$p_{bar}(t) = \left[ (V(t) - V_{min}) \cdot \frac{1000}{S} \right] + p_c, \tag{1}$$

where:

$p_{bar}(t)$ - the scaled course of pressure in time domain [bar],
$V(t)$ - the recorded course of voltage signal [V],
$V_{min}$ - minimal value of voltage signal for each cylinder course [V],
$S$ - the final sensitivity [mV/bar],
$p_c$ - engine's charging air pressure [bar].

*Tab. 3. Sensors and amplifiers data*

| Cylinder No: | Amplifier4705M5 | | Sensor2200C5 | | Final sensitivity [mV/bar] |
|---|---|---|---|---|---|
| | S/N | Gain [mV/pC] | S/N | Sensitivity[pC/psi] | |
| 1 | 10433 | 1.05 | 2528 | 1.18 | 17.9702 |
| 2 | 10434 | 1.07 | 2533 | 1.06 | 16.4502 |
| 3 | 10435 | 1.06 | 2529 | 1.12 | 17.2189 |
| 4 | 10436 | 1.06 | 2530 | 1.16 | 17.8338 |
| 5 | 10437 | 1.06 | 2531 | 1.13 | 17.3726 |
| 6 | 10438 | 1.06 | 2532 | 1.10 | 16.9114 |

The required crank degree signal is obtained from shaft encoder providing a resolution of 0.1 that is installed on the test bed engine shaft-line (free end of the hydraulic break). The encoder's TDC dedicated reference pulse is able generate simultaneously at the cylinder 1 and 6 in TDC position. To ensure the encoder index pulse was properly aligned with engine crankshaft and piston position, supplementary settings and checks were done statically, according to the factory mark and manufacturer recommendation. Additionally, the static crosscheck of the TDC position was done. The accuracy of the static calibration was evaluated as 0.2 deg of the crankshaft revolution. The crucial system signals: from the six pressure sensors and encoder are recorded simultaneously by means of fast digital acquisition system. The system allows a several engine cycles to be measured with satisfactory precision and fine resolution. To develop relatively low cost PC-based data acquisition and analysis system, commercial NIcDAQ-9172 board with the LabVIEW software was employed – Fig. 4.

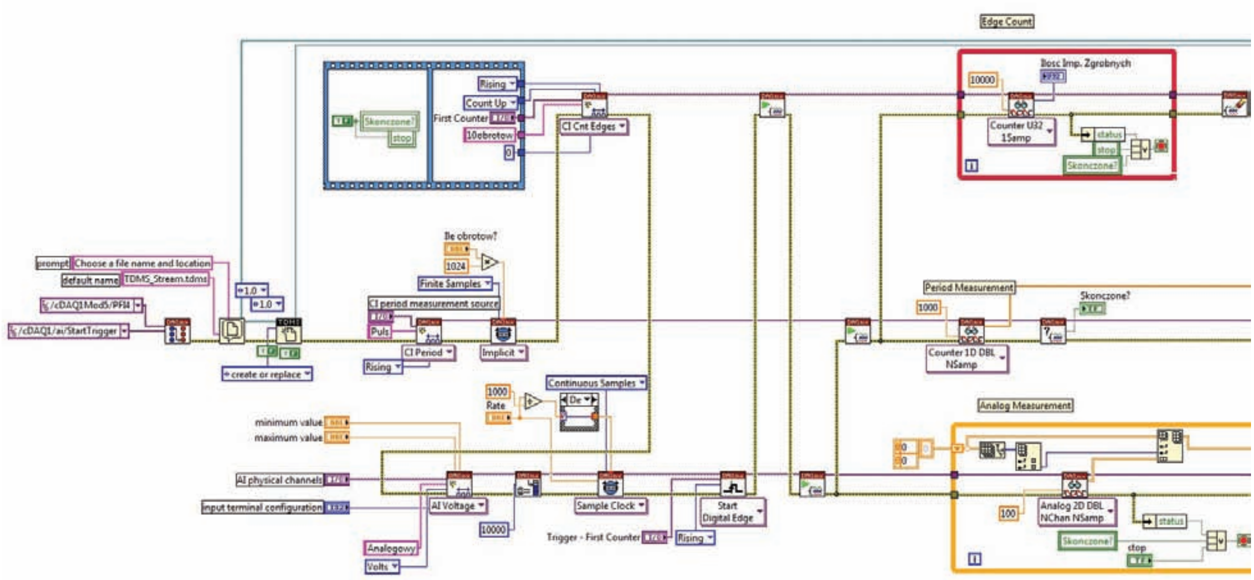


*Fig. 4. The acquisition application (Lab-View) outline*

The general measurement circuit is shown in Fig. 5. The maximum engine crankshaft rotational speed is 750 rpm (approx. 78.54 rad/s) and when the encoder with 1024 pulses per revolution used it can produce a maximum frequency of 12.8 kHz. To eliminate The potential noise was removed by means of passive low-pass filter that is characterized by first-order cut-off frequency - approximately 16.0kHz and Schmitt's trigger. In the measurement circuit a Schmitt trigger was engaged as a filtering element. The Schmitt trigger is a semiconductor comparator circuit which generates logical 0 or 1, dependent on the input signal value. The applied Schmitt trigger has a very short latency - 20ns. The shortest recorded period Ti was 200 µs, which is 10000 times longer than the trigger latency. Assuming that the latency is constant, it has no significant influence on the results of experiment.

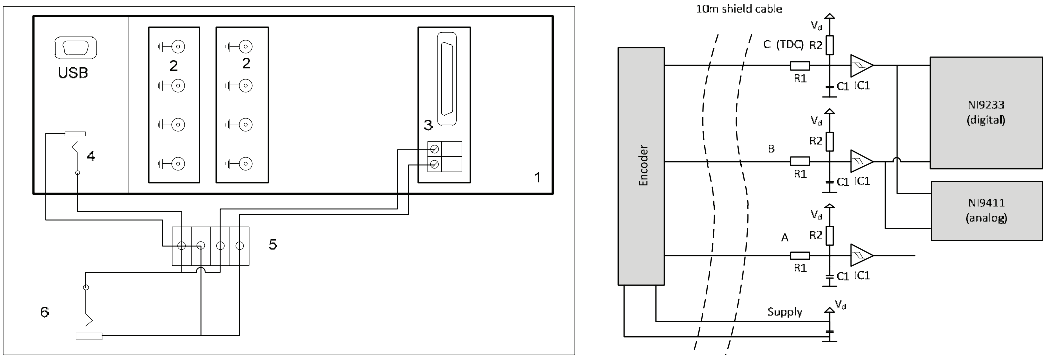


*Fig. 5. The acquisition board (left) and low-pass filter and Schmitt trigger structure (right): 1 - acquisition module NIcDAQ-9172, 2 – analog module NI9233, 3 - digital frequency measurement module with rotary pulse transducer NI9411; 4 - power supply housings, 5 - power distribution terminals; 6 - power connector*

Acquisition application was created in order to read and form fast data record file. The main purpose of the recording application is real-time operation with NI9411 acquisition card, thus incoming data stream is delivered and modified before the storing. The functional diagram is presented in Fig. 6.

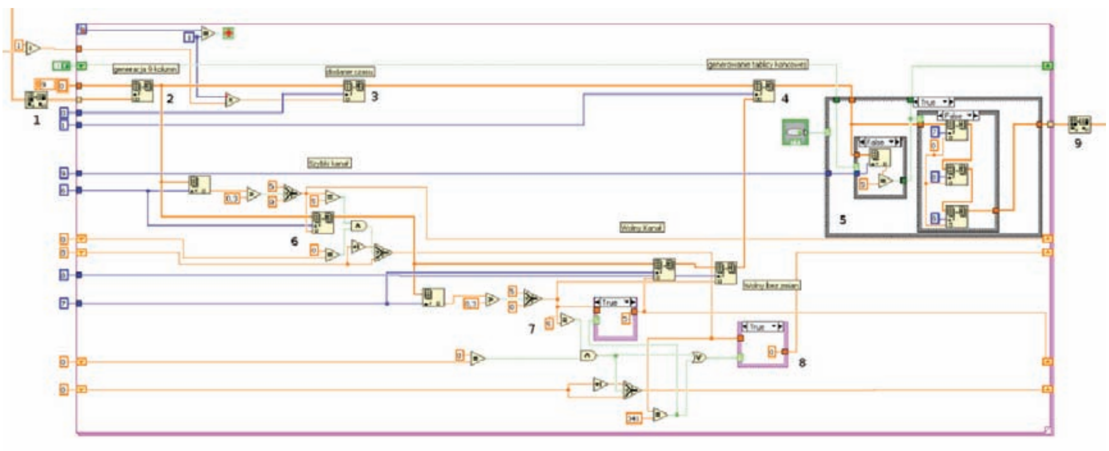


*Fig. 6. The acquisition application functional layout*

All incoming pressure signals data array which represent the six cylinder sensors set is read through the NI9411 card operation and marked with orange colour. Effectively, it forms the first six columns of pressure data array, the two following channels contain the quantitative encoder's signals. The encoder's transmitter delivers the data using two form signals: one labelled as "Fast" delivers 1024 pulses per one revolution, while the second labelled as "Index" directs TDC index - one pulse per one revolution. The first step of the formatting data task is array pre-processing where the matrix is interpolated. Successfully, program creates a new modified results matrix which will be passed for further operations and is marked as 1 and 2 position in Fig. 6. The next important task of the formatting procedure is timestamps generations which are placed in the first column of the time matrix. In simplified method, the timestamp is generated by multiplying a specific sample number and adequate sampling period – marked 3. Fragments of the diagram marked as 6 and 7 are designated procedures for changing the transport voltage levels in 0-5V range. The general rule of a conversion is assigning each voltage level value higher than 0.3V to 5Vand each voltage level below 0.3V is changed to 0V.The processed data matrix value is used to generate additional pulses in the column “TDC index”. The supplementary pulses are added when the engine shaft rotates by 120 degrees and encoder generates 341 pulses. As a final result, two additional pulses are added to an indexing column. This function is achieved by means of diagram section marked8. There is also the filtration function of recorded data, which cuts down pulses that might arise before the first index pulse will be generated and is marked 5.Lastly, the third task is matrix modification at each step loop, through indexing input that is reserved as one data frame. The application rewrites the measured six analog channels matrix with timestamp, while digital signal will be additionally used and formed. The explicit form of data array is presented in Fig. 7.

| | | | | |
|---|---|---|---|---|
| Time | Analog measurement (8 channels) | Channel Fast | Channel Slow (resampled) | Channel Slow (true) |

*Fig. 7. The single frame of data array*

The acquisition card is equipped with low capacity input, so delivered signal doesn’t include the constant component and is distorted. An example of acquired signal is shown in Fig. 8.

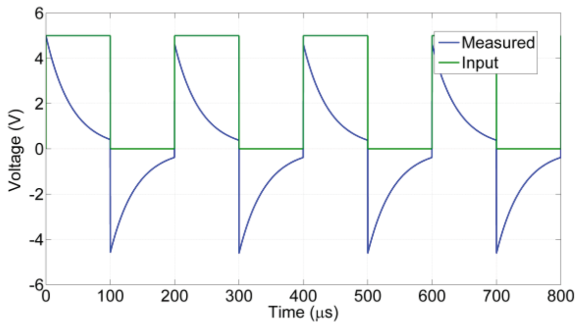


*Fig. 8. The delivered signal forms: input (green) and read by card (blue)*

## 4. Results and conclusions

Recording of engine all-cylinder pressure system development and its qualified evaluation is expected aid for maintenance and operation. A practical design and methodology to process the engine multi in-cylinder pressures and crankshaft angle signals, for combustion diagnosis has been presented. The operation system properties and methodology is aimed the on line applications. The fundamental design of engine all-cylinder pressure system based on sensors set mounted on the indicator pipes, equipped with valves was considered as a standard engine option. Additionally, a complex timing system was developed for individual cylinder TDC and crankshaft positioning definition. Before real time data acquisition starts, the number of engine cycles is defined for recording and the first pulse of each crankshaft revolution is used as trigger signal, so that all instantaneous pressure and crank angle signals acquisition can be started at the identical crankshaft position. The fast encoder signal is used for the instantaneous sampling and the each cylinder TDC, following cylinder 1 and 6 is created, so that in-cylinder pressure evolution measured can be synchronized with the crankshaft angle. These signals are necessary for the angular absolute reference of the pressure of all cylinders. The angular resolution of 0.1 degree is used as remarked. The dynamic pressure data, measured at different engine speed and a recorded example of extracted raw pressure and crank angle signals is presented in Fig. 9. When assembled and averaged data examined it was possible to calculate the key parameters of the each engine individual cylinder. Conventional calculation of IMEP has been done by numerical integration of the measured pressure (filtered) to ensure high accuracy. However, the analysis of selected successive cylinder performance data shows reasonable pressure deviation caused by manufacturer sensors' calibration inadequacy.

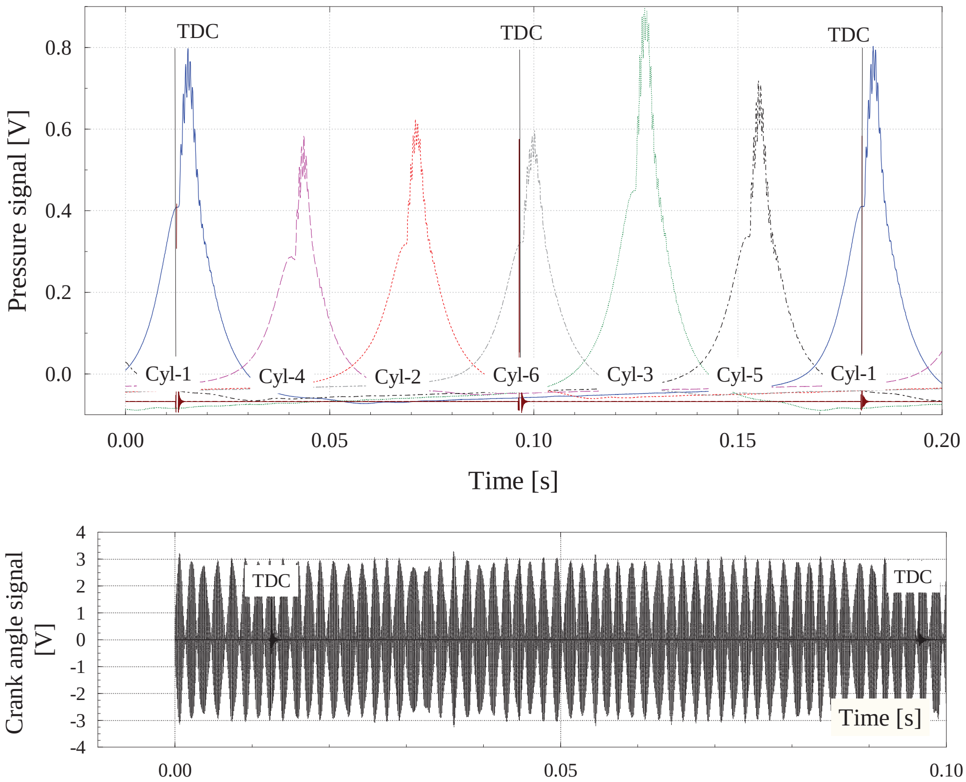


*Fig. 9. The example of raw combustion pressure data set for six engine cylinders*

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