CONCEPTION OF CYLINDER PRESSURE BASED DIESEL INJECTION CONTROL SYSTEM

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Abstract

Control of diesel fuel injection is very important and has influence not only at engine operating conditions but also at emission of toxic gases as NO_x, HC, and Particulate Matter (PM) are effect of combustion process. Directly observing of combustion process is very difficult, but implementation to injection control algorithm procedures based on additional sensors as knock sensor, cylinder pressure sensor and observing of rotational speed course could give enough information to optimize control algorithm. In traditional diffusion-burn diesel combustion start of combustion occurs a cetane-number based time delay after the start of the fuel injection. To fulfill of new emission standards is need to observing not only start of combustion but also whole combustion process. In the paper conception of injection control system applied with combustion process observer based on additional sensors. Closed-loop feedback control of cylinder pressure sensor and advanced control algorithm with high-resolution rotational speed sensor offers the potential to improve controllability of combustion process. Advanced control system based on heat release estimated from cylinder pressure and rotational speed fluctuations enabling improving engine exhaust emissions, engine performance and reduced noise emission. Introducing into control system a low cost glow plug integrated cylinder pressure sensor allow to achieve complete injection control system with advanced functions which could be very effective also in aspect of fuel consumption reduction.

Keywords: *diesel injection, cylinder pressure, control system, emission, heat release*

1. Introduction

Nonroad vehicles become year to year more restrictive regulation about emission level. Fulfilment of very restrictive new emission standards that limited emission of NO_x, HC, CO, and PM is with each next version of EURO Stage/TIER IV and other regulation much difficult [1, 6, 12]. At Diesel engine real problem are emission of NO_x and PM. Modifications introduced to nonroad vehicle engines have to fulfil demanding regime of reliability and also low cost hardware solutions.

Many researchers try to find best method to reduction of exhaust emission. There are two ways to achieve this target: aftertreatment applications and reduction of emission during combustion process optimization. At the future emission regulations both of them is essential. Apart from these aftertretment applications is very expensive and also not service friendly for users. Concentrate with cylinder pressure observation is one of the best solution to achieve information about combustion process, and influence of their course during feedback as analysed signal. There are proposed to observe motored and fired cylinder pressures [7-10, 14] and calculate difference of them. Estimation of heat release from cylinder pressure is also discussed from researchers [2, 8, 15], and there are proposed modified/ new control system using sensor based control of injection system [3, 5, 7, 9, 13]. Application of new low cost additional sensor especially cylinder pressure sensors is presented also at publications [8, 13, 17].

Measuring and analysing of cylinder pressure are very important because of many factors that has influence of their course. Diesel combustion process is so influenced by:
- Injected fuel quantity, injection timing and phase distribution.

- Fuel properties (quality and droplet size)
- Charge air pressure, temperature and humidity.
- Exhaust Gas Recirculation rate, etc.

Example of influence of fuel quantity distribution at cylinder pressure course and EGR control is presented at Fig. 1, 2.

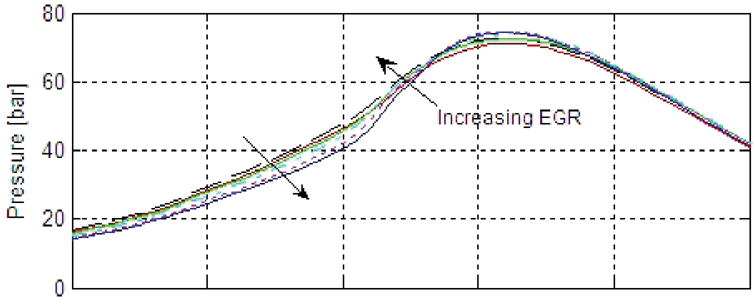

Fig. 1. Influence of EGR control at course of cylinder pressure [4]

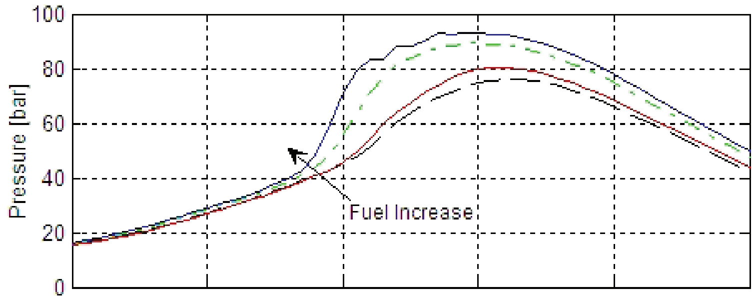

Fig. 2. Influence of fuel injection system control at course of cylinder pressure [4]

Differences of pressure course with pilot and without pilot injection gives effect at engine performance, but mostly at engine emission properties. The influence of exhaust gas recirculation factor at cylinder pressure is also very important (Fig. 1), but change of injected fuel and their distribution (multiphase injection) has much more influence (Fig. 2).

2. Cylinder pressure based injection control system for nonroad vehicles

2.1. Main conception of control system

Standard control of diesel injection focuses on different sensors, which gives information to ECU (Electronic Control Unit) about temperatures, pressures, air mass flow, positioning and displacement of actuators and engine subassemblies also engine rotational speed, etc. Almost all of mentioned parameters described engine operating condition indirectly if we take into account that there are combustion engine. These parameters are taken out of combustion chamber where take place the combustion process. Supervising of combustion process could give more and directly information about engine operating conditions. This is possible with application a cylinder pressure sensor to control system. Monitoring of combustion process in each cylinder were very good idea and there are many reason to make such control system, but that will rise rapidly cost of complete control system. At first step only one pressure sensor could be mounted into engine combustion chamber (at cylinder no. 1) (Fig. 3).

The cylinder pressure signal is converted and evaluated to cylinder heat release at CPAM unit (Combustion Process Analysis Module). Combustion process is not identical at all cylinders. There are many reason that course of combustion process in each cylinder could be different. One of them is connected with injection system and differences of injected fuel quantity to each cylinder. Advanced control system have to made online correction of injected fuel between all injection sections. Balanced injection quantity is very important to reach stable idle speed and also limiting emission of harmful substances and noise. Observing of engine speed fluctuation enable analysis and evaluation of eventually unbalanced injection quantity and calculate their correction value (SFC – Speed Fluctuation Analysis). Standard rotational speed could be replaced with sensor (S- Speed sensor) characterized with better resolution (about 2^o of CA -Crackle Angle).

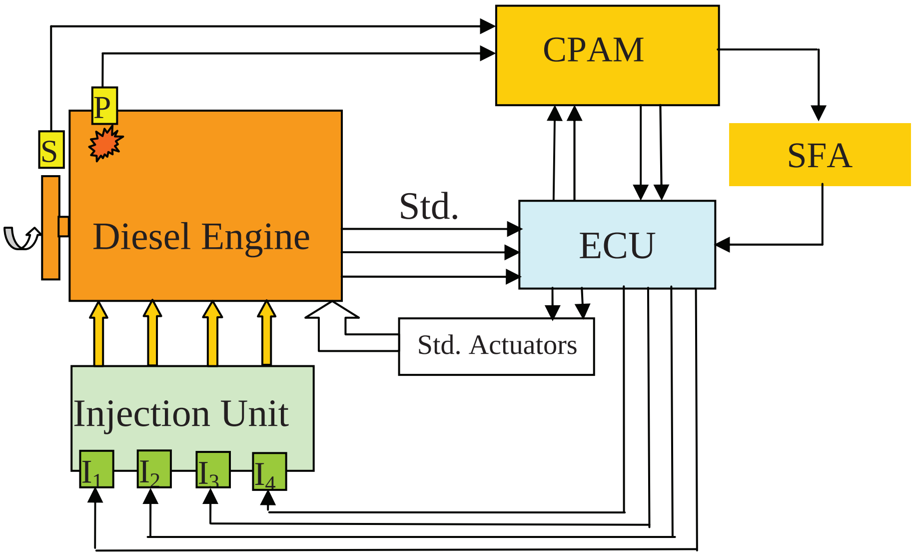

Fig. 3. Conception of Advanced control of injection system with additional analysis modules

2.2. Combustion Process Analysis Module

Proposed advanced control system using cylinder pressure signal is based on heat release estimation (Fig. 5). Calculated heat release rate is compared with target heat release rate coming from ECU control MAP and at CPAM module with regulator is control signal generated to operate in fuel injection system. As effect of injected fuel during pressure sensor is cylinder pressure obtained. At research engine is an AVL pressure sensor (P) installed, but this could be after first experiments, and validation during low cost pressure sensor replaced (Fig. 4)

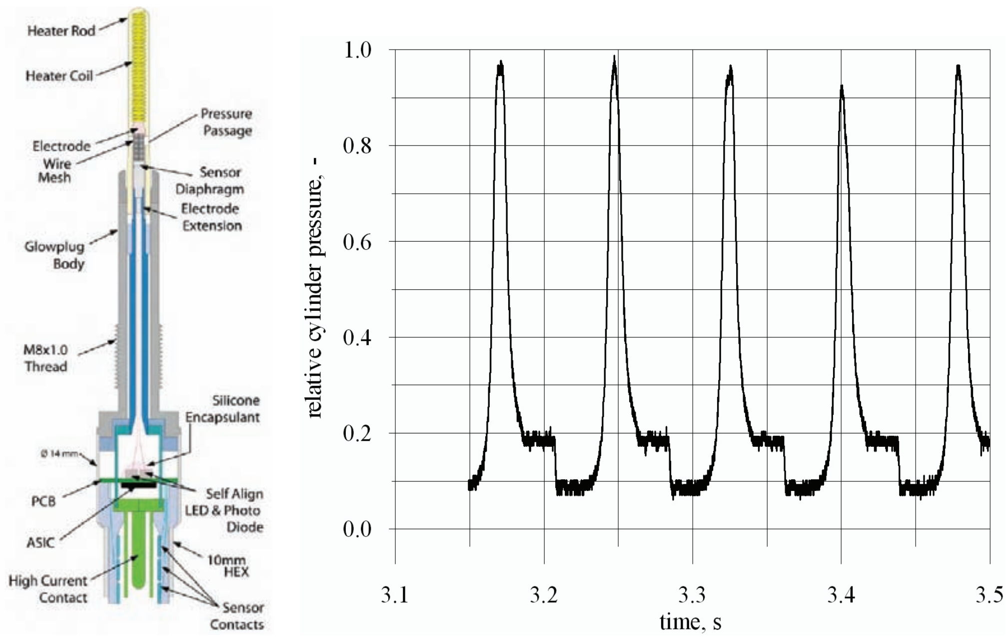

Fig. 4. Cylinder pressure: a) low cost sensor integrated on glow plug [17], b) exemplary pressure course obtained from pressure sensor

At this pressure course are essential calculations of combustion parameters executed. Estimated heat release rate is at closed loop applicated to generate with target heat release rate (HR_{target}) correction signal to control diesel injection.

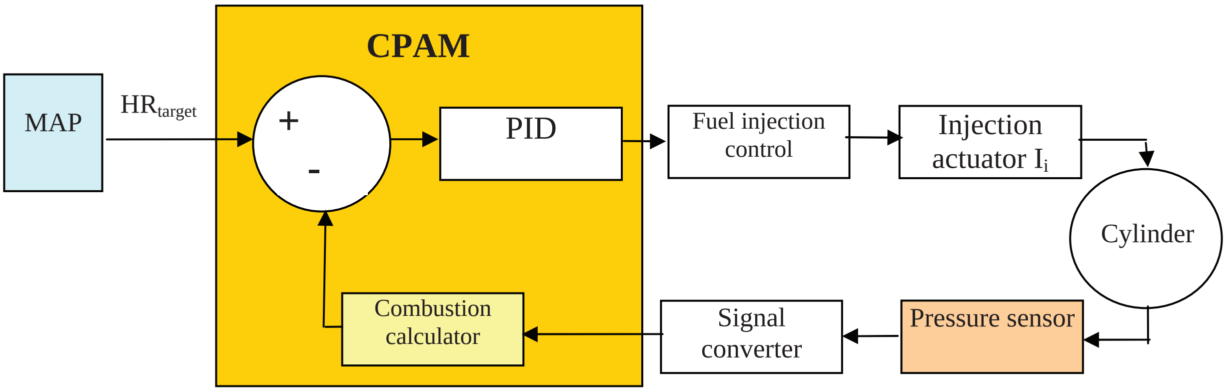

Fig. 5. Schema of injection control with CPAM and cylinder pressure sensor

Combustion process analyzing module include combustion calculator which enable evaluate of heat release rate which is defined as a rate at which the chemical energy of the fuel is realised by combustion process. Heat release rate is used as combustion indication parameter, and is calculated as follow [16]:

$$\frac{dQ_{fuel}}{d\theta} = \left[1 + \frac{\sum_i m_i c_{v_i}}{\sum_i m_i R_i}\right] P_{cyl} \frac{dV_{cyl}}{d\theta} + \left[\frac{\sum_i m_i c_{v_i}}{\sum_i m_i R_i}\right]\left(V_{cyl}\frac{dP_{cyl}}{d\theta}\right) - \frac{dQ_w}{d\theta}, \tag{1}$$

were:

m_i - mass of charge at inlet port, kg,
c_{vi} - constant volume specific heat, kJ/kg·K,
R_i - gas constant, kJ/ kg·K,
P_{cyl} - cylinder pressure, Pa,
V_{cyl} - cylinder volume, m^3,
dQ_w - heat transfer through combustion chamber walls,
θ - crank angle, ^{o} after TDC (Top Dead Center)

Then the cylinder volume dependent of crankle angle (θ) could be calculated with follow equation:

$$V_{cyl} = V_o + \left(l_{cr} - \sqrt{l_{cr}^{\;2} - s^2 \sin\theta} + s - s\cos\theta\right)\frac{\pi}{4}d^2, \tag{2}$$

were:

l_{cr} - connection rod length, m,
s - crank offset, m,
d - cylinder bore, m,

Heat transfer could be calculated with simplified equation [11]

$$\frac{dQ_w}{d\theta} = \frac{\alpha A}{6n}\left(T_{cyl} - T_w\right), \tag{3}$$

were:

α - heat transfer coefficient, $W/m^2 \cdot K$,
A - surface of combustion chamber walls, m^2,
n - engine speed, min^{-1},
T_{cyl} - cylinder gas temperature, K,
T_w - cylinder walls temperature, K.

Heat transfer coefficient as correlation of cylinder volume, pressure and temperature was described and discussed by Hohenberg [16] and is better suited for diesel direct injection engine as other empirical equation:

$$\alpha = 130 V_{cyl}^{-0,06} \cdot P_{cyl}^{0,8} \cdot T_{cyl}^{-0,4} \left(v_{pis} + 1,4 \right)^{0,8}, \tag{4}$$

Additional the average gas temperature could be formulated as:

$$T(i) = \frac{p(i) \cdot V(i)}{\sum_i m_i (i-1) \cdot R_i (i-1)}, \tag{5}$$

were the following pressures, cylinder volumes *V*, charge mass *m*, and gas constants *R* are calculated with step *i*

Presented equation 1-5 are the main steps at combustion calculator included in CPAM module, and enable essential estimation of HR.

2.3. Speed Fluctuations Analysis - SFA

Very high quality of control will enable to application of one pressure sensor to each cylinder. This will make complete control system much more expensive and complicated. Using of rotational speed sensor with higher resolution (Fig. 6b) as standard one (Fig. 6a) enable to observing of engine speed fluctuations with satisfactory quality. The rotational speed fluctuation is formulated as follows:

$$\Delta\omega(CA) = \omega(CA_i) - \omega(CA_{i-1}), \tag{6}$$

were:

ω - engine rotational speed

CA - crank angle

There is a short time fluctuation measured between each cylinder combustion process and there could be formulated relatively as rotational speed fluctuations index F_s:

$$F_s = \frac{\Delta\omega(CA)}{\overline{\omega}} \in \langle 0;1 \rangle \cdot \tag{7}$$

High resolution of additional rotational speed sensor was tested on 129 tooth engine starter rim (Fig. 6b). This solution hasn't TDC marker, but at the test the additional speed sensor was completed standard speed sensor which has TDC marker and 36 – 2 tooth (with resolution 10^o crank shaft turn).

a) b)

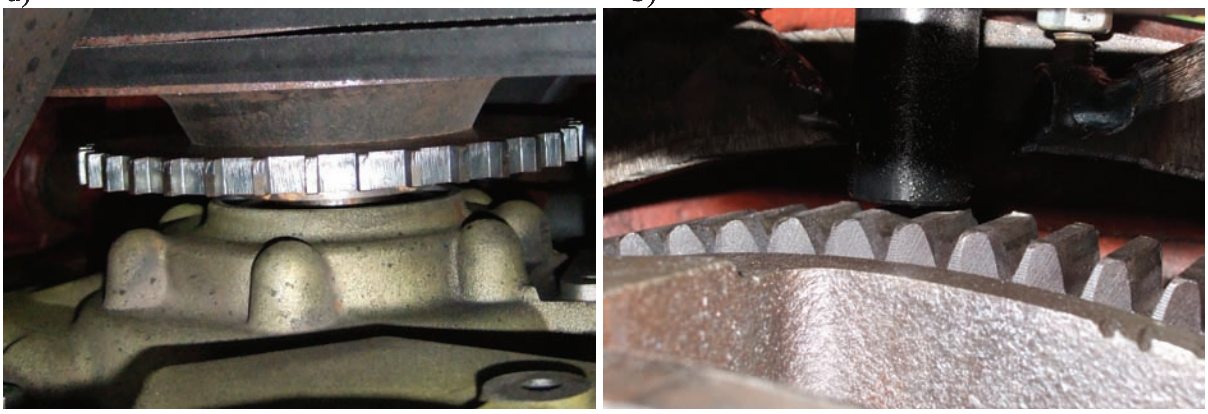

Fig. 6. Engine speed sensors: a) standard-36 tooth, b) high resolution -129 tooth

Using of speed analysis fluctuations enable reduction of cylinder pressure sensors to minimum (1 pressure sensor for 4 cylinder engine), and enable lower cost of complete system but this has also disadvantages. At proposed configuration system has less control accuracy, but at nonroad vehicles improvement of control quality will be satisfactory.

3. Initial research results

3.1. Cylinder pressure

The test engine is an agricultural tractor turbocharged engine with air intercooler and recirculation system EGR. The injection system enable to control of multiphase injection. This engine was mounted on test bench and equipped with many additional sensors During all experiments the cylinder pressure at 4rd cylinder was observed. To indentify of cylinder number the injection pump marker or engine rotational speed sensor with TDC could be applied. At tests the injection pump marker PPM as cylinder identifier was chosen. The follows figures (Fig. 7-9) presents also course of indicated pressure differential dPi/dt.

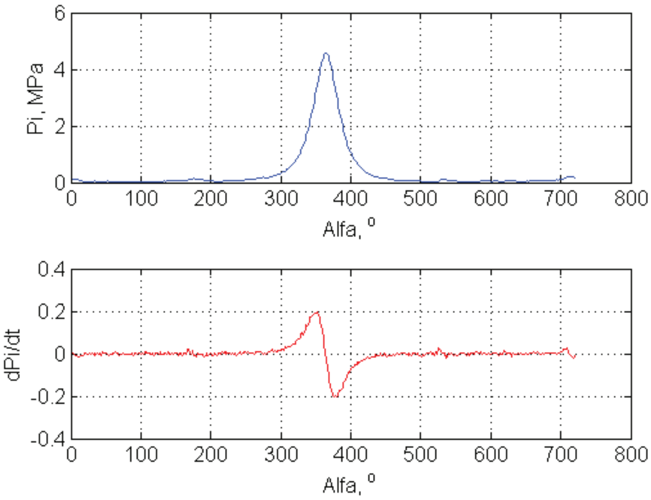

Fig. 7. Cylinder pressure at idle speed with 1-phase injection and malfunction at 4rd cylinder

The PPM (Pump Position Marker) presented at follows graph (Fig. 7–13) is shifted 90° crank shaft turn after TDC. To test the SFA module and module with cylinder pressure sensor at 4rd cylinder was simulated malfunction of injection system. The measured cylinder pressure has regular course but reach only to 4.4 MPa (Fig. 7). Compared this with cylinder pressure at 1-phase injection without any malfunctions (Fig. 8) could be ascertain that the maximum pressure has higher level (5.5 MPa) and their course isn't so smooth.

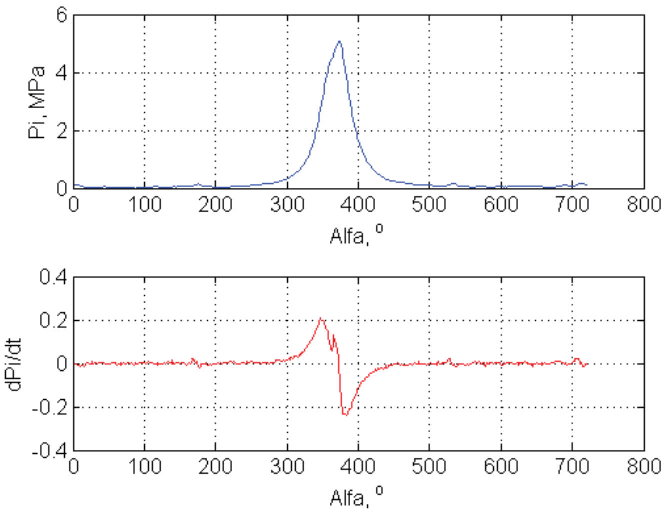

Fig. 8. Cylinder pressure at idle speed with 1- phase injection

Injection of fuel with 2-phases (pilot and main fuel portion) has an effect of smoother pressure course with 5.4 MPa maximum (Fig. 9).

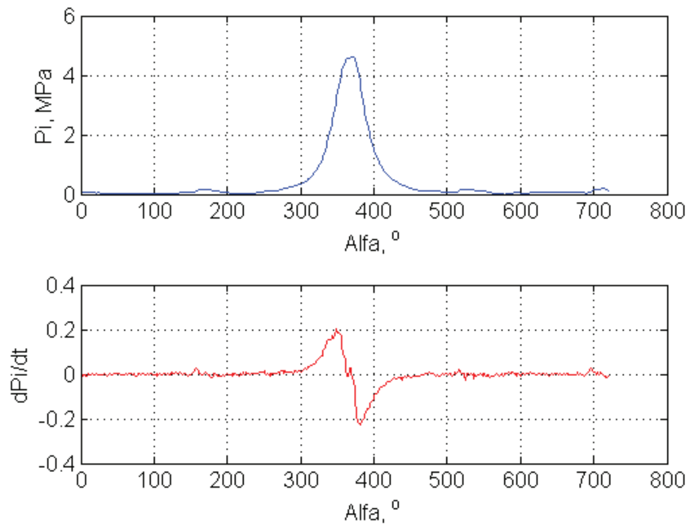

Fig. 9. Pressure at 1st cylinder at idle speed with 2-phase injection (modified)

3.2. Rotational speed fluctuations

Analysis of engine speed fluctuation were made at first in usage of standard speed sensor (Fig. 10). As the graph shows resolution of 10^{o} crank shaft turn is not enough to make discerning speed fluctuations analysis. First additional rotational speed sensor with about 3 times higher resolution gives satisfactory results (Fig. 14a).

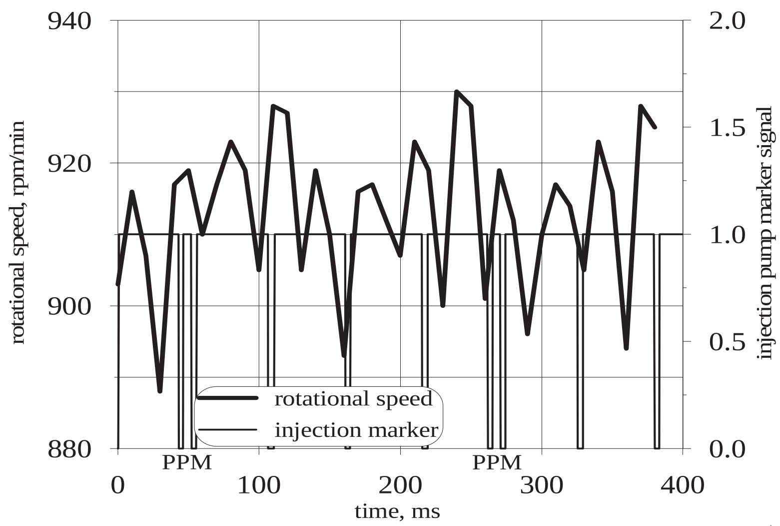

Fig. 10. Rotational speed fluctuation at idle speed with 1-phase injection and malfunction at 1st cylinder from standard rotational speed sensor

Usage of TDC or PPM marker enable to identify of each cylinder and definitely also identification of malfunction of injection system on 4rd cylinder. In this case in remaining cylinders control system try to reach the average engine speed of about 910 rpm/min (Fig. 11a).

To appreciate the quality and accuracy of SFA module comparison between engine speed fluctuations at 1-phase (Fig. 11b) and 2-phase injection (Fig. 12) was made.

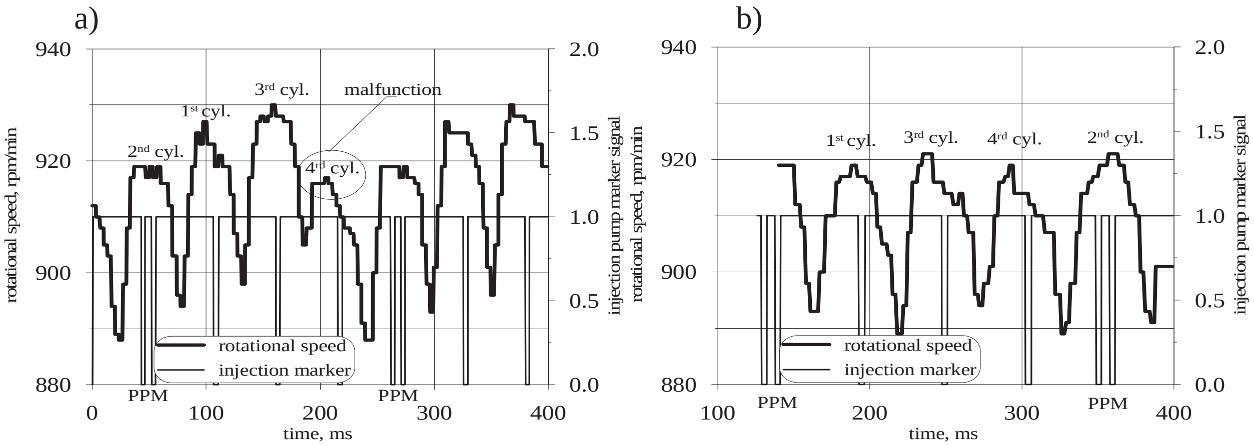

Fig. 11. Rotational speed fluctuation at idle speed with a) 1-phase injection and malfunction at 1st cylinder b) 1 phase and injection correction at 1st and 4rd cylinder

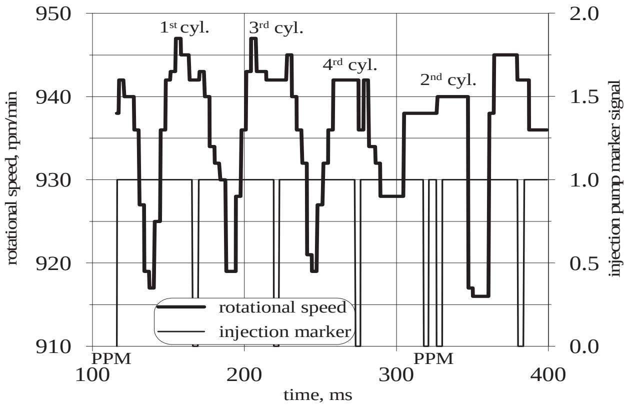

Fig. 12. Rotational speed fluctuation at idle speed with 2-phase injection

As the figures shows also the smoothes cylinder pressure grows at 2-phase injection has implications at course rotational speed fluctuations.

4. Conclusions

Control of diesel injection based on cylinder pressure as feedback signal allows to application additional functions to control algorithm. Analysis of cylinder pressure signal which gives information about combustion process with additional high resolution rotational speed sensor allows to:
- improving of ecological properties (reduces emission of toxic substances and noise)
- improving engine performance and economical properties (as fuel consumptions)
- compensation of injection quantity tolerances
- free detection of injection units malfunction

These advantages is available during introduction to advanced control system new control algorithms which based at additional low cost pressure sensor integrated with glow plug and replacing or of standard rotational speed sensor with their high resolution version. Application of additional high resolution rotational speed sensor should give possibilities to individual injection correction (in each cylinder) and in results also to equalize idling speed and reducing of noise emission.

Acknowledgments

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