ATTEMPT OF INJECTORS FAILURE DETECTION BASED ON MEASUREMENT OF THE ANGULAR SPEED DISCRETE VALUE

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Abstract

The paper presents results of the experiment focused on detection of faulty injector of medium speed diesel engine, in way of analysis of IAS (Instantaneous Angular Speed) of the crankshaft. The experiment was carried out at laboratory stand in Gdynia Maritime University, equipped with diesel engine Sulzer 3AL 25/30 driving electro-generator. Sulzer 3AL 25/30 is three cylinder, medium speed, four stroke marine diesel engine, with maximum output 400 kW at 750 rpm. In order to evaluate of IAS utility for diagnosis of the engine, two kinds of wrong adjustment of fuel injection valve's spring were simulated. First malfunction was too weak spring (initial tension of 15.0 MPa against 25.0 MPa in normal condition), the second was too strong tension of the spring (35.0 MPa). The base of experiment was to angular speed recording, in three different conditions of the engine: healthy one and with two simulated malfunctions. Measurements were carried out at two different loads, respectively 150 kW and 250 kW. The IAS was measured and recorded by the measurement system ETNP-10, which mode of operation was based on perforated disc mounted at the shaft and photo-optic sensor counting laser impulses. Noise decomposition of measurement results was based on triple smoothing using Savitzky-Golay filter. IAS runs of faulty engine were compared with healthy engine measurement, in order to detect all deviation from normal condition.

Keywords: *diagnostics, marine diesel engine, angular speed, photo optical signal, failure simulation*

1. Introduction

Many malfunctions of diesel engines are related to the combustion process. The process can be disturbed because of wrong functioning of elements of injection system (high pressure pumps and injectors). Most common method of getting diagnostic information about combustion is measurement of gas pressure's changes inside combustion chamber. In-cylinder pressure contains many data about the combustion process and enables detection of injectors malfunctions [1]. However, direct measurement of in-cylinder gas pressure is possible for engines equipped with indicator cocks [2]. Disadvantage of that method is due to pressure sensors tend to have limited lifetime caused by exposure at high temperature and pollutants.

Analysis of the crankshaft Instantaneous Angular Speed (IAS) variation as a source of diagnostic information has been already tested for detection of injection pumps [3]. Advantage of this method is non-invasive measurement and relatively easy mounting of measurement elements of the system.

This work is dedicated to validation of IAS discrete measurement as a source of diagnostic information for detection of injection valves return spring's faults.

Valve opening pressure is the pressure value when the needle starts moving upward. It directly depends on the force created by return spring. The second pressure, which value depends on return spring adjustment is valve shutdown pressure. The shutdown pressure is lower than opening pressure because when needle is open, the fluid acts on full surface of the needle front, which is bigger than hydraulic ring surface of the needle, exposed at fluid action when needle is in closed position [4]. Both pressures have impact at minimal volume of fuel dose injected to the cylinder (1).

$$v_s = \frac{V_{pp}}{k}(p_o - p_c), \tag{1}$$

where:
v_s – minimal fuel dose injected to combustion chamber,
V_{pp} – volume of fuel in high pressure pipe,
k – coefficient of compressibility of fuel,
p_o – opening pressure,
p_c – shutdown pressure.

When required amount of fuel for one dose is lower than minimum, what can occur at idle run, the needle is not move up, and engine's uniformity of running is disturbed.

Regulation of opening pressure is carried out by regulation of tension of the return spring. Every deviation from correct value results with changes of crankshaft angle of injector's opening and diminishing of quality of fuel spray formation [5].

Early detection of incorrect action of injection valves enables undertake proper countermeasures and avoid consequences of wrong combustion, such as increase of pollutants in exhaust gases or clogging of sprayer holes.

2. The characteristics of the engine and test rig

The experiment was fully carried out at the test bed in Mechanical Faculty Engine Laboratory.

The main engine was a turbocharged, medium speed diesel engine designed by Sulzer. This 3-cylinder in row engine develops 408 kW at rotational speed of 750 rpm. The engine drives alternate current electro generator GD8-500-50, 500kVA, connected to the main electric board. The load of the engine can be fluently adjusted by changing of the load of generator (adjustable resistor). The high-pressure fuel system has three separate injection pumps, one for each cylinder.

The rig for carrying out the experiment consist of instantaneous angular speed measurement set consisting of perforated disc and optical sensor, Fig. 1, and data processing and storage block ETNP – 10.

The crankshaft angular speed variations were measured at the crankshaft free end. Measurements were carried out at two different loads, i.e. 150, 250 kW.

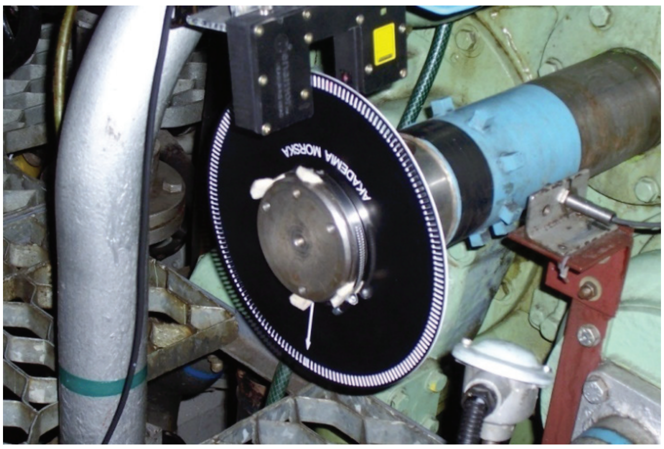

Fig. 1. Perforated disc and laser sensor mounted at crankshaft's free end

3. Diagnostic parameters

The aim of the experiment was to find the answer, whether disturbances of combustion process caused by malfunction in form of incorrect tension of the return spring was reflected by angular speed of the crankshaft. For diagnostic purposes, necessary is to distinguish three basic information: whether detection of malfunction is possible, whether localisation of malfunction is possible and whether evaluation of severity (fault level) of malfunction is possible. Answers for all above questions shall come from one source – analysis of angular speed deviation. For detecting and localisation of malfunctions, three diagnostic parameters were elaborated. First one was designated as a difference between relative angular speed of runs with simulated malfunction and healthy engine. Example of runs of healthy and faulty condition comparison and the curve of coefficient δ_f are presented in Fig. 2.

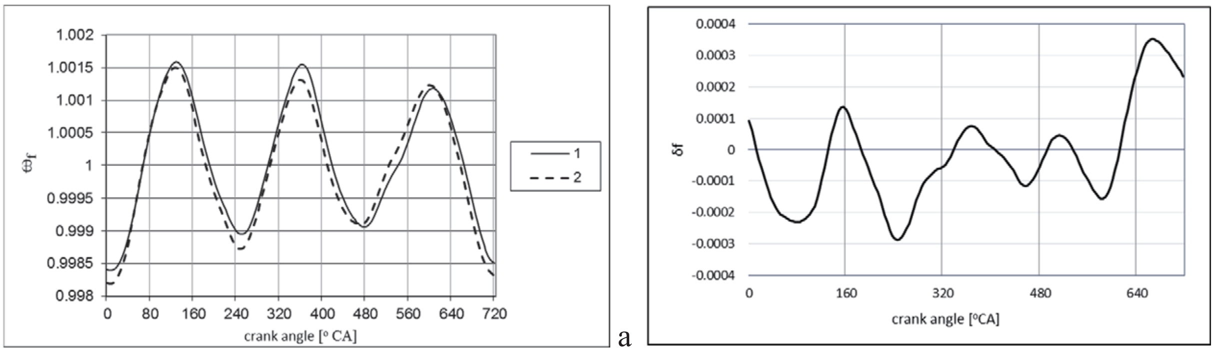

Fig. 2. Runs of relative angular speed of healthy engine (line 1) and faulty (line 2) – a, and related to that failure values of parameter δ_f – b

Second parameter was designated as an area underneath the $\delta_f(\alpha)$ curve, within angular interval starting from TDC (Top Dead Centre) when injection occurs, and with interval width depending on number of cylinders. Method of parameters' designation is presented in Fig. 4. It represents changes of kinetic energy in reference to healthy run. The width of the interval for three-cylinder engine was established at level of 180° of CA, because of broad angular distance between injections (240°).

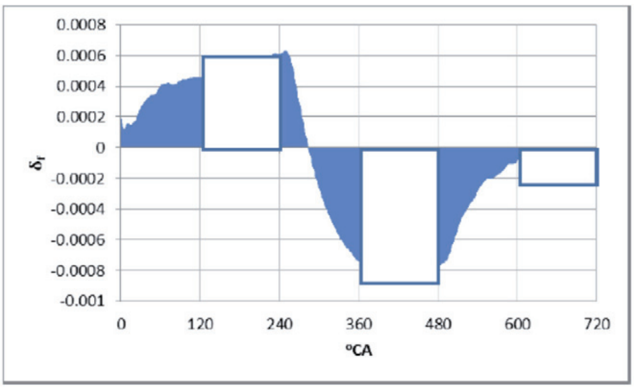

Fig. 3. Determining of the area underneath of δ_f curve in selected angular intervals

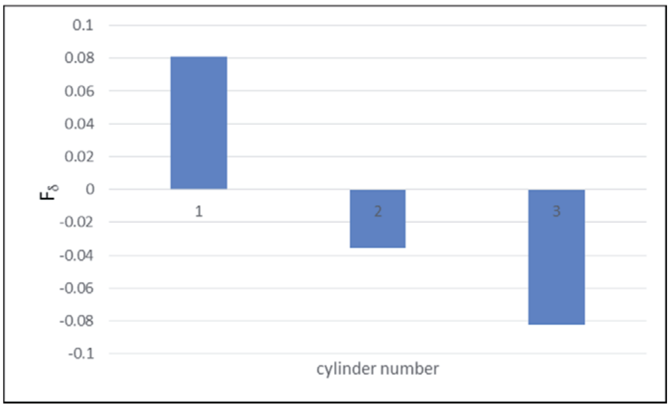

Fig. 4. Example of pattern of diagnostic parameter F_δ for 3-cylinder engine

Third parameter was a difference of δ_f value in the end and the beginning of interval and was signed as $\Delta\delta$. Example of parameter's values for three cylinders is presented in Fig. 5. This parameter describes general tendency of relative angular speed changes in angular interval between TDC's of subsequent working strokes.

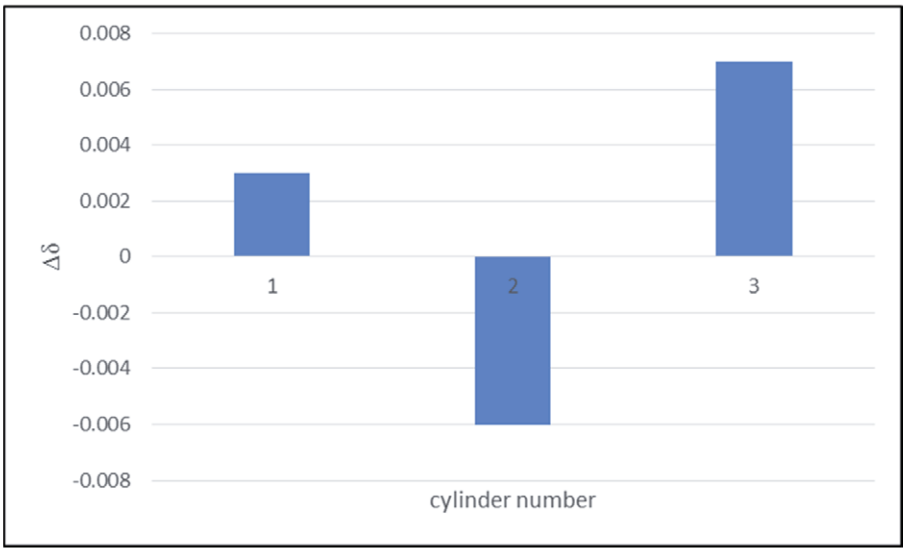

Fig. 5. Example pattern of diagnostic parameter $\Delta\delta$ of 3-cylinder engine

4. Results of experiment.

First simulated malfunction was the incorrect return spring adjustment set at 15.0 MPa instead of required 25.0. Faulty injector was installed in second cylinder. Measurements were carried out at load of 150 kW and subsequently at 250 kW. Every record consisted of 10 revolutions (5 cycles) and was repeated three times for further averaging. Averaged record was smoothed using triple noise decomposition by Savitzky – Golay Filter. After smoothing, the curve was compared with healthy engine run and diagnostic coefficient were calculated. Results of attempt of detection weak spring malfunction are presented below. Comparison of runs of healthy engine and with malfunction are presented in Fig. 6.

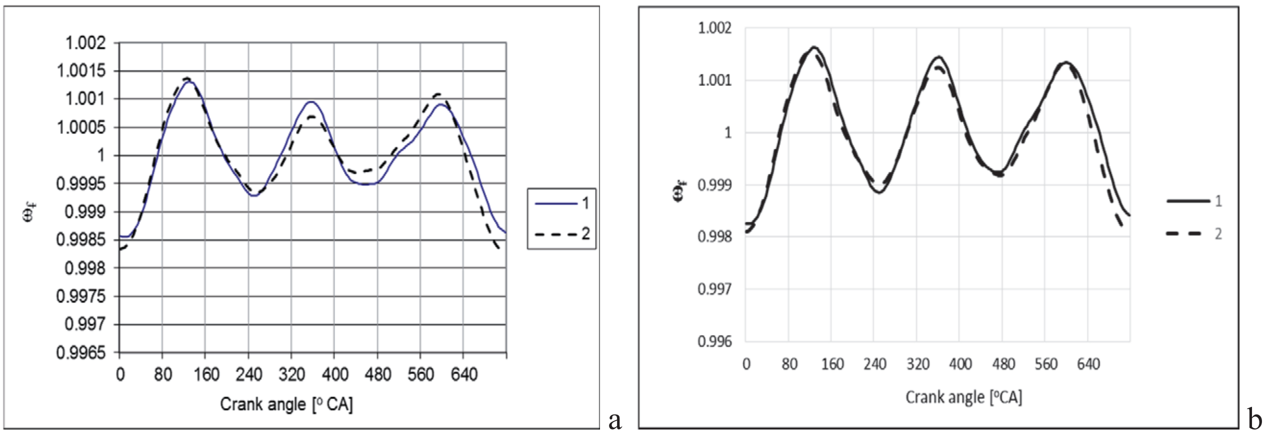

Fig. 6. Angular speed variations of healthy engine (2) and "weak spring" (1): a – load 150 kW; b – load 250 kW

Coefficient δ_f presented in Fig. 7 reflects deviations from healthy run. Maximum value of deviation's span is about 23% of maximum value of healthy engine fluctuation. The picture shows difference between runs, in interval of 320°-600° CA, what indicates influence of load at angular speed disturbance due to malfunction of the injection valve.

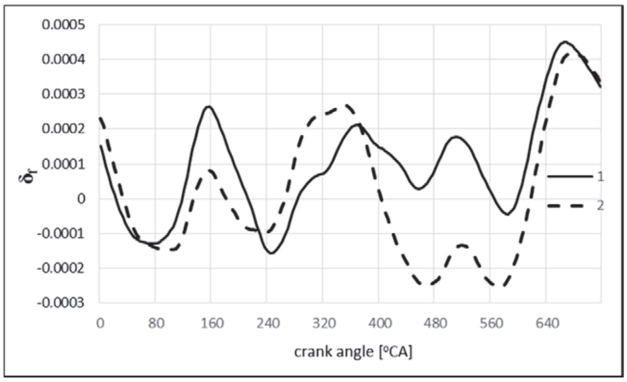

Fig. 7. Values of parameter δ_f "weak spring": 1 – load 250 kW, 2 – load 150 kW

Coefficient Fδ presented in Fig. 8 shows tendency of changes of kinematic energy of rotation. Irregularity of pattern indicates that engine is in state of malfunction. The biggest deviation from normal condition is observed in zone of the 2nd cylinder, at load of 150 kW, and the 3rd cyl. at load of 250 kW.

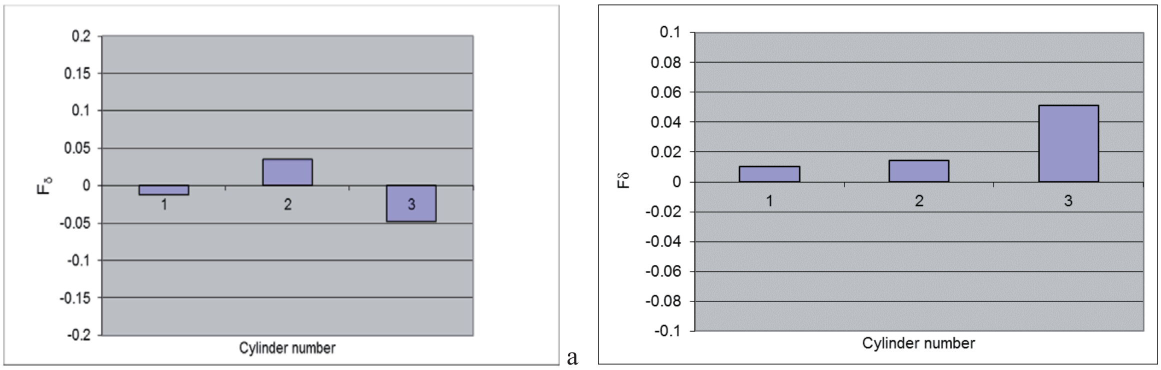

Fig. 8. Pattern of coefficient F_δ "weak spring": a – load 150 kW, b – load 250 kW

Coefficient Δδ presented in Fig. 9. shows general tendency of relative angular speed deviation from normal condition run. This parameter points faulty cylinder in way of comparison of absolute values, where highest value indicates the faulty one.

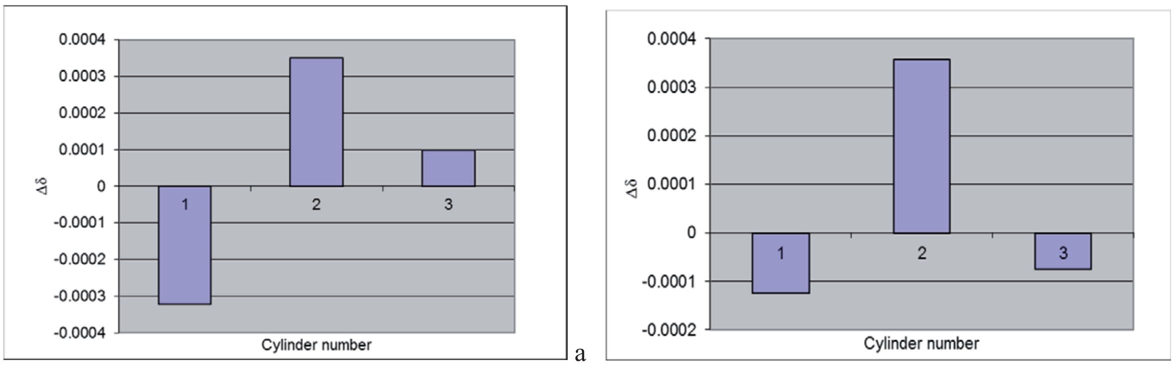

Fig. 9. Pattern of coefficient Δδ" weak spring": a – load 150 kW; b – load 250 kW – b

Second simulated malfunction was the incorrect adjustment of the return spring, increased up to 35.0 MPa instead of required 25.0. Faulty injection valve was installed in the second cylinder. Measurements were carried out at load of 150 kW and subsequently at 250 kW. Every record consisted of 10 revolutions (5 cycles) and was repeated three times for further averaging. Averaged record was smoothed using triple noise decomposition by Savitzky-Golay Filter. After smoothing, the curve was compared with healthy engine runs and diagnostic coefficients were calculated. Results of attempt of detection of the "strong spring" malfunction are presented below. Runs comparison is presented in Fig. 10, coefficient δ_f in Fig. 11, coefficient F_δ in Fig. 12 and coefficient $\Delta\delta$ in Fig. 13.

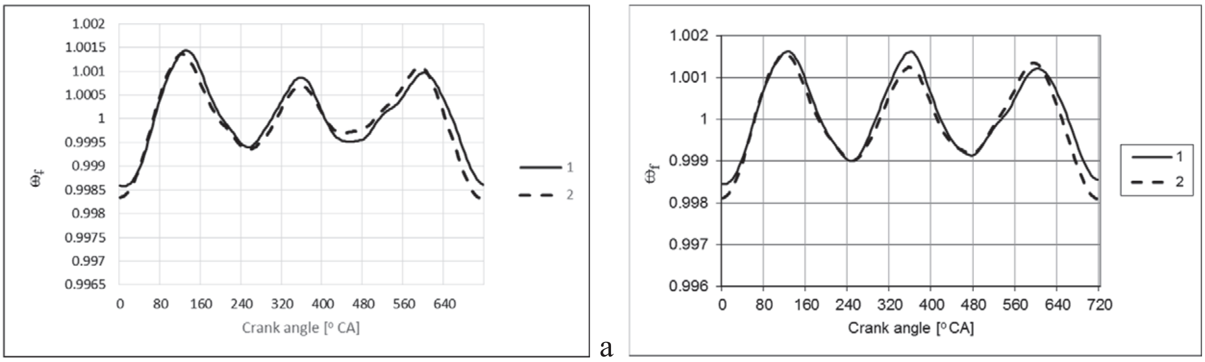

Fig. 10. Angular speed variations of healthy engine (2) and "strong spring" (1): a – load 150 kW; b – load 250 kW

Coefficient δ_f presented in Fig. 11 shows deviations from healthy run. Maximum value of deviation's span is about 33% of maximum value of the healthy engine fluctuation, what is 10% higher than recorded for "weak spring". Picture shows difference between runs in interval of 320-540° CA, what indicates influence of the engine load at value of deviation caused by the injection valve malfunction.

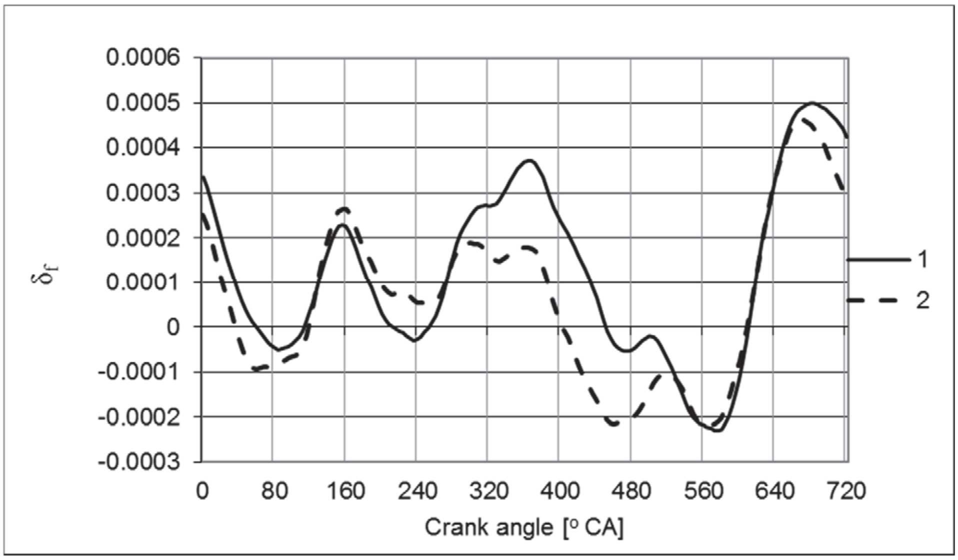

Fig. 11. Values of parameter δ_ω for "strong spring": 1 – load 250 kW, 2 – load 150 kW

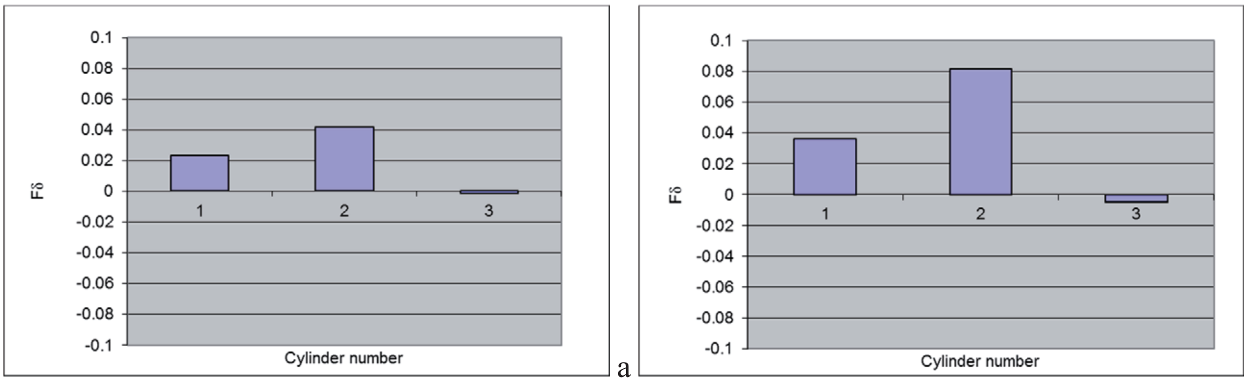

Fig. 12. Pattern of coefficient F_δ for "strong spring": a – load 150 kW, b – load 250 kW

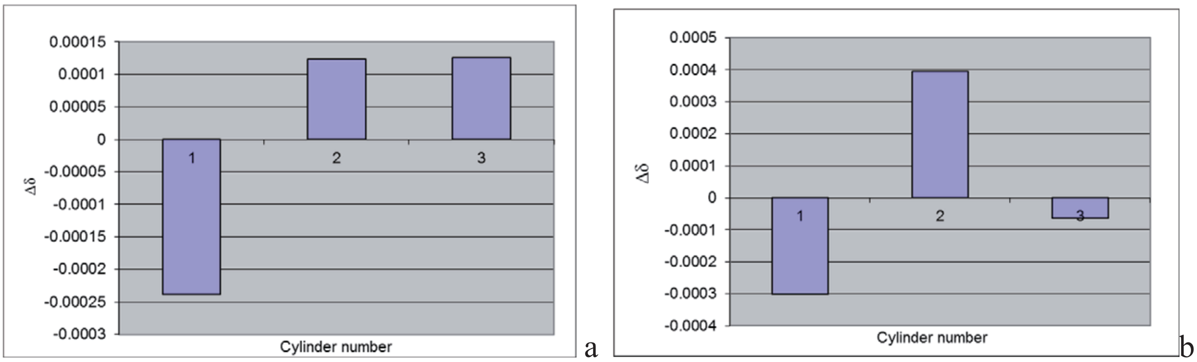

Fig. 13. Pattern of coefficient Δδ for "strong spring", a – load 150 kW; b – load 250 kW

5. Conclusion

The results of conducted experiment shows that malfunctions of injection valves were the source of angular speed deviations from normal condition. The level of deviations is strong enough to be detected by photo-optical measurement system. The signal obtained from the perforated disc after decomposing of noise, is a base for diagnostic analysis focused on identification and definition of reason of faulty condition. The way to receive diagnostic information is the analyse of diagnostic parameters elaborated in way of processing IAS waveforms. The conclusion coming from above is that for detection and localisation of malfunction, necessary is having template measurements of a healthy engine. From diagnostic practice is well known that collecting of healthy engine data can be done during commissioning of an new engine or during trials after repair process. To avoid that inconvenient limitation, a template in a form of healthy engine measurements shall be replaced by very accurate mathematical dynamic model of a crankshaft movement. Construction of such model should enable easy adjustment to any type of diesel engine by setting changeable factors related to certain technical particulars of a piston, a connecting rod, a crankshaft and in-cylinder pressure data.

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