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Evaluation of combustion of engine Sulzer 3AL 25/30 by measuring of crankshaft angular speed

Abstract: *Analysis of Instantaneous Angular Speed (IAS) of the crankshaft is considered as one of non intrusive and effective method of detection of combustion quality deterioration. In this paper are presented results of experimental verification of high pressure fuel system's malfunction detecting, using optical encoder for IAS recording. The implemented method relay on comparison of measurement results recorded under healthy and faulty condition of the engine. Elaborated dynamic model of angular speed variations enables to build templates of engine behavior. Data processing of raw angular speed signal was noise decomposition in way of implementation of Savitzky-Golay filter. Measured signal of faulty and healthy conditions were compared and value of difference was taken as an indicator of malfunction.*

Keywords: *Fault detection, instantaneous angular speed, noise decomposition, Savitzky-Golay filter*

Ocena procesu spalania w silniku Sulzer 3AL 25/30 metodą pomiaru oscylacji prędkości obrotowej wału korbowego

Streszczenie: *Analiza chwilowej prędkości kątowej wału korbowego silnika jest uważana za efektywną i nieinwazyjną metodę wykrywania pogorszenia jakości procesu spalania w cylindrze. W artykule zaprezentowano wyniki weryfikacji eksperymentalnej wykrywania uszkodzenia systemu paliwowego wysokiego ciśnienia w oparciu o pomiar prędkości kątowej enkoderem optycznym. Zastosowana metoda polega na porównaniu wyników pomiaru na silniku sprawnym oraz z symulowanym uszkodzeniem. Model matematyczny ruchu obrotowego wału pozwala na tworzenie teoretycznych wzorców krzywej zmian prędkości dla różnych symulacji uszkodzeń. Dekompozycja zakłóceń sygnałów pomierzonych została przeprowadzona z wykorzystaniem filtrów Savitzky'ego-Golaya. Wartość różnicy pomiędzy wygładzonymi przebiegami prędkości chwilowej w stanie bez i z symulacją uszkodzenia stanowi wskaźnik uszkodzenia.*

Słowa kluczowe: *Wykrywanie uszkodzeń, chwilowa prędkość kątowa, dekompozycja zakłóceń, filtr Savitzky'ego-Golaya*

1. Introduction

Diesel engines are one of the most critical mechanisms on board of merchant vessels. Unpredicted failures of engines, installed as main propulsion or electro-generator units can, result with serious consequences, affecting human life and environment. One of the most common problems occurring during diesel engines operation are malfunctions of fuel injection systems. Faults developed in high pressure fuel systems directly changes combustion process and engine performance. Engine misfires increase NO_x and SO_x contents in exhaust gases and multiplies vibrations level. To prevent the occurrence of unpredicted engine failures or its exploiting at low efficiency and high pollutants emission level, continually monitoring of engine performance and deviations from normal state is necessary.

The most common method of engine condition diagnosis is measurement of in-cylinder pressure. This technique can provide information direct indication of engine performance and the state of combustion process. Unfortunately, due intrusive nature of the method, its application is limited to the engines equipped with indicator cocks (mostly medium and low speed diesel engines). Moreover, because of high temperature and soot containment of exhaust smoke, expensive and delicate pressure sensors cannot be exposed at exhaust gases action for long time [2]. Above facts are reasons of limitations of MIP (Mean Indicated Pressure) employment as a continuous engine monitoring. Considered as non-intrusive method, measurement of instantaneous angular speed, due to significant development of data acquisition and processing, has gained broad spectrum of applications for condition monitoring. IAS technique was used for misfiring detection in OBD systems [1], monitoring of gear transmission [4], fault detection of high speed diesel engines [5] and multicylinder diesel engines driving electro-generator sets [6]. Instantaneous angular speed analysis can be used for monitoring of engine performance because oscillations of crankshaft angular speed reflects directly gas pressure torque produced by piston-conrod assembly during combustion process.

For IAS analysis and fault diagnosis it is useful to create a model of dynamic system aimed at the simulation of angular speed variations of healthy and non-healthy diesel engine. Two degree of freedom, simple dynamic model enables to predict angular speed fluctuation of three cylinder four stroke diesel engine. The angular speed is strongly affected by tangential force coming from gas pressure and vertical imbalance inertial forces induced by reciprocating masses of piston and connecting rod. The character of acting forces let assume that IAS can be utilized for detecting engine faults related to combustion process changes i.e. high pressure fuel system leakage. IAS technique enables not only fault detection but also identification of faulty cylinder. Desbaseille at al [5] presented the method of comparison of angular speed difference between healthy and faulty condition.

For instantaneous angular speed measurements in this experiment, the method based on optical encoder was implemented. That method is considered as more practical due to its simplicity and less likely to be affected by ambient interference. Recently several approaches to the noise reduction subject have been presented [4,5]. This paper presents the method of raw signal optimizing using moving polynomial approximation (Savitzky-Golay filter). The instantaneous angular speed signal after noise decomposition is compared with angular speed runs based on the simplified model. Comparison of both is a base for failure detection and identification.

3. Description of experiment

In order to find the answer, whether instantaneous angular speed of the crankshaft is carrying information about combustion process, it was necessary to carry out measurements in engine's healthy and fault condition. the experiment was carried out in test bed in Maritime University in Gdynia. Test engine, medium speed, four stroke Sulzer 3AL 25/30 were typical drive of electro-generator (fig. 1).

Fig. 1. Test bed with Sulzer 3Al 25/30

Test bed is equipped with installation for permanent measurement of in-cylinder pressure. Signals from Kistler sensors are recorded in computer data base with discretion of 0,5 degree of crank angle. Measurement of angular speed is executed using optical encoder. The disc with 180 circumferential slits is installed at free-end of the crankshaft. Sensor head with laser emitter and photodiode receiver is mounted at a bracket attached to the engine body (fig. 2). Laser signals emitted with frequency of 16 MHz passing through slits are received by photodiode. Electronic recording module counts number of signals exciting photodiode and number of "blind signals" when laser beam is stopped by tooth (fig. 3). The span of a couple of slit and tooth is 2^o of crank angle (CA). Number of signals corresponding to one couple lets calculate time of passage of 2^o section and angular speed:

$$\omega_i = \frac{2 * \frac{2\pi}{360}}{\frac{n_i}{16 * 10^6}} \quad \left[{}^{rad}/_{s}\right] \qquad (1)$$

where n_i is number of recorded impulses for section *i.*

Simulation of injector failure was done by changing of spring tension adjustment, what resulted with valve opening pressure change from 250 bar to 150 bar.

Fig. 2. Encoder disc and sensor mounted at the crankshaft

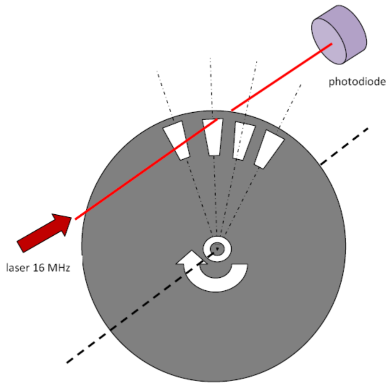

Fig. 3. Mode of work of optical encoder

Simulation of injector fault was done at second cylinder head. Measurement was carried out at load of 250 kW. Set up of the load is executed using adjustable resistor. Every record of instantaneous angular speed consist of ten subsequent revolutions and was repeated three times. In the same time, five records of in-cylinder pressure were conducted. The same procedure was repeated after setting engine back to healthy condition. The aim of measurement was to built the data base for further comparison of angular speed waveforms of healthy and faulty conditions.

4. Data processing

Raw signal of instantaneous angular speed generates quite high noise component. For signals' smoothing the method of moving approximation by exponential polynomial was implemented. The idea of Savitzky-Golay Filter way of smoothing is to obtain, for sequence of samples *x* [n] of signals, for a group of 2M +1 samples with the centre at *n=0* , the coefficients of a polynomial

$$p_n = \sum_j^N a_j n^j, \qquad (2)$$

in way to minimize the mean-squared approximation error for group of samples

$$\varepsilon = \sum_{n=-M}^{M} (p(n) - x[n])^2 \qquad (3)$$

within determination in every centre of interval point *n* of measurement series, an approximation value of moving approximation interval with 2M+1 width.

For smoothing of recorded waveforms the moving approximation by polynomial degree N = 3 was implemented. The width of intervals and polynomial degree have an impact on results of smoothing. Higher degree preserves and narrows profiles of smoothed data, but gives some loses of broad features. In order to get best fitting, the raw signal was treated by several filters with different point number. Comparison of results pointed most fitting curve, which was a result of triple decomposition, with three subsequent filters, with intervals 2M+1 = {8, 24, 36}. Implemented smoothing polynomial and triple way of smoothing is authors' own elaboration. Obtained in that way smooth line profiles shall be superposed with model ones, in order to evaluate the level of conformity. Sample of IAS waveform before and after smoothing are presented in fig. 4.

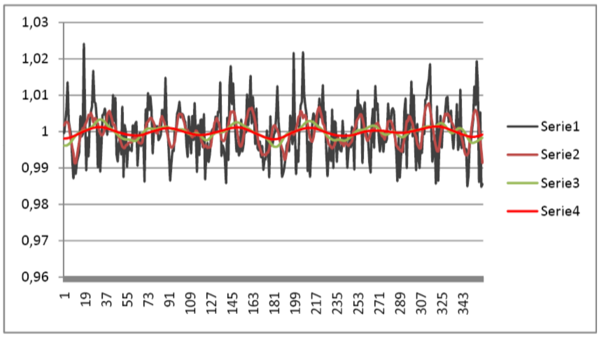

Fig. 4. Raw IAS signal and results of three subsequent steps of S-G filter. Domain of samples; serie 1 – raw signal , serie 2, serie 3, serie 4 – subsequent steps of smoothing

5. Dynamic model of crankshaft rotation

For modeling purposes one has to assume that the crankshaft is sufficiently rigid, the load torque is constant and engine is decoupled from the load, thus the engine dynamics can be described by equation (4):

$$J_E(\varphi)\frac{d^2\varphi}{dt^2} = T_{gas} - T_{mas} - T_{load} - T_{fr} \qquad (4)$$

where:

J_E – mass inertia on engine side

T_{gas}, T_{mas}, T_{load}, T_{fr} - respectively gas, mass, load and friction torques.

The gas torque, deriving from in-cylinder pressure was calculated basing on directly measured gas pressure in engine's health condition and with fault simulation. The mass force was calculated using data from technical documentation of the engine and generator. Fig. 5 presents scheme of rotating masses of the generator set.

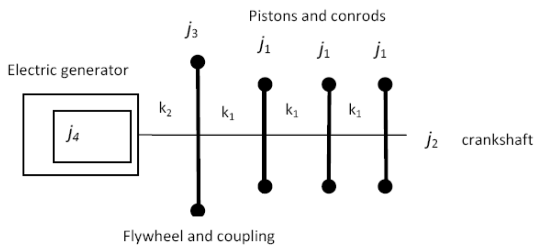

Fig. 5. Schematic diagram of a medium speed genset

For simplification of the model, it was assumed that load torque is constant and equal to average value of 10 revolutions. Friction torque was calculated according to equation (4) basing on measurement of mean indicated pressure during idle run of the genset. Results of modeling of IAS for healthy and some faults of engine are presented in fig. 6 and fig. 7. Calculated value ω is the oscillation around mean speed value during one cycle (two revolutions).

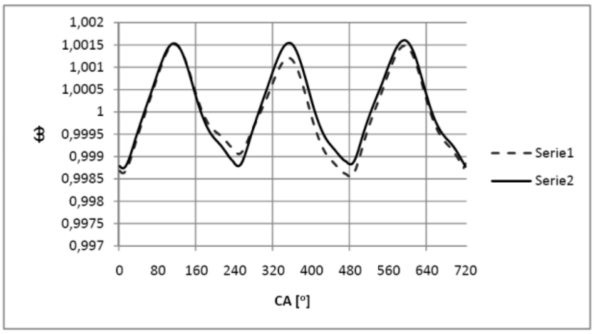

Fig. 6. Model waveform of angular speed of fault condition (Serie 1) and healthy engine (Serie 2)

One has to notice that simulation of strong fault, presented in fig. 6, equal to 15% lower cylinder pressure in cyl. 2, results with significant deviation of waveform run.

In order to build the model of crankshaft speed of engine working with weak spring injector in 2nd cyl., real values of combustion pressure measured under faulty condition were inserted into model's equations. As it can be observed in fig. 7, deviations from normal run are very small, and only in zone of 2nd cylinder.

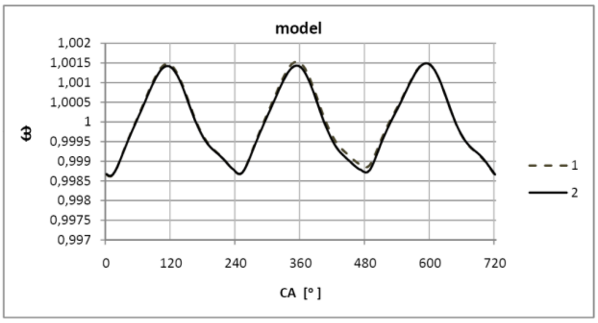

Fig. 7. Waveform of angular speed of simulation of weak spring injector (1) and healthy engine (2)

6. Results of in-cylinder pressure measurement

In order to recognize how simulation of injector failure affect combustion process, pressure in every cylinder was measured during engine's run out with simulated injector malfunction and in good state. Comparison of in-cylinder pressure waveforms enables preliminary determination of expected angular speed run's behavior. Comparison of cylinder pressure in cylinders 1, 2 and 3 is presented in fig. 8.

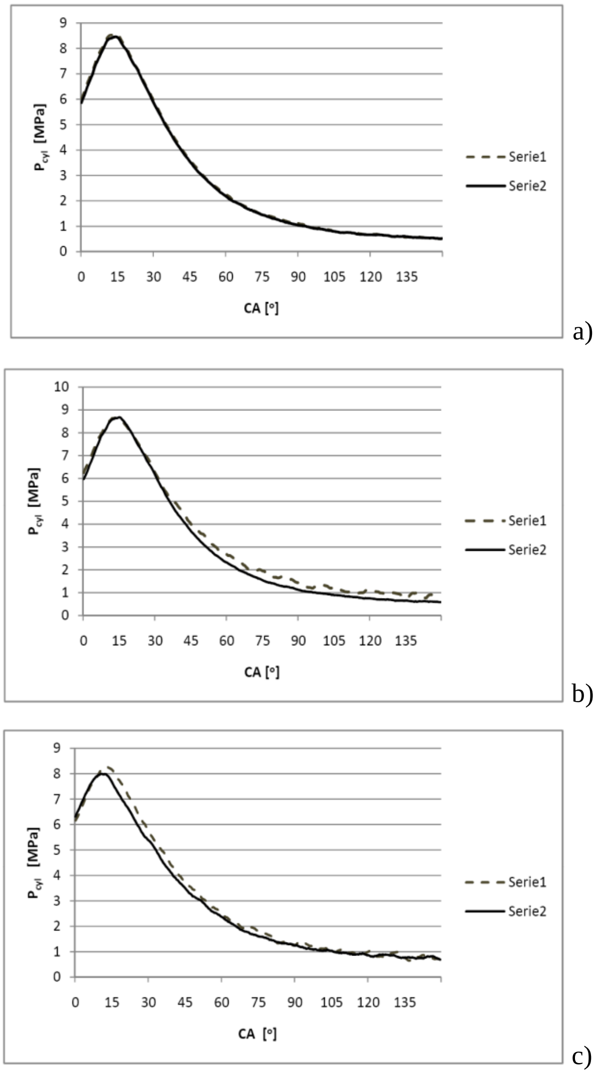

Fig. 8. Cylinder pressure of health (serie 2) and failure (serie 1) state; a - cyl. 1, b - cyl. 2, c - cyl. 3

Because pressure in cylinder strongly affects tangential force, its variation should be reflected by angular speed fluctuation. Difference between Mean Effective Pressures for individual cylinders were at level of 2% for cyl. 1, 8% for cyl. 2 and 5% for cyl. 3.

7. Results of angular speed measurement

Angular speed of healthy engine was recorded three times at load of 250 kW, every record duration was 10 revolutions. The same procedure was carried out for simulation of injector failure. Final raw signal was an effect of average of six revolutions of everyone from three records. Raw signal noise was decomposed using S-G filter.

Final waveforms of healthy engine in domain of 720^{o} of CA was compared with model one in order to determine the level of correlation (fig. 9). The correlation levels were calculated for subsequent intervals 120^{o} broad. High level of linear correlation gives evidence that modeling reflect real fluctuations of angular speed (fig. 10).

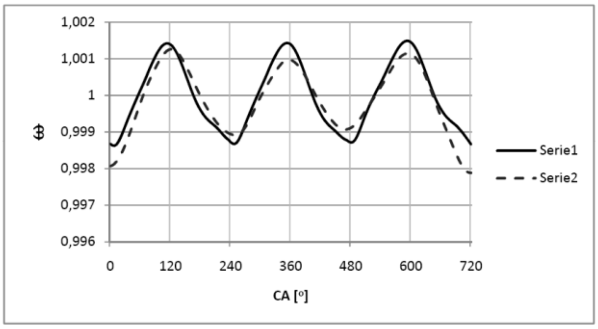

Fig. 9. Comparison of model and real run of angular speed; Serie 1 – model, Serie 2 – measurement

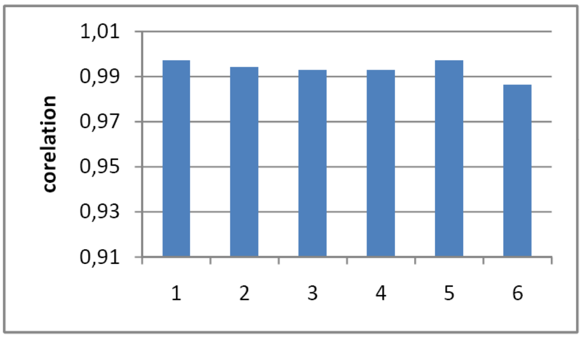

Fig. 10. Correlation level between model and real waveform

Healthy and faulty state measurements waveforms were superposed, aiming to detect malfunction (fig. 11)

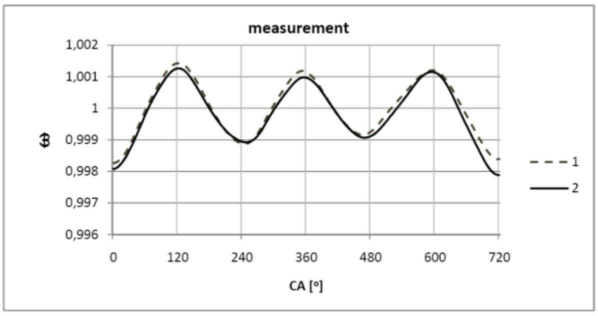

Fig. 11. Superposition of healthy and faulty waveforms of angular speed; 1 – faulty, 2 – healthy

8. Conclusions

Presented results of experiment lead to conclusion that fluctuation of instantaneous angular speed reflects changes of pressure indicated in cylinder. However, indication of malfunction strictly depends on "energetic level" of disturbance. In our case even straight measurement of in–cylinder pressure hardly pointed occurrence of malfunction. Weak spring of injector does not strongly affect combustion process, thus detection and definition of malfunction was impossible.

High level of correlation between model and real waveforms proofs utility of implemented S-G smoothing method. Relaying on results of model simulations one can assume, that fuel system faults which stronger disturb combustion process will be detected by instantaneous angular speed analysis.

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