ANALYSIS OF DIAGNOSTIC UTILITY OF INSTANTANEOUS ANGULAR SPEED FLUCTUATION OF DIESEL ENGINE CRANKSHAFT

Mirosław Dereszewski, Adam Charchalis
Stanisław Polanowski

Gdynia Maritime University, Faculty of Marine Engineering
Morska Street 81-87, 81-225 Gdynia, Poland
tel.: +48 58 6901398, fax: +48 58 6901399
e-mail: achar@am.gdynia.pl

Abstract

Frequent crew rotation, a shorthand, and various levels of technical crew skills, are the facts with the ship-owners has to cope very often. Having the proper level of engine exploitation as a main objective is necessary to implement a constant engine monitoring system, in order to obtain quick and reliable diagnostic information. One cannot omit the financial aspect of monitoring system implementation, created by its price and costs of service. In this paper, the analysis of diagnostic utility of the signal deriving from a propulsion shaft fluctuation during its one revolution is presented. The angular speed of the shaft was measured using a laser sensor of torque meter ETNP-10. Diagnostic utility validation has been verified on a basis of combustion quality, in cylinders of two-stroke, turbocharged Marine Diesel Engine. Test was carried out on board of a container vessel during its sea passage. In order to evaluate the effectiveness of the method, the crew simulated engine's malfunction by fuel injection cut-off in various cylinders (only one in the same time).The interference signals decomposition was carried out using the method of synchronous averaging and moving approximation with polynomial of 3rd exponent.

***Keywords**: two stroke diesel engine diagnostics, diagnostics of combustion process, angular speed variation, angular acceleration, moving approximation*

1. Introduction

Internal combustion pressure or torque values are very significant parameters, which enable to carry out monitoring of diesel engines [1]. The most common method of controlling of two stroke marine diesel engines is cylinders mean indicated pressure measurement. Analysers of combustion and injection pressure enables to estimate maximum combustion pressure, mean pressure and mean indicated power, TDC pressure and rotational speed. Diagnostic concluding is based on interpretation of deviations between measured values and samples. Leaders of marine engine market are used to offer their own monitoring systems. Moreover, numerous systems dedicated to marine propulsion, elaborated by well-known manufacturers are available on the market. Above-mentioned solutions, even very sophisticated, cannot be used for constant monitoring. The reason of this weakness is relatively low robustness and immune of sensor against very harsh measurement condition (high temperature and pollution). Due to its relatively high price and vulnerability, the pressure indicators service usage is limited to periodical engine control [1], [2]. Taking the facts stated above under consideration, one comes to conclusion that implementation of a system based on toothed disc and optical sensor, which enable constant measurement, is justified. That system represents advantages deriving from the detection of the Instantaneous Angular Speed (IAS) deviation. Charles in his paper [3] presents similar opinion. Proposed method's advantages are as follow:

- Method is non-invading,
- Easy adaptation to any propulsion configuration,

- High immunity against outer condition,
- Low price,
- Easy operating, no periodical calibration,
- Clear data presentation.

The optical rotational speed measurement system with toothed disc fulfils all above points. Many papers presents the opinion that analysis of non uniformity of rotational speed is useful for medium speed diesel engine's work monitoring, mostly of those working as a driver for electric generators, vehicles but also ferries propulsion. A torque wave-form in domain of a crankshaft rotation angle shall be assumed as a signal giving information about a quality of a combustion process. It is expected that an analysis of above-mentioned signal will result with information about a value of torque given by cylinders in its firing order. Diagnostic value of the process is to be a waveform of instantaneous angular speed fluctuation in domain of crankshaft rotation angle. Due to a cyclic character of torque creation process, what is related to a piston engine's work principle, instantaneous acceleration of masses taking part in rotation occur. Data logging, and subsequently analysis of shaft acceleration's changes shall provide us with information about a value of torque created by pistons. In papers published by Charles [3], Gawande [6], and Boguś [7], many experiments carried out on industrial and railway engines were cited, proving a practical utility of instantaneous speed tracking for evaluation of combustion process. The main objective of this paper is to show, that above presented signals can be used for evaluation of correctness of combustion in cylinders of two-stroke Marine Diesel Engine.

2. Object of the experiment

The object, selected for carrying out the experiment, was a fast container ship with capacity of 3500TEU, and cruising speed around 25 knots. The diagrammatic drawing of its propulsion is presented on Fig.1. That solution for ship's propulsion is typical for most of bulk carriers, tankers and container vessels. Main Engine is connected straight to a fixed propeller by an intermediate and a propeller shaft, without any dumping elements or gearbox. That solution simplifies analysis of measurements as interference of either gearbox teeth clearance or elastic couplings dumping effect can be omitted. The main engine is a 7. cyl. two - stroke turbocharged marine diesel engine, with output MCR (Maximum Continuous Rating) 32,000 kW, and a revolutionary speed of 104 rev/min. All junctions between the engine and the propeller are stiff collar couplings. The mounting location of measurement-toothed discs on the shaft is pointed in Fig. 1.

All measurements were carried out at sea, during standard passage with cargo. Due to sea state condition (wages and wind) and jawing, we assume that the main engine load was varying and a torque was unstable. The main engine was set up at 25% of nominal load; rotational speed was ~67 RPM.

The basic parameters of the main engine and the screw propeller are presented in the Table 1.

Tab. 1. Main engine and propeller particulars

Main Engine Particulars	
Type	Two-stroke Marine Diesel Engine
No. Of cylinders	7
Firing order	1 – 7 – 2 – 5 – 4 – 3 – 6
Output (MCR) at RPM.	31920 kW/ 104 RPM
Max. torque	2931 kNm
Max. Continuous RPM	104 RPM
Min. RPM	26 RPM
Cyl. bore / stroke	900/2300 mm

Screw Propeller Particulars	
Type	Fixed pitch, D = 7750 mm, H for 0.7R = 7091 mm
H/D	0.915
No. of blades	5

2. Data acquisition

One of advantages of every cylinder combustion quality evaluation based on IAS analysis is a possibility to utilise a flywheel teeth as a signal source [1], [3]. In that case however, one encounter of the problem of limited samples number, depending on a flywheel construction (number of teeth at flywheel), and necessity of marking a crankshaft position when 1st piston reaches TDC, in order to establish an angular domain for measurements function, and identify pistons' angular phases related to a combustion stroke. Better solution is an installation of an additional toothed ring, with number of slots or teeth which multiplication gives 360 degrees. The slots number must not be less than 60, otherwise accuracy of measurement is to low to evaluate dispersion of mean effective cylinder pressure [1].

All measurements were carried out using photo-optical torque meter ETNP-10, fabricated by the P&R Enterprise ENAMOR Ltd. The torque meter has two toothed rings, 90 teeth and slots each. Sampling is done by laser sensor with photodiode, on the way of counting impulses when slot is crossing a laser ray (value "1") and when a tooth is crossing a laser ray (value "0"). Number of counted impulses (emission is with constant frequency) represent width of the slot at instant angular velocity, and a number of "blind" impulses represent width of a tooth. The torque meter possess two discs necessary for a measurement of shaft's torsion and subsequently torque calculation. For IAS analysis purposes one disc is enough, thus two discs mounted on shaft can be treated as one disc with double slots number, or two independent measurements with a phase shift. One disc has an additional narrow slot, which role is to mark 1stcylinder TDC position. Measurements data are recorded at a memory card of PLC (Programmable Logic Controller) SAIA PCD 3. Data, after conversion by dedicated computer program, can be transferred to MS Excel format, for further analysis. ETNP – 10 measurement arrangements with discs mounted on intermediate shaft and laser sensor installed at a support is presented at Fig. 2.

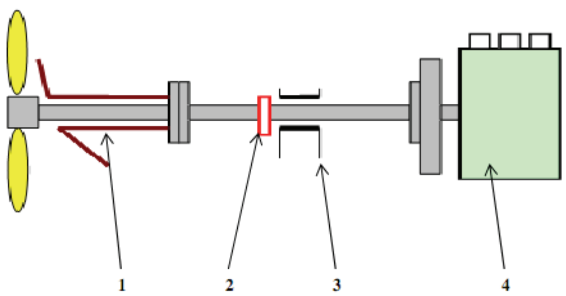

Fig. 1. Layout of ships propulsion with toothed rings mounted at intermediate shaft.
1 – stern tube; 2- measurement toothed rings; 3 – intermediate shaft bearing; 4 – main engine

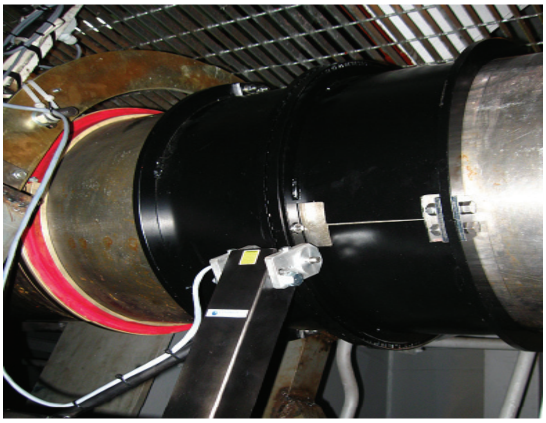

Fig. 2. Toothed rings and laser sensor mounted at intermediate shaft

3. Results of measurement

The results of measurement are in a form of numbers of impulses representing subsequent slots and teeth time of the laser beam exposure. When a slot, and a tooth dimensions, and sampling frequency are known, instantaneous angular speed in domain of samples' number can be calculated. Used toothed rings had angular dimension ≈ 0.01745 rad. Formulas below represents relations between numbers of impulses and angular speed for one tooth.

$$\omega_i = \frac{\alpha_z}{t_i}, \quad (1)$$

$$t_i = \frac{n_i}{\varphi_g}, \quad (2)$$

$$\omega_i = \frac{\alpha_z}{n_i} \cdot \varphi_g, \quad (3)$$

where: α_z - angular width of tooth, ω_i – angular speed of tooth, t_i - time of array crossing, n_i – number of impulses for one tooth, φ_g – impulse emission frequency, $\alpha_z \cong 0.01745$ rad.

The vave-form of the angular speed for 10 subsequent revolutions, all healthy cylinders, is presented in Fig. 3.

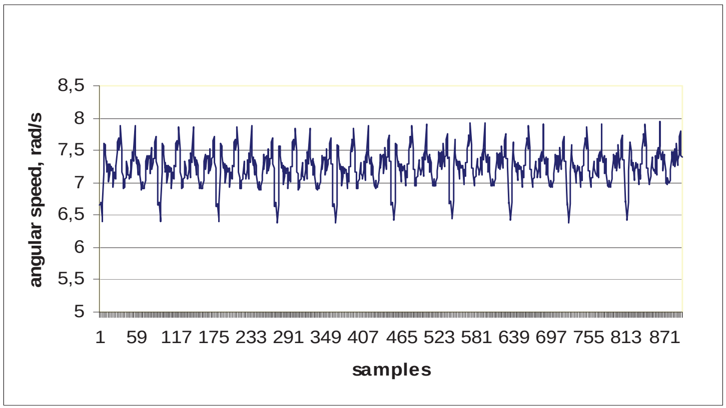

Fig. 3. Wave-form of angular speed fluctuation, 7 healthy cylinders, 10 revolutions recorded

In order to eliminate random disturbances and obtain wave-form's smoothing, a moving approximation with approximation object in a form of polynomial exponent 3 was implemented. This method is most proper for analysis of an angular speed and acceleration changes due to its usefulness for non - periodic functions treatment [1].Results of first step of approximation are presented in Fig. 4.

The chart in Fig. 5. presents a comparison of the angular speed raw record wave-form and its wave-form after the third step of smoothing using the moving polynomial of exponent 3. approximation.

In order to define the general tendencies of changes of the angular speed caused by misfiring, one carried out a calculation of the ratios between instantaneous angular speeds values of the healthy run and misfiring in 4. cyl. (ω_4) / (ω_n), and subsequently the relation between the healthy run and misfiring in cyl. 7. (ω_7) / (ω_n) in the domain of samples during one crankshaft's revolution. The graph of quotients is presented in Fig. 6.

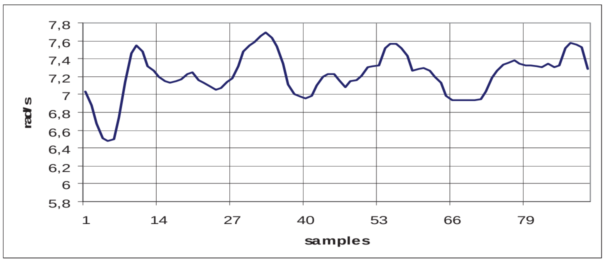

Fig. 4. Angular speed wave-form after smoothing, 7 healthy cylinders, sampling of one revolution

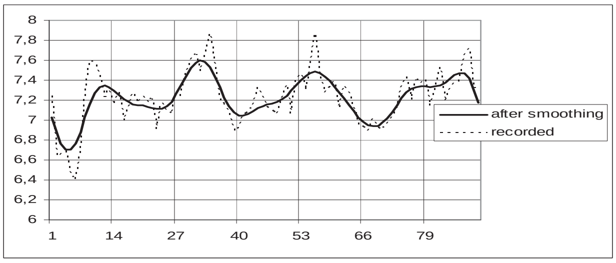

Fig. 5. Recorded angular speed waveform (dotted line) and the same after third step of smoothing.7 healthy cylinders

The disturbance caused by lack of firing in one cylinder is resulting with a significant changes of angular speed fluctuation. Zones when ratio $\omega_{normal} / \omega_{disturb}$ is ≥ 1 are different in both cases and depends of which cylinder is out of work. In order to compare general character of wave-forms, graphs are overlaid with a phase shift equal to angular distance between firing in 4^{th} and 7^{th} cylinder. Results are presented in Fig. 7. Periodical similarity of wave-forms proofs that deviations are caused by changes of instantaneous torque value, due to misfiring, and carrying diagnostic information.

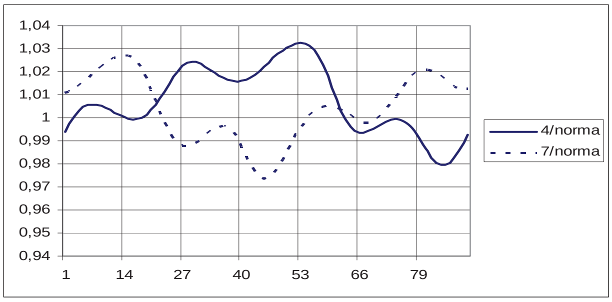

Fig. 6. The graph of instantaneous speed quotients (ω_4/ ω_n) and (ω_7/ ω_n) in the domain of samples of one shaft revolution

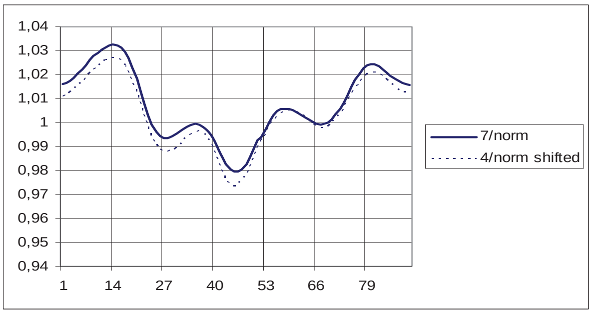

Fig. 7. Comparison of angular speed ratio's graphs. Shifted (39 samples) ω_4/ω_n and ω_7/ω_n

Doing a comparison of the angular speed of the healthy engine and working with misfiring (see Fig. 8), one can observe deviations of wave-forms representing non –healthy engine run from basic line of healthy engine (the status when all cylinders are working is assumed as healthy, the mean effective pressure spread is omitted). Partly higher angular speed of runs with misfiring is caused by reaction of a speed governor. Due to time gaps of 10 minutes between measurement sessions, one has also to assume an impact of changes of ambient condition (wind direction and wages).The mean angular speed of the shaft was 7,229 rad/s for the healthy engine, and 7,268 rad/s with misfiring in 4^{th} cyl. (deviation +0,5%), and 7,238 rad/s with misfiring in 7^{th} cyl. (deviation + 0,1%).

Information about an angular acceleration is given by calculation of a derivative of an angular speed. The instantaneous acceleration functions for three engine's states: normal, misfiring cyl.4., and misfiring cyl. 7., after smoothing by polynomial with exponent 3. are presented in Fig. 9.

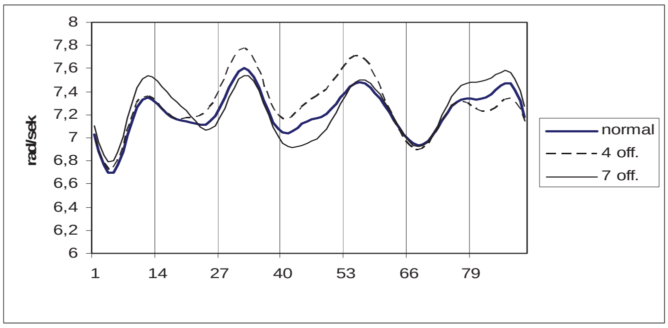

Fig. 8. Comparison of angular speed fluctuation during one revolution, representing three states of engine condition

Analysing three functions, one can observe different deviations of runs representing non-healthy condition from normal state, depending on angular sectors of the shaft turn. Significant deviations occurs in the sector of 14 – 27 samples when cyl. 7. is cut off and in the sector 53 – 65 samples when cyl. 4. is not working. The sector 14 – 27 corresponds with combustion stroke of 7^{th} cylinder and the sector 53-66 with the combustion stroke of 4^{th} cylinder, due to firing order. The function of the square deviation enhancing peaks (with changing of a polarisation of negative value) in sectors corresponding with lack of combustion, is presented in Fig. 10.

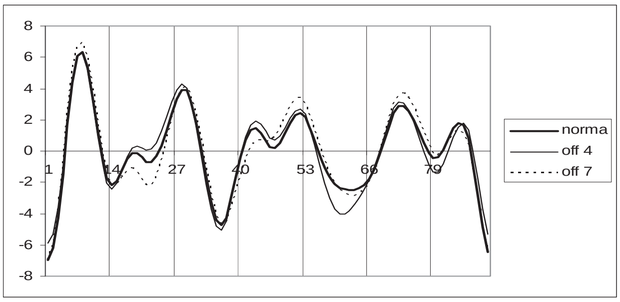

Fig. 9. Angular acceleration of normal working engine and with cylinders off. Samples of one revolution

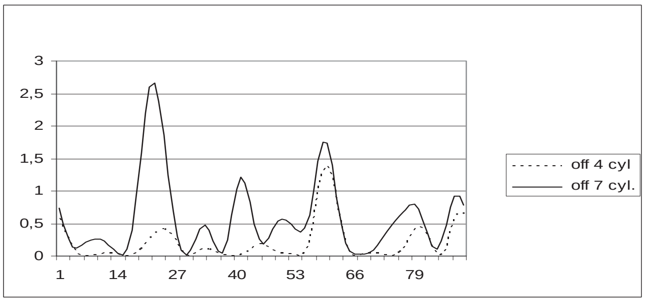

Fig. 10. Mean square deviation of angular instantaneous acceleration of non-healthy engine (misfiring in cyl.4. and 7.) from normal state

Conclusion

Results of experiment presented in this paper, let assume that using of very accurate fabricated toothed rings shall to eliminate errors due to flywheel construction. Analysis of measurements carried out using the torque meter ETNP-10 enable to detect disturbances of engine work, in the case of misfiring in one cylinder. One has to realise that for marine two stroke engines, misfiring has not happen very often but its detection is very important, because any imbalance of combustion order creates additional vibrations, and finally additional zones of barred rotational speed. Results of presented experiments are a justification of further development of the method of IAS based at a toothed ring and a optical sensor. The aim of further investigations will be determination of a boundary value of an angular speed fluctuation possible to detect, and determination of interdependence between the IAS signal level and the power produced in a cylinder.

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