ANALYSIS OF DIAGNOSTIC UTILITY OF TORQUE AND ROTATIONAL SPEED FLUCTUATION OF PROPULSION SHAFT OF A VESSEL

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Abstract

In the paper has been presented the analysis of diagnostic utility of signals, deriving from torque (measured value is an instantaneous shaft's torsion angle, torque value is subsequently calculated basing on shaft's steel Kirhoff's modulus or Young's modulus values) and angular acceleration of the propulsion shaft. All measurements has been carried out using photo optic torque meter ETNP-10, which was installed at the propulsion shaft run by two-stroke low speed marine diesel engine. In order to distinguish diagnostic signals, measurements of healthy engine run and subsequently simulations of a failure by one cylinder cut-off (suspending of a fuel pump) were done. Analysis of torque, revolutionary speed, angular acceleration were and subsequently, in order to distinguish spectral attributes of above functions, fast Fourier transform of speed waveforms were carried out. Diagrams presented in the paper shows comparison of mentioned above signals' waveforms. The most significant influence of simulated combustion process deviation at a signal's variation was noticed when rotational speed and angular acceleration of the shaft were considered. Acquired results of research and measurements are to be a subject of further analysis in order to define representative symptoms and diagnostic values corresponding to propulsion system and engine failures.

Keywords*: marine diesel engine, diagnostics, failure simulation, torque and speed analysis*

1. Introduction

Diagnostic systems dedicated to controlling of marine diesel engines, which functional mode is basing on constant pressure indication are expensive and not reliable. Their implementation at low speed, high power engines is very seldom. The most expensive and unreliable elements of such systems are sensors of combustion pressure. Contamination of gas canals joining combustion chamber with a sensor appears as a major problem. One cope with completely chocked gas canals, considering low speed engines with heavy fuel feed. It is reason of substantial limitation of information in diagnostic control mode, when main source of information is analysis of diagnostic parameters.

It is obvious than combustion gas pressure in cylinders is converted to torque course and gas interaction is result of summation of components. Due to above, in shipbuilding, first attempts to implement torque measurements as a source of diagnostic information were undertaken quite early. Strain gauge method, which signal has continuous character, has found limited implementations, because of their low reliability. One has to assume that signal's continuum could not bring additional information in comparison with discrete signal, if primary signal is not carrying expected information.

Limitation of amount of information about pressure course in cylinders, carried by torque run, derives from one- to- one masking , what is result of torque summing and friction forces coming from: cylinder- liner assembly, connecting rod and journal bearings, propulsion shaft bearings, and reaction of propelled system (propeller reaction, hull drag). Final effect of torque variation is variation of instantaneous rotary speed and angular acceleration.

The object of high attention is possibility of diagnostic utilisation of speed and acceleration signal values, acquired from rotating toothed rings connected to a crankshaft (i.e. flywheel) or special discs mounted around a shaft [7, 10, 11].

Methods basing on angular speed and torque measurement, has found broad implementation for diagnostics of land vehicles engines (OBD systems) [2, 3].

Some authors are even assuming a possibility of cylinder's pressure course reproduction basing on angular speed and torque analysis [12].

Photo-optical torque meter enables discrete measurement both torque and angular speed. Evaluation of diagnostic value of acquired information in relation to marine engine's technical condition requires carrying on researches at real object under exploitation conditions. It is due to expected negative influence of outer factors such a propeller reaction, hull drag, sea state as well as internal interaction of neighbour cylinders.

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 the fixed propeller by the intermediate and the 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. cylinders, 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 location of measurement-toothed discs on the shaft is pointed in Fig. 1.

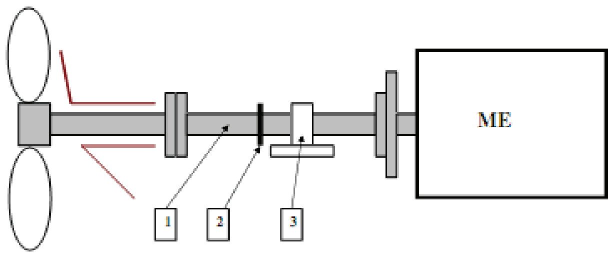

Fig. 1. Layout of ships propulsion with toothed rings mounted at intermediate shaft. 1 – intermediate shaft; 2- measurement toothed rings; 3 – shaft bearing; ME – main engine

All measurements were carried out at sea, during standard passage with cargo. The main engine was set up at 25% of nominal load and rotational speed was ~67 RPM.
The basic particulars of the main engine and the screw propeller are presented in the Tab. 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. Continous 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, 5]. 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. Other solution is mounting on a shaft f a 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 assumed 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. For torque measurement purposes, the distance between cylinders' ends, clamped around the shaft is 40 cm. 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. Phot. 1 presents ETNP – 10 measurement arrangements with discs mounted on intermediate shaft and laser sensor installed at the support connected to the bearing basement.

Phot. 1. Toothed rings and laser sensor mounted at intermediate shaft

3. Analysis of 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.

$$\omega_i = \frac{\alpha_z}{t_i}, \tag{1}$$

$$t_i = \frac{n_i}{\varphi_g}, \tag{2}$$

$$\omega_i = \frac{\alpha_z}{n_i}\cdot\varphi_g, \tag{3}$$

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 sample wave-form of the angular speed for 10 subsequent revolutions, all healthy cylinders, is presented in Fig. 2.

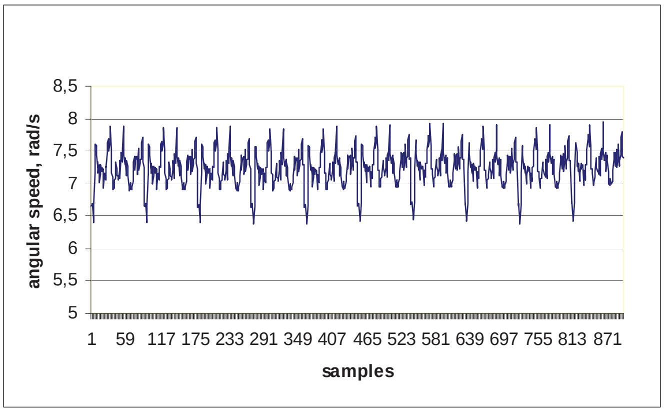

Fig. 2. Wave-form of angular speed fluctuation, 7 healthy cylinders, 10 revolutions recorded

In order to eliminate random disturbances and obtain wave-form's smoothing, moving approximations 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]. The chart in Fig. 3. presents a comparison of the angular speed raw record wave-form and its wave-form after the third step of smoothing using the approximation by moving polynomial of exponent 3.

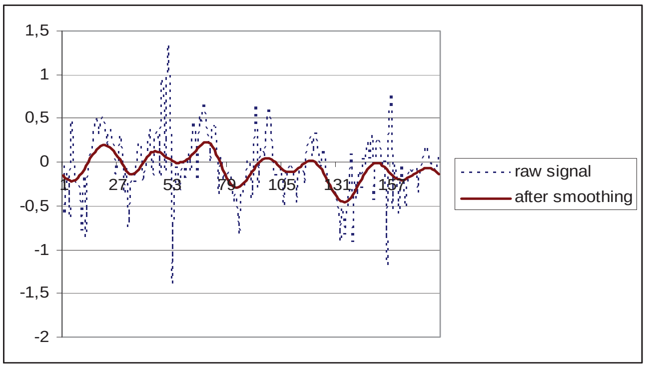

Fig. 3. Recorded angular speed waveform (dotted line) and the same after third step of smoothing. All healthy cylinders, one revolution samples

The disturbance caused by lack of firing in one cylinder is resulting with 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 (see Fig. 4.). In order to compare general character of wave-forms, graphs shall be overlaid with a phase shift equal to angular distance between firing in 4^{th} and 7^{th} cylinder (77 samples).

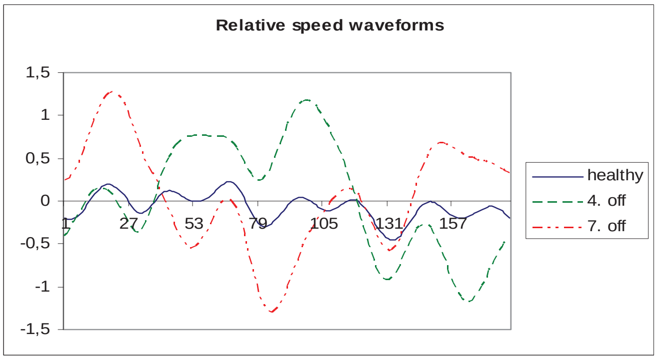

Fig. 4. Comparison of relative angular speed waveforms

Despite of significant differences of instantaneous speed, deviation of mean value angular speed between for healthy and disturbed state of the engine was not significant. Recorded values were as follow: 7.229 rad/s for the healthy engine, and 7.268 rad/s with misfiring in 4th cal. (deviation +0.5%), and 7.238 rad/s with misfiring in 7th cyl. (deviation + 0.1%).

Results of instantaneous torque value measurements are presented in Fig. 5. There are no significant differences between torque variations in healthy and misfire state thus torque signal is not carrying information useful for misfiring detection.

Analyse of harmonics of torque run confirms that the signal given by healthy and disturbed engine are similar. Results of fast Fourier transforms of speed signal are presented in Fig. 6.

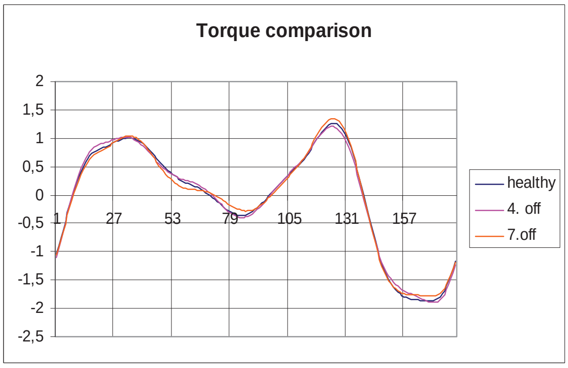

Fig. 5. Comparison of torque run of healthy and misfiring states

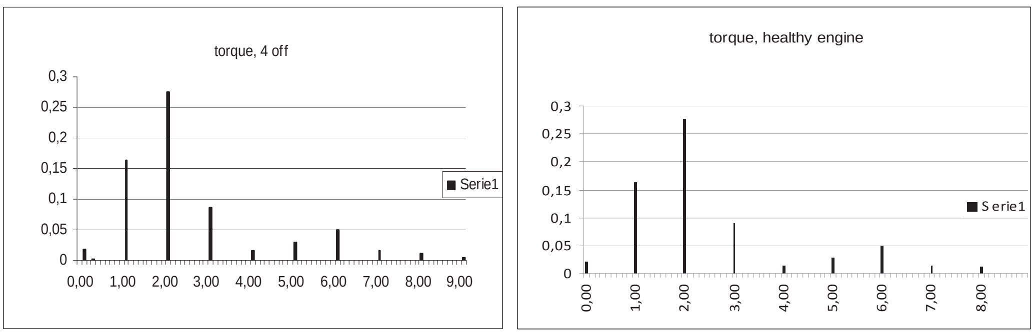

Fig. 6. Spectral analysis of torque course, 4.cyl. off and healthy eng. Domain of frequency (1/eng. cycle)

Analysis of basic frequencies of angular speed in domain of periods per cycle, obtained implementing FFT contributes more information regarding misfiring influence. Pictures presented in Fig. 7. shows rise of first harmonic magnitude of and relative decrease of seventh – harmonic when misfiring occurs.

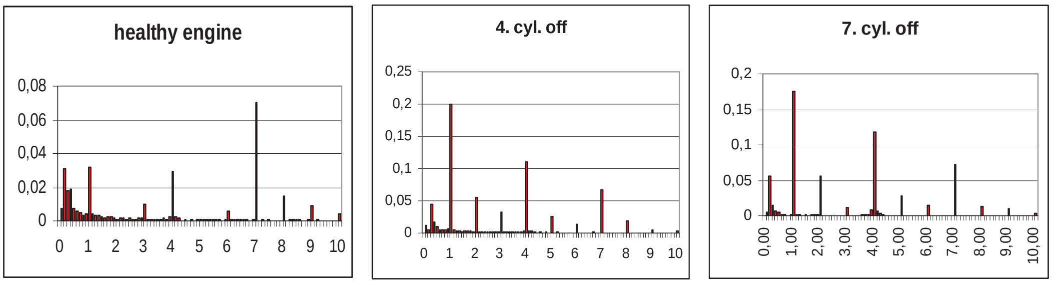

Fig. 7. Spectral analysis of angular speed in domain of frequency (1/eng. cycle)

Angular acceleration is obtained in the way of calculation of derivative of 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. 8 and 9. 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 (low peak) occurs in the sector of 27-53 samples when cyl. 7. is cut off (Fig. 7a), and almost lack of peak in the sector 105-131 samples when cyl. 4. is not working (Fig. 7b). The sector 27-53 corresponds with combustion stroke of 7th cylinder and the sector 105-131 with the combustion stroke of 4th cylinder, due to firing order.

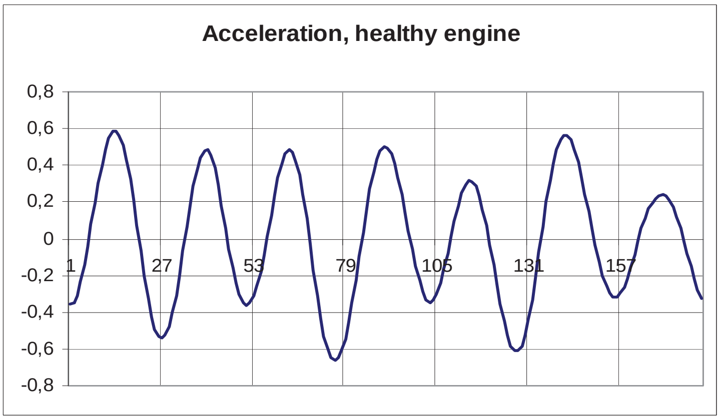

Fig. 8. Angular acceleration of normal working engine, samples of one revolution

(a)

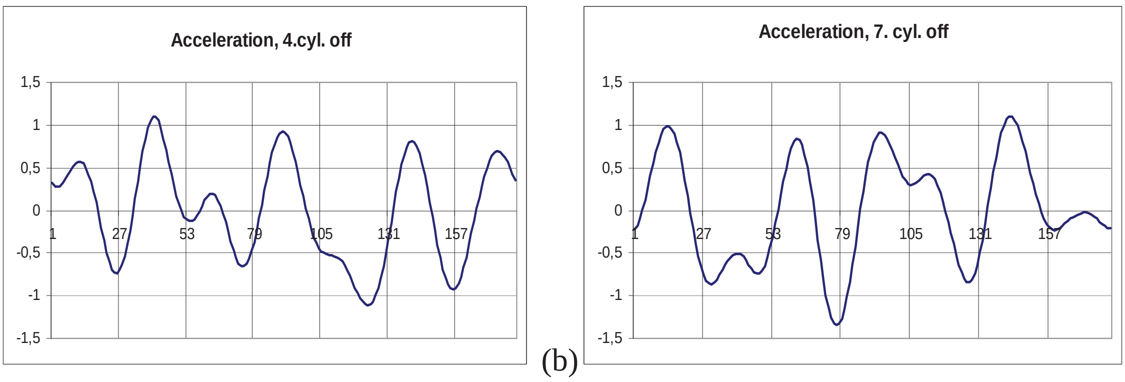

Fig. 9. Deviation of angular instantaneous acceleration (misfiring in cyl.4.and 7)

4. Conclusion

Results of experiment presented in this paper, let assume that using of very accurate fabricated toothed rings are very useful speed signal source. Analysis of measurements carried out using the torque meter ETNP-10 enable to detect disturbances of engine work, and to point the affected cylinder in the case of its misfiring. 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 an optical sensor. Angular acceleration signal after smoothing is assumed as most contributing and reflecting combustion process disturbances The aim of further investigations will be determination of a boundary value of angular speed and acceleration fluctuation reflecting engine run changes, and determination of interdependence between the IAS signal level and the power produced in a cylinder.

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