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IMPACT OF SEA WAVING AT FLUCTUATION OF INSTANTANEOUS ANGULAR SPEED OF SHIP'S PROPULSION SHAFT

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Abstract

The paper presents results of analysis how sea waves affect variation of angular speed of a propulsion shaft of the ship during sea passage. That information is necessary to evaluate the level of credibility of measurements taken as reference value for detection of main engine combustion failures and evaluation of cylinders' contribution to total power based on shaft's angular speed irregularity observations.

Utilization of IAS (Instantaneous Angular Speed) for diagnostic purposes is mostly based on comparison of actual state measurement with characteristics taken during healthy engine run in certain outer conditions. All variations of atmospheric pressure and air temperature have noticeable impact at instantaneous value of angular speed, they and must be considered during comparison procedure. For marine propulsion set, two weather deriving factors, having impact at angular speed of the shaft, can occur. First one is mentioned above values of air temperature and air pressure, the second one is torque variations caused by changes of propeller's draught due to pitch of the hull. Any deviations from sampling course of angular speed are treated as malfunction symptoms.

The aim of analysis was to evaluate how pitching frequency affect run of IAS and how whether omitting of that impact can lead to wrong conclusions.

Keywords: *diagnostics, low speed diesel engine, shaft's angular speed, wave influence*

1. Introduction

Irregularity of sea waving and ship's pitching has an impact on working condition of screw propeller. It results with fluctuation of revolutionary speed of a propulsion shaft. Irregularity of instantaneous value of angular speed of the propeller cannot be omitted when this value is taken as a factor for detection of combustion failures of a main engine.

Failure detection by Instantaneous Angular Speed (IAS) analysis is based on comparison of shaft's angular speed records called "evaluation run" with a sample run recorded at the engine in very good technical condition [1]. Any deviations from sampling course of angular speed are treated as malfunction symptoms. This method seems to be very reliable in laboratory conditions, when ambient conditions are quite constant and recurrence of measurements is high. During normal exploitation of the ship at sea, one encounters completely different conditions due to weather impact. It is the reason for carrying out analysis of reliability of the method implemented at real objects and attempt of determination of potential inference errors, which can occur due to variable sea state in time of angular speed measurement. In order to exclude errors, conformity of condition when template runs and evaluation run were conducted. When impact of sea state is to be determined, is possible to give clear weather limits when evaluation run can be carried out and measured values are reliable for further concluding.

2. The characteristic of sea waving and propeller's vertical movement

For analysis of waving impact on angular speed of the propeller, only pitch (swinging of a hull in longitudinal plane) is to be considered. Due to that hull movement, the propeller's change its position in reference to sea surface. The propeller draught h in static conditions depends on ship construction and its load status (under load or under ballast). Hull's pitch creates deviation of the draught from static position and the value of position's shift Δh is related to characteristic of sea waving [3].

Sea waving has random characteristic and is difficult for modelling. The sources of information are long-term observations and measurements, and statistic classification of most frequent values. From our point of view, two parameters of a wave are interesting: significant magnitude and interval. Those parameters depend on geographical position, for example, North Atlantic is different from North Pacific, and wind force. In Tab. 1 examples of significant heights of waves and its intervals are presented.

Tab. 1. Significant heights of waves and intervals [4]

Wind force ^oB	Significant height of wave [m]			Characteristic interval [s]		
	North Atlantic	North Sea	Baltic	North Atlantic	North Sea	Baltic
3	1.70	1.00	0.45	6.3	4.6	2.9
4	1.95	1.40	0.60	6.5	4.9	3.4
5	2.40	2.00	0.85	6.9	5.4	3.8
6	3.10	3.00	1.20	7.4	6.1	4.4
7	4.00	4.00	1.60	8.0	6.8	4.8
8	5.25	5.60	1.95	8.5	7.7	5.3
9	6.45	6.60	2.50	9.1	8.4	5.8
10	7.45	7.20	3.15	9.6	9.0	6.0
11	8.40	7.50	3.80	10.1	9.6	6.3
12	9.20	7.70	4.30	10.6	10.3	6.5

All hydrodynamic forces have form of a random, no harmonic function in time domain. That fact has been proved in theoretical and experimental way in test tanks. In Fig. 1 are presented effects of experiments using self-propelled ship's model presented by Lipis [3]. Fluctuation of propeller's draught h results with random fluctuation of propeller's resisting torque M_ξ, thrust force P_ξ and vertical force P_ζ.

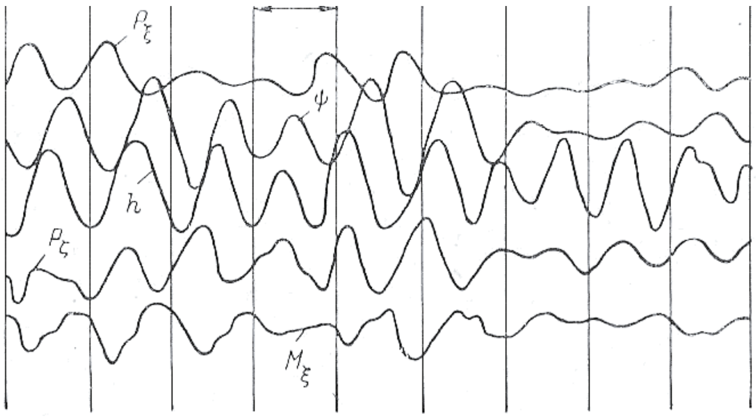

Fig. 1. Model – based courses of: propeller's draught – h, revolutionary torque – M_ξ, thrust – P_ξ and vertical force – P_ζ as result of hull's pitch angle ψ [3]

Variation of the torque causes fluctuation of propeller's angular speed $\omega(t)$. Magnitude of $\omega(t)$ function depends on pitch angle and intervals between speed maximum and minimum are related to hull's swinging frequency. In Fig. 2, motional characteristics of cargo vessel sailing under heavy weather condition (7^{o}B) are presented [3]. The conclusion coming out from that picture is that similarity between courses of propellers depth h and revolutionary speed n can be observed. In addition, course of torque has similar shape but phase shift between maxima and minima of torque M and propeller's depth h can be observed.

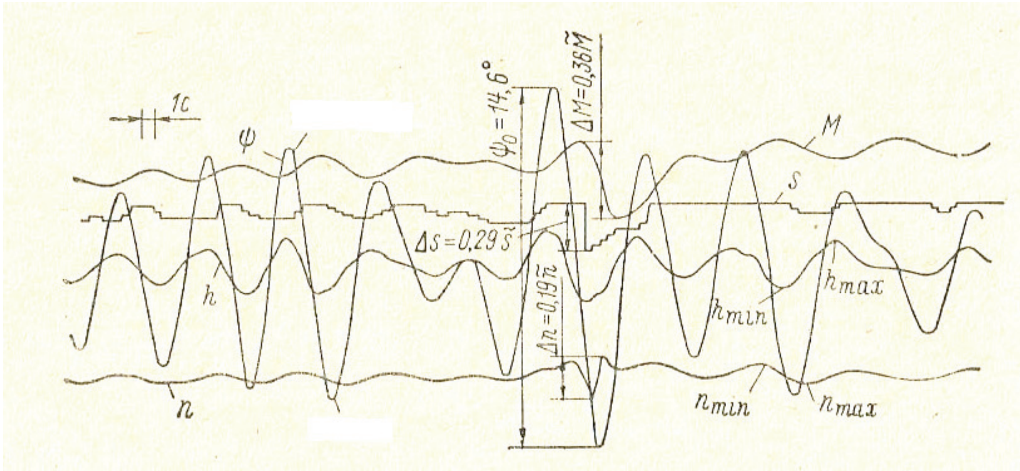

Fig. 2. Records of ship' pitch angle – ψ, torque – M, and rotational speed – n, of motor vessel sailing in sea state 8 [3]

3. Ship characteristic and measurement system

The object, selected for carrying out the measurement, was a cargo ship, bulk carrier of 120 DWT and cruising speed around 15 knots. The diagrammatic drawing of its propulsion system is presented in Fig. 3. 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 5-cylinders, two – stroke turbocharged marine diesel engine, with output MCR (Maximum Continuous Rating) 16,000 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 by number 2 in Fig. 3.

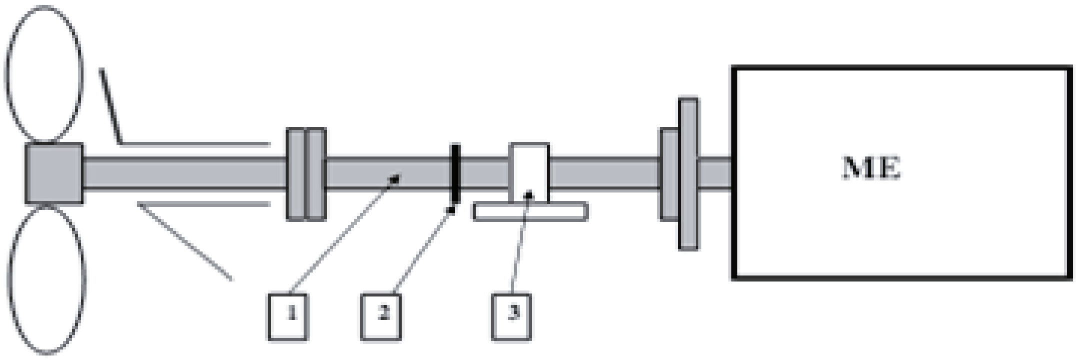

Fig. 3. Perforated disc and laser sensor mounted at crankshaft's free end

4. Data acquisition

One of the most effective methods for measurement and recording of angular speed of the shaft is optical counter of impulses going through slots in mounting on a toothed ring mounted at shaft, 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 too 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) represents 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 1^{st} cylinder 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. Fig. 4 presents ETNP – 10 measurement arrangements with discs mounted on intermediate shaft and laser sensor installed at the support connected to the bearing basement.

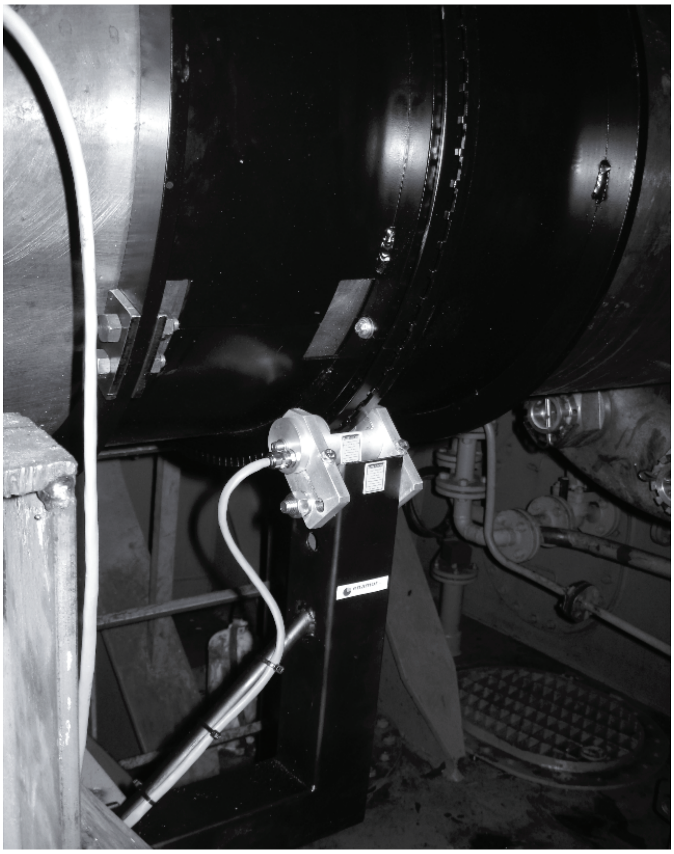

Fig. 4. Toothed rings and optical sensor installed at ship's propulsion shaft

5. Results of measurements

Due to ETNP program configuration, duration of every record was 10 seconds. Data collection was done four times with interval of approximately 2 minutes. Measurement process was repeated two and four days after first one in order to obtain different weather conditions.

Recorded data were processed using Savitzky-Golay filter for elimination of random noise. Instantaneous Angular Speed value was referred to the mean angular speed of the record $\omega/\bar{\omega}$ and presented in form of fluctuations around mean value. Obtained results show two kinds of speed fluctuations. Firs one is angular speed variation within time of one revolution (Fig. 5) caused by contribution of every piston to instantaneous torque value and frequency related to cylinder number and revolutionary speed. Second fluctuation form is modulation of angular speed by impact of sea waves (Fig. 6).

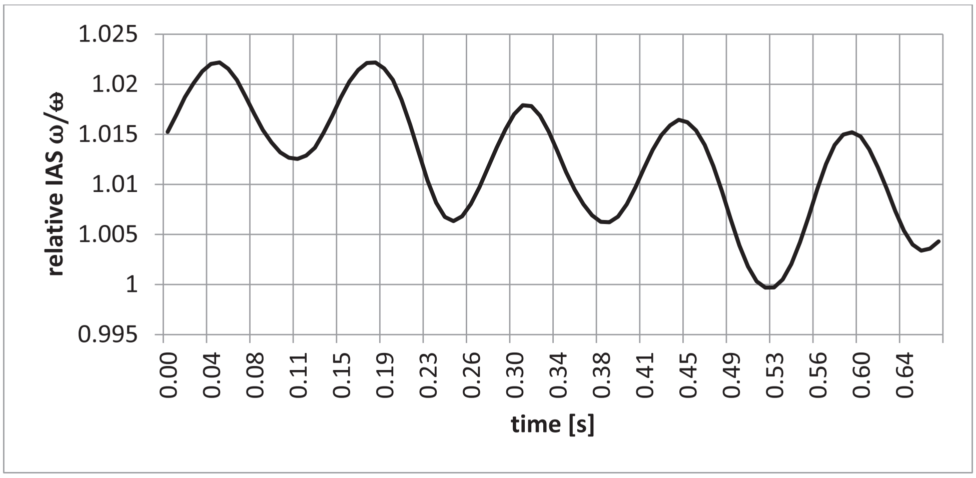

Fig. 5. Angular speed fluctuation due to pistons contribution (one revolution)

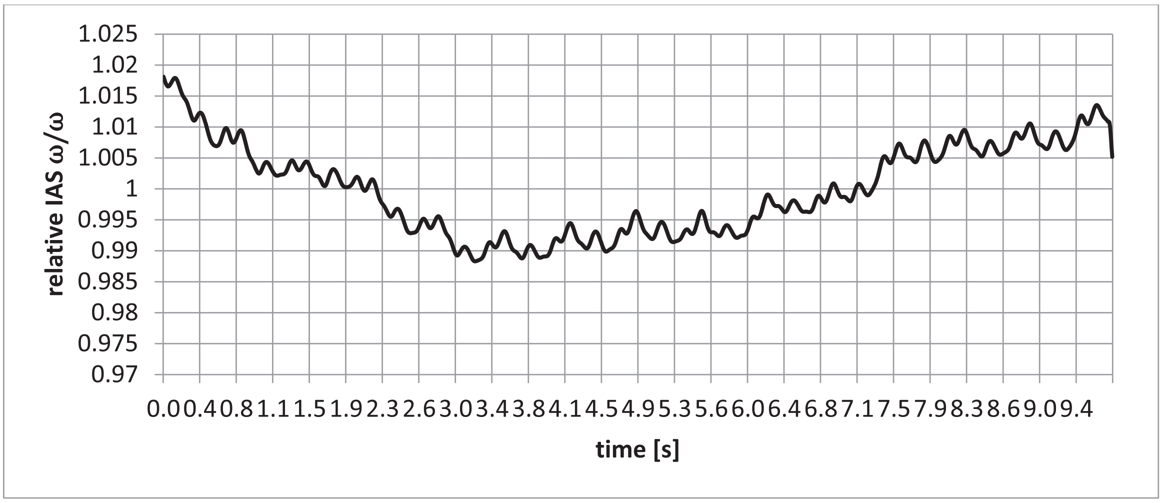

Fig. 6. Angular speed fluctuation caused by superposition of piston contribution and sea impact

Analysis of sea waving modulation leads to the conclusion that despite of irregular character of the phenomenon, sinus-like shape of the course can be observed. Interval between maximum and minimum value of modulation wave is around 5 seconds what is in accordance of general observations concerning ocean waters and moderate wind force 3-4^{o}B. Comparison of subsequent records assuming phase shift confirms general interval between wave's minimum and maximum (Fig. 7). Difference between minimum and maximum of the course reaches 4% of angular speed mean value. Conclusion coming from results of measurements is that even moderate sea state has observable impact at the course of angular speed of the shaft. Above fact must be taken under consideration when detection of potential engine faults is concerned.

Angular speed based method of fault detection relays on comparison of template run with recorded for analysis. Value of difference between compared records is a factor for evaluation of engine combustion. That kind of analysis is unreliable when components of the angular speed function, not deriving from the combustion forces cannot be omitted or eliminated.

Results of comparison random taken records referring to one shaft revolution shows how sea state can disturb results and make analysis completely useless (Fig. 8). Solid line is difference between reference template and revolution recorded in period with low sea wave impact, value is very close to zero what proof good engine condition. Dotted line presents difference between reference course and run taken during time interval encompassing sea wave high positive magnitude period. Although the engine in both cases is in healthy condition, results referred to dotted line suggest problems with combustion what is not true.

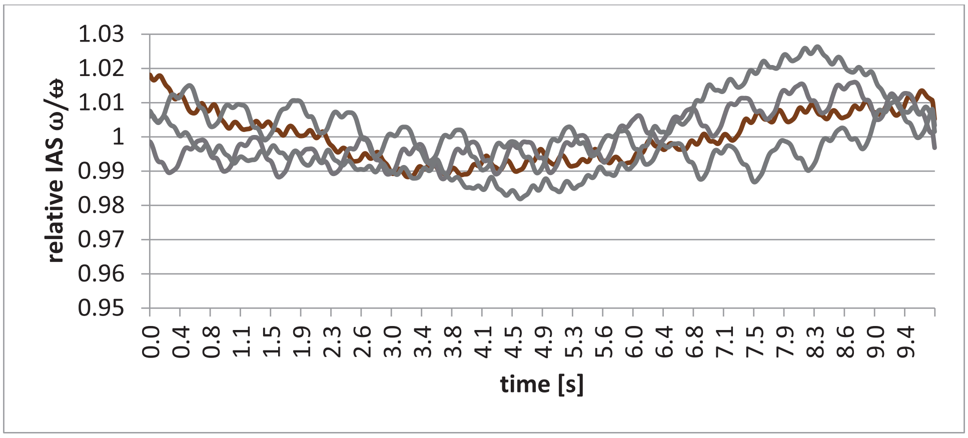

Fig. 7. Subsequent records (with interval between measurements of 120 sec.) of angular speed of the propulsion shaft

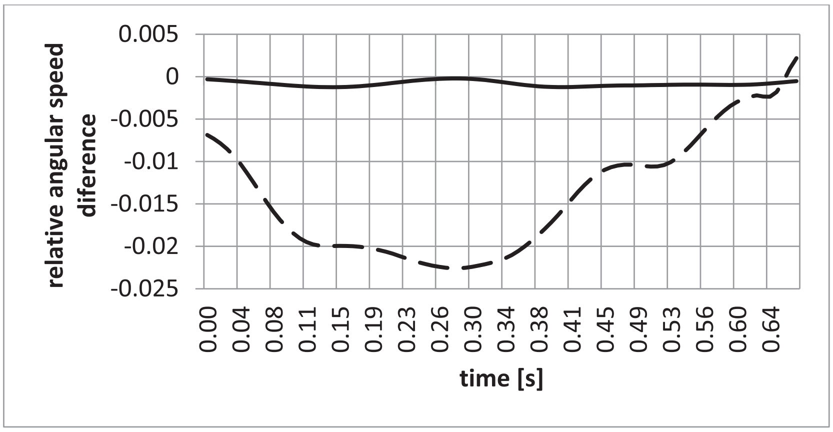

Fig. 8. Difference value between reference course of angular speed and measurement results with wave impact-dotted line and without wave impact – solid line

6. Conclusion

Conclusion coming out from above presented measurements and analysis are that sea state impact at fluctuation of angular speed of the propulsion shaft is strong and can lead to incorrect evaluation of engine's condition. Fault detection method based on angular speed alteration due to variation of piston-deriving forces although effective for stationary engines [2] cannot be straight transferred for ship's propulsion control. To make that method effective and reliable for ships engines, several conditions has to be fulfilled and there are three basic ways to do it:

- to collect healthy engine records under different sea state condition and create separate reference template for each,
- to carry out engine condition tests when sea state is not rough and wave impact can be omitted,
- to create mathematical model consisting of two elementary elements, i.e. engine angular speed fluctuation in stationary condition and sea waving modulation which let make the simulation of outer condition and conclude based on similarity recognition.

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