VALIDATION OF FAILURE DETECTION BY CRANKSHAFT ANGULAR SPEED ANALYSIS UNDER SEA WAVING CONDITIONS

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Summary

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. For marine propulsion set, the weather deriving factor, having impact at angular speed of the shaft, is torque variation caused by changes of propeller's draught due to pitch of the hull. The aim of analysis was to evaluate how pitching frequency affect run of IAS and how to process obtained data to eliminate harmonics deriving from sea waving.

Keywords: diagnostics, marine diesel engine, combustion control, angular speed variation

OCENA WYKRYWANIA USZKODZEŃ ZA POMOCĄ ANALIZY CHWILOWEJ PRĘDKOŚCI KĄTOWEJ WAŁU W WARUNKACH FALOWANIA MORZA

Streszczenie

W artykule zaprezentowano rezultaty analizy wpływu falowania morza na zmiany chwilowej prędkości kątowej wału napędowego statku podczas rejsu morskiego. Wnioski z powyższej analizy są niezbędne do oszacowania poziomu wiarygodności rezultatów pomiarowych przyjętych jako wartości porównawcze służące do wykrywania nieprawidłowości procesu spalania w poszczególnych cylindrach silnika o zapłonie samoczynnym. Metoda diagnostyczna oparta na ocenie zmian chwilowej prędkości kątowej wału wymaga porównania wartości uzyskanych w chwili dokonywania oceny stanu technicznego z wartościami wzorcowymi uzyskanymi z badania silnika będącego w doskonałym stanie technicznym. Na pracę układu napędowego statku mają wpływ czynniki atmosferyczne a jednym z nich jest falowanie morza, powodując zakłócenia regularności prędkości obrotowej wału wskutek zmiennego zanurzenia śruby napędowej. Celem analizy było sprawdzenie czy matematyczna obróbka danych może wyeliminować składowe od falowania morza.

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 tovariable sea state in time of angular speed measurement. In order to exclude errors, conformity of condition when template run 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 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 [3,5].

Sea waving has random characteristic and is difficult for modelling. The source 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 depends on geographical position, for example North Atlantic is different than North Pacific, and wind force. In table 1. are presented examples of significant heights of waves and its intervals. 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.

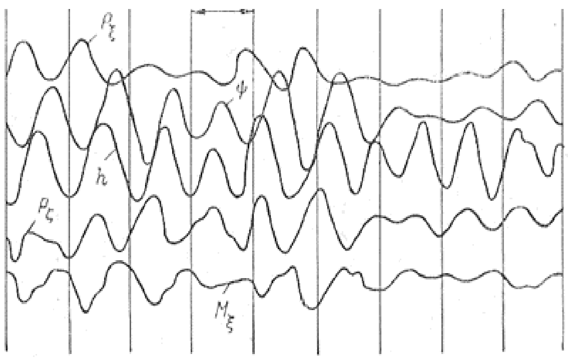

Fig. 1. Model – based courses of: propeller's draught – h, revolutionary torque - M_ξ, thrust - P_ξ and vertical force - P_ζ as result of hull's pitch angle ψ [2]

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

3. SHIP CHARACTERISTIC AND MEASUREMENT SYSTEM

3.1 Propulsion arrangement

The object, selected for carrying out the measurement, was a cargo ship, containers carrier of 120 DWT and cruising speed around 20 knots. The diagrammatic drawing of typical for that kind of ships propulsion 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.2.

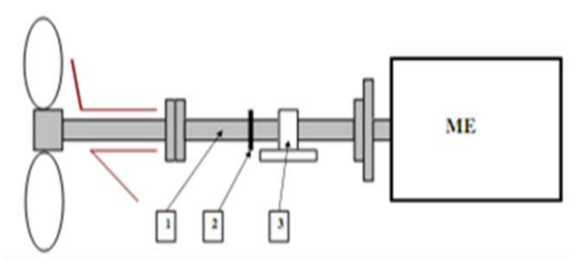

Fig. 2. Scheme of ship's shafting arrangement

3.2 Measurement equipment

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 [4].

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 [2]. 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.

4. SIMPLIFIED MODEL OF SPEED'S FLUCTUATION

4.1. Simplified model of angular speed in stabile conditions

The value which is taken as the base for detection of potential combustion failures is "speed factor", described as a relation of instantaneous angular speed in time "i" to the mean value of angular speed during recorded interval:

$$\Omega_i = \frac{\omega_i}{\omega_{mean}} \tag{1}$$

Above factor value is a variable in time and depends on crankshaft angle and engine condition. For simulation purposes, can be described by simple cosine function:

$$\Omega(t) = 1 + \mathrm{A}\cos(\omega_{mean}\, t + \varphi\tau) \tag{2}$$

where:
A – magnitude depending on engine's load
φ – phase shift

Value of magnitude of the curve has to be established empirically by analysis of records carried out during different engine loads and must be assumed that will be different for every individual engine (can not be taken generally for a engine type) because deviations between output characteristics of two stroke low speed marine engines. Differences between output power can reach even 5% of nominal power. Above facts has to be taken under consideration when a model is elaborated.

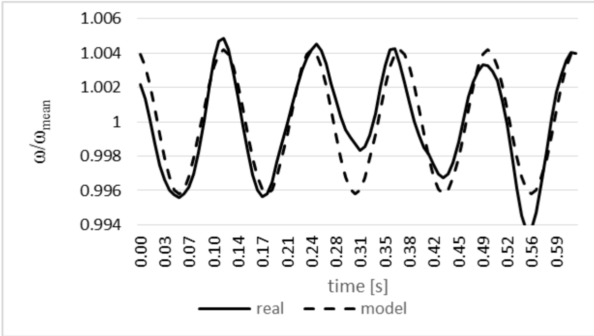

Fig. 3. Comparison of recorded run of speed factor (solid line) and model one (dotted line)

In Fig.3 is presented result of modelling of angular speed fluctuation based at equation (2). Obtained run sustain general character of speed factor changes and is quite close to recorded value. Obtained value of correlation at level of 0.915 gives us justification for further simulation of engine behaviour under fault impacts.

4.2. Sea state impact at speed factor

During operation at sea, the propeller's draft is variable, what cause fluctuations of revolutionary speed and subsequently different value of speed factor Ω. Deviations span from the modelled run and value of speed factor based on recorded speed values can reach 5% of mean (Fig. 4).

That fact makes impossible detection of potential failures in way of comparison of runs and differential analysis. The changes of revolutionary speed caused by propeller's submerging can be taken by mistake as speed disturbance due to engine failure. Analysis of records coming from ships sailing under harsh conditions shows that magnitudes of mean speed fluctuation caused by sea impact are very closed to magnitudes of speed factor fluctuation caused by pistons contributions.

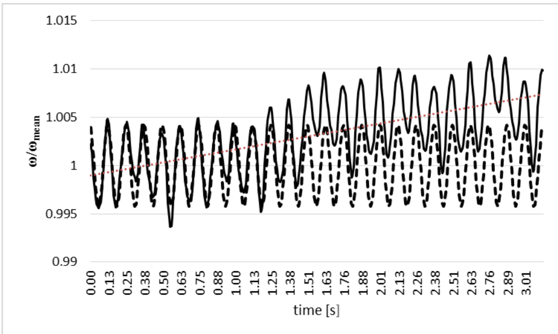

Fig. 4. Comparison of modelled function of speed factor (dotted line) and function of speed factor recorded on real object at waving sea(solid line)

Generally speaking, behaviour of instantaneous angular speed function in time domain depends on superposition of fluctuations caused by pistons contribution and impact of sea waving (Fig.5).

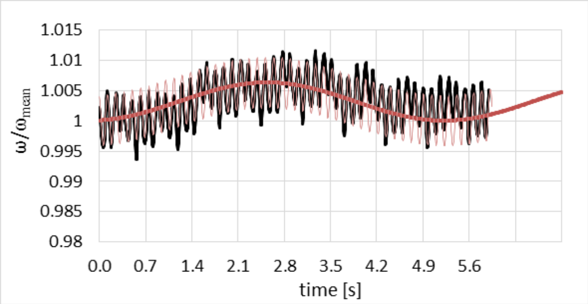

Fig. 5. Speed factor course as superposition of pistons contribution and sea waving.

In comparison method of failure analysis, diagnostic determinant D is presented in form of deviation from basing (sampling) and can be described by equation 3.

$$D = \Omega_i - \Omega_s \qquad (3)$$

Fig.6 presents comparison of value D established for healthy engine at flat sea condition (no waves) and healthy engine working at sea waves. Is clear that higher value of determinant obtained in harsh condition can lead to wrong diagnosis.

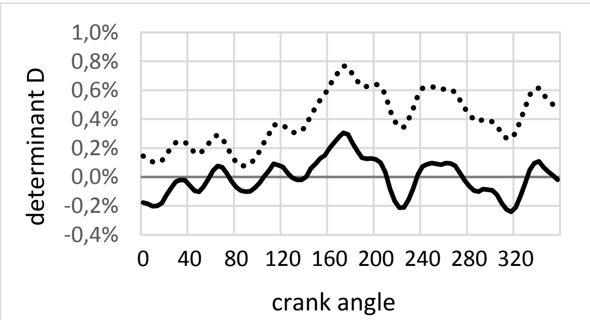

Fig. 6. comparison of determinant D for healthy engine working at calm sea (solid line) and rough sea (dotted line)

4.3 Simplified model of angular speed considering sea state impact

In order to built useful model of healthy engine speed factor course, the component contributing sea wave impact must be added. Despite of irregular character of propeller vertical movement, in every record with duration approximately 10 sec. some intervals having cosine or sine character can be selected. For approximation reasons, angular speed factor component due to waving, can be presented in form:

$$\Psi = 1 + B\sin(f\,t + \delta), \qquad (4)$$

where:
f – frequency of vertical fluctuation of propeller
B – magnitude of fluctuation
Δ – phase shift

Above values can be determined using fluctuation curve based on mean values of speed factor calculated for subsequent revolutions of the shaft. Example of such curve is presented in Fig. 7.

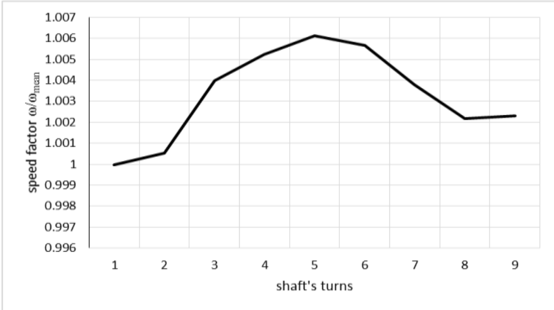

Fig. 7. Mean values of speed factor referring to subsequent shaft revolutions recorded during sea waving (9 revolutions)

Finally, after superposition of modelled function of pistons contribution (2) and wave contribution (4) one obtain modelled course of speed factor considering sea impact (Fig.8).

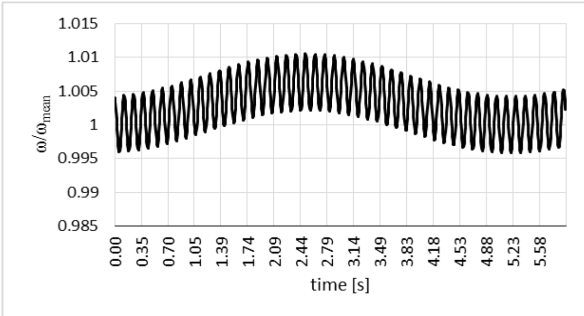

Fig. 8. Model course of speed factor of an engine working at wavering sea

That function is quite general and not fully correlated with real course at required level. The situation can be improved by selection of most similar parts of model and real runs. The selection is relaying at moving Pearson's correlation *r* analysis. Every speed record consist of several subsequent shaft's revolutions and every revolution is described by set of instantaneous angular speed values. Let assume that every one revolution set consist of 90 data, then moving correlation means that first comparison step sets are data number 1,2,3….90 of real and model, second step consist data number 2,3….91; third step 3,4…….92 etc. As result of moving correlation the function with clear maximums and minimums is to be obtained (Fig.9). Selecting the maximum value of Pearson's *r* , the beginning point of most accurate approximation interval of modelled course can be pointed. The interval selected that way can be taken for calculation of determinant's D values.

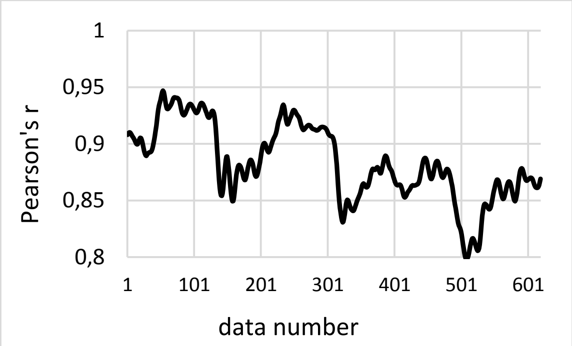

Fig. 9. Moving Pearson's correlation

The simply model, built basing on only one harmonic component of irregular function of shaft's angular speed fluctuation caused by variation of submersion significantly improved results of determinant D calculations. As presented in Fig. 10, impact of sea waving was diminished five times from 0.5% to 0.1% what finally lowering the risk of wrong diagnosis.

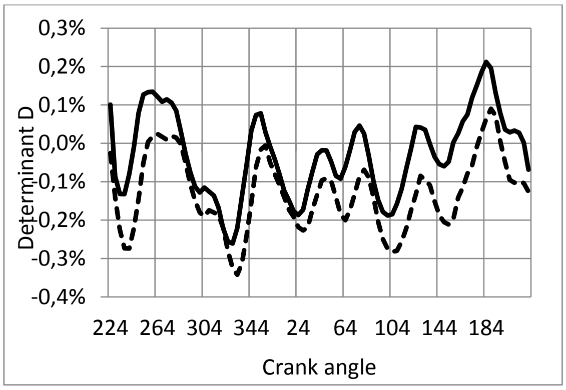

Fig. 10**.** Comparison of determinant D of healthy engine obtained from data collected without waving impact (dotted line) and with waving (solid line)

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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