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Analysis of crankshaft's angular velocity waveforms as a method of long term monitoring of engine performance quality

Analiza prędkości kątowej wału korbowego jako metoda długoterminowego monitoringu jakości pracy silnika

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Key words: diagnostics, marine Diesel engine, angular speed, mean effective pressure, photo optical signal

Abstract
The paper presents an idea to utilize crankshaft's angular speed variation and its derivative for monitoring of trouble of Diesel engine combustion quality. Measurement of instantaneous angular speed, recording and archive of values is easy to obtain using optical indicator and programmable logic controller. Advantage of this method is simple installation and constant signal. Collected data can be processed on board, basing on MS Excel formulas. Observation of changes of instantaneous speed and acceleration can not replace more accurate monitoring systems like Main Effective Pressure measurement or vibration monitoring, but is an excellent tool for early warning. When a signal about deteriorating of engine performance is obtain, more accurate diagnostic can be implemented. Expected final result will be elimination of engine's cycle's irregularity. Proposed method is at early stage of investigation and further steps to prove its utility and to develop concluding rules are to be conducted. In the paper are presented preliminary analysis of some bunches of data collected from two bulk carriers, operating in similar condition.

Słowa kluczowe: diagnostyka techniczna, okrętowy silnik spalinowy, prędkość kątowa wału, ciśnienie efektywne, sygnał fotooptyczny

Abstrakt
W artykule przedstawiono ideę wykorzystania funkcji zmian prędkości kątowej wału korbowego oraz jej pochodnej do monitorowania zakłóceń równomierności pracy cylindrów. Pomiar prędkości chwilowej, zapis i archiwizacja wartości jest łatwe do uzyskania przy zastosowaniu głowicy fotooptycznej sprzężonej ze sterownikiem programowalnym. Zalety powyższej metody to łatwość instalacji systemu oraz uzyskiwanie bieżącego sygnału. Zebrane dane mogą być obrabiane na statku w oparciu o formuły zapisane w programie MS Excel. Obserwacja zmian chwilowej prędkości i przyspieszenia kątowego nie zastąpi typowych pomiarów, takich jak pomiar ciśnienia indykowanego lub monitoring drgań, jest jednak doskonałym narzędziem do wczesnego informowania i ostrzegania. W przypadku otrzymania sygnału o pogarszającym się stanie jakości pracy silnika można przystąpić do dokładnego ustalenia przyczyn przy pomocy dokładnych metod pomiarowych. Oczekiwanym efektem finalnym tych działań powinno być usunięcie przyczyn nieregularnej pracy silnika. Przedstawiona metoda jest na wczesnym etapie badań i wymaga dalszych analiz w celu wykazania jej użyteczności diagnostycznej. W artykule przedstawiono wstępne analizy pakietów danych pochodzących z dwóch masowców operujących w podobnych warunkach.

Introduction

Internal combustion piston engines, due to its work principles create periodical forces with variable directions and values. It is a source of torsion stress and resonance torsion vibrations affecting crankshaft and periodically variable mechanical loads affecting main and journal bearings.

For every main engine, its barred revolutionary speeds are known and procedures how to increase and decrease load avoiding danger values are presented in manuals, or automatically executed by automatic control systems. Prohibited revolutionary speed is related to main harmonics, and must be avoided due to risk of crankshaft damage. One has to take under consideration, that during low speed passages (canals, fairways and harbor manoeuvring) engine works on partly load, and due to higher probability of improper combustion creates additional stress and subsequently higher than calculated magnitudes of torsion vibrations [1].

The most often reason of slide bearings damages is material fatigue caused by periodically variable forces in function of combustion pressure and revolutionary speed. Probability of crack occurring is strictly related to forces irregularity, caused by improper combustion or changeable load (periodically partly submerged screw propeller). Improper combustion is a reason of additional dynamic load of bearings what cause in primary phase small cracks and finally lost of sliding layer [1]. The conclusion from above facts is that constant control of combustion and proper fuel pumps regulation can be crucial for extension of engines' lifetime.

Mentioned above stress creating factors, can caused in long term exploitation periods, shaft's, bearings and couplings material fatigue, and finally be a reason of serious damages, creating not only economical looses, but also risk of setting ship in distress situation.

Even most modern vessels are not very often equipped with systems dedicated to constant monitoring of engine performance [2, 3]. The most effective method of combustion control which is measurement of in-cylinder pressure can not be executed permanently because of temperature immensity of gauges. What more, standard routine is engine's indication when is on nominal load. During manoeuvres or passing canals, machine crew is focused on steaming safety and is not performing measurements. Taking above into consideration, one has to come into conclusion that any system giving on-line information about quality of combustion or instantaneous rotational speed changes would be very useful engine control aid.

Object of analysis and measurement method

As objects of analysis, has been selected two sister bulk carriers, propelled by two stroke marine Diesel engines the same type. Particulars of the engines are presented in table 1. For further considerations vessels are identified as "*object 1*" and "*object 2*".

Both vessels were performing its duty under similar condition, and were encompassed by the same maintenance and exploitation routines. The bulk carrier propulsion arrangement composes of a main engine, straight connected with a screw propelled by intermediate and propeller shaft (all couplings are stiff, flange type). Due to straight connection, one can assume that torsions measured at the intermediate shaft reflect piston forces action.

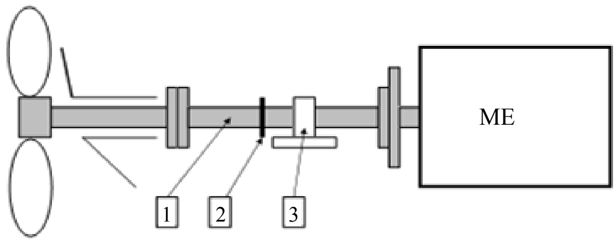

Fig. 1. Layout of ships propulsion with toothed rings mounted at intermediate shaft: 1 – intermediate shaft, 2 – measurement toothed rings, 3 – shaft bearing, ME – main engine
Rys. 1. Schemat układu napędowego z tarczami zębatymi zamontowanymi na wale pośrednim: 1 – wał pośredni, 2 – tarcze pomiarowe, 3 – łożysko wału, ME – silnik główny

The engine's parameter taken as its condition identifier is instantaneous angular speed of the crankshaft. This parameter is pointed by many authors as representative and adequate value for combustion quality evaluation [4, 5, 6].

Table 1. Main engine and propeller particulars
Tabela 1. Dane techniczne silnika i śruby napędowej

Main Engine Particulars	
Type	Two-stroke Marine Diesel Engine
No. of cylinders	5
Firing order	1–4–3–2–5
Output (MCR) at RPM	9319 kW/ 89 RPM
Max. torque	999 kNm
Max. Continous RPM	89 RPM
Min. RPM	26 RPM
Cyl. bore / stroke	600/2400 mm
Screw Propeller Particulars	
Type	Fixed pitch, D = 6600 mm, H for 0.7R = 5491 mm
H/D	0.832
No. of blades	5

All data measurement and collecting has been carried out using torque meter ETNP-8, produced by enterprise ENAMOR Ltd. The torque meter is mounted at intermediate shaft and measure instantaneous angle of shaft torsion and instantaneous angular speed. Measured values are given in the form of numbers of laser beam impulses emitted with constant frequency, received by photodiode when a slot is crossing laser beam and blind signal when tooth is cutting the beam. Example of measuring discs mounted at the shaft is presented in Photo 1.

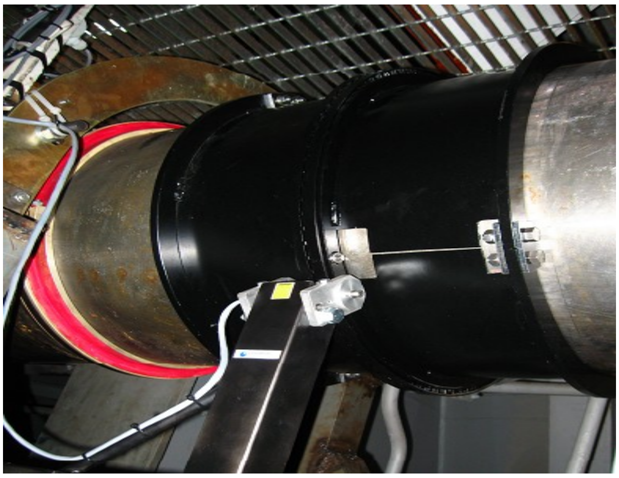

Photo 1. Toothed rings and laser sensor ETNP-8 mounted at intermediate shaft
Fot. 1. Tarcze zębate momentomierza ETNP-8 zamontowane na wale

All data has been collected during vessels' exploitation and cover a period of three years. The aim of analysis is to proof utility of constant measurement of angular speed variation and further comparison with a corresponding waveforms template for preliminary engine diagnostics. As a base condition status, shall be measurement registered during sea trials of new vessel or after periodical repair, confirmed by accurate internal combustion pressure indication. When engine technical condition is declared as proper, recorded angular speed waveform can be treated as a template. Any deviation from a status determined as a basic, shall be a signal to improve combustion uniformity, on the way of fuel pumps regulation and subsequently checked by using electronic indicators. Even proposed method cannot replace the indicator graphs, the advantage of on-line information and early warning seems to be obvious.

Measurements results

Instantaneous angular speed (IAS) was recorded on board of both object under different loads of main engines. Measurements were performed for two most common rotational speeds zones occurring during exploitation, low speed in range 29–39 r/min and sea passage speed in range 79–84 r/min.

As a value representing angular speed variations, deviation from one revolution's mean speed is taken. Mean speed is calculated on the basis of 5 subsequent revolutions.

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 [2]. The chart in figure 2 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.

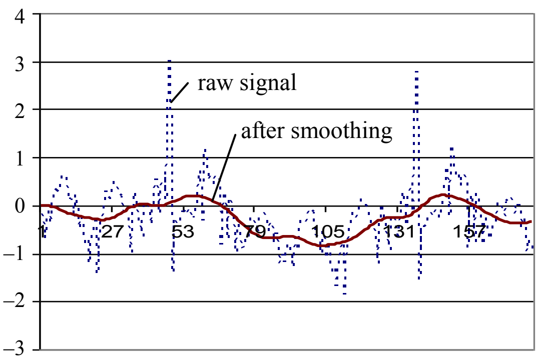

Fig. 2. Recorded angular speed waveform (dotted line) and the same after third step of smoothing
Rys. 2. Zarejestrowane wartości prędkości chwilowej (linia kropkowana) oraz jej przebieg po aproksymacji (linia ciągła) w dziedzinie próbek (dwa kolejne obroty)

In order to obtain an information concerning dynamics of instantaneous angular speed variations derivative of function of speed deviations is calculated. Waveforms obtained in this way are a subject of comparison and analysis. All charts present sampling of one revolution of the crankshaft.

Comparison of low speed derivative waveforms

In figures 3 and 4 are presented recorded waveforms of angular acceleration of the shafts of *object 1* and *object 2* when engines were running with low speed. That situation occurs during manoeuvring or canal passages. Very clear 5 regular peaks, corresponding with periodical forces created by five cylinders can be observed. Picture of *object 1* is similar to the picture of *object 2*. Magnitudes of *object 1* are included between values of –2 to 1.5 and are higher than *object 2*. The more regular waveform of *object 2* is due to better combustion at higher rotational speed. Both pictures give information that in all cylinders combustion process is proper.

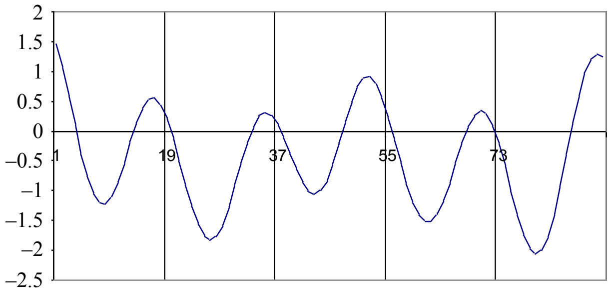

Fig. 3. Recorded angular speed derivation waveform, object 1, running with 28 r/min
Rys. 3. Przebieg przyspieszenia kątowego w dziedzinie próbek, obiekt 1, średnia prędkość 28 obr/min

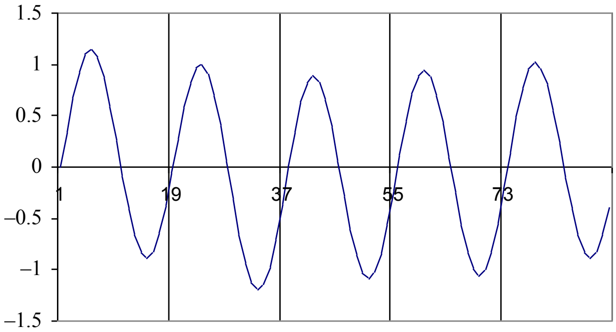

Fig. 4. Recorded angular speed derivation waveform, object 2, running with 39 r/min
Rys. 4. Przebieg przyspieszenia kątowego w dziedzinie próbek, obiekt 2, średnia prędkość 39 obr/min

Increasing of engine load and rotational speed will effect with less symmetric peaks pattern and decreasing of magnitudes, what means more regular instantaneous speed. Example of speed increasing impact at acceleration waveform is presented in figure 5.

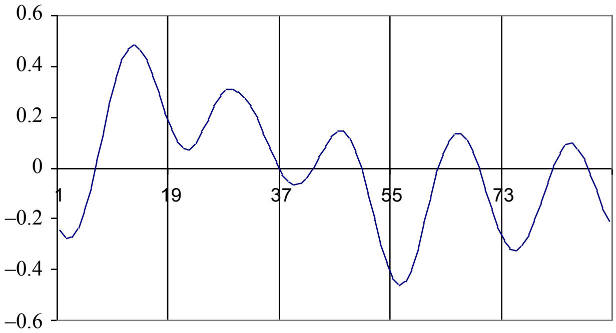

Fig. 5. Recorded angular speed derivation waveform, object 1, running with 77 r/min
Rys. 5. Przebieg przyspieszenia kątowego w dziedzinie próbek, obiekt 1, średnia prędkość 77 obr/min

Comparison of speed derivative waveforms of engine under nominal load

Under nominal load, forces of rotating engine masses and strong impact of a screw propeller action masks signals coming from pistons forces, thus acceleration waveform is more irregular and peaks in zones corresponding with subsequent strokes are not observed. Nevertheless, as long as engine is sustaining combustion characteristic, the run of acceleration function keeps constant form. Every change, either improving or decreasing combustion quality, will change the waveform and become diagnostic signal. In figure 6, the comparison of waveforms and the impact of maintenance action carried out in 2009 are presented.

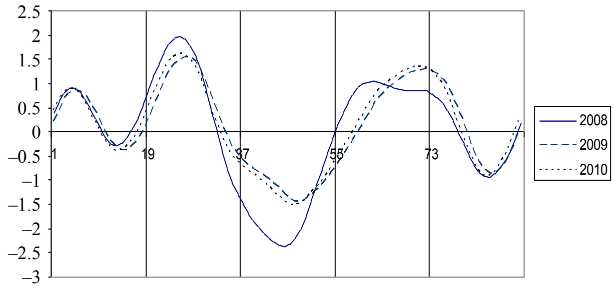

Fig. 6. Comparison of recorded angular speed derivation waveform, object 1, running with 82 r/min, records from years 2008, 2009, 2010
Rys. 6. Przebieg przyspieszenia kątowego w dziedzinie próbek, obiekt 1, średnia prędkość 82 obr/min, zapis z lat 2008, 2009, 2010

Taking *object 2* for analysis, one has to notice that in the period between year 2007 and 2010, the form of waveform of angular acceleration did not changed significantly (see Fig. 7).

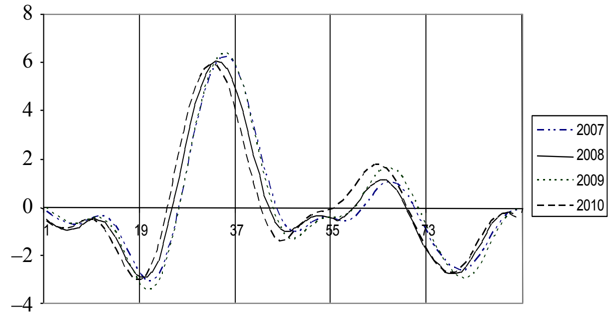

Fig. 7. Comparison of recorded angular speed derivation waveform, object 2, running with 84 r/min, records from years 2007, 2008, 2009, 2010
Rys. 7. Przebieg przyspieszenia kątowego w dziedzinie próbek, obiekt 2, średnia prędkość 84 obr/min, zapis z lat 2007, 2008, 2009, 2010

From the other hand, is visible that maximum magnitude observed for *object 2* is much higher than maximum observed for *object 1* (Fig. 8), but only in the zone of one cylinder stroke. Taking above under consideration, one could came into conclusion, that mean effective pressure (MEP) in one cylinder should have higher value than in other four. As the results of MEP indication are available, comparison of angular speed and MEP pattern is possible. Figure 9 presents angular speed oscillation and figure 10 presents MEP deviations from mean value. The correspondence between two pictures can be observed, both functions taking negative and positive values in the same zones.

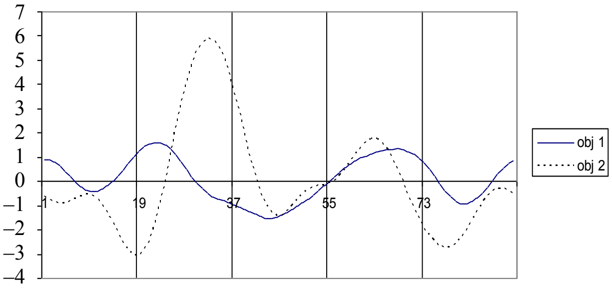

Fig. 8. Comparison of recorded angular speed derivation waveform, object 1 and object 2, running with 84 r/min
Rys. 8. Przebieg przyspieszenia kątowego w dziedzinie próbek, obiekt 1 i obiekt 2, średnia prędkość 84 obr/min

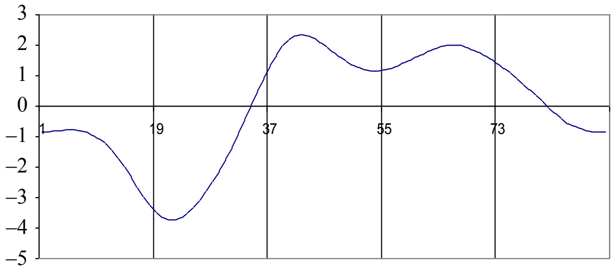

Fig. 9. Recorded angular speed waveform, object 2, running with 84 r/min
Rys. 9. Przebieg prędkości kątowej w dziedzinie próbek, obiekt 2, średnia prędkość 84 obr/min

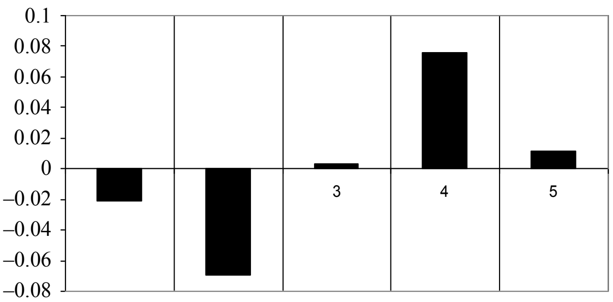

Fig. 10. Graph of deviation from mean value of mean effective pressure, object 2, running with 84 r/min
Rys. 10. Wykres odchyleń średniego ciśnienia efektywnego od wartości średniej dla 5 cylindrów, średnia prędkość 84 obr/min

Conclusions

Results of experiment presented in this paper let assume that using photo optical speed indicator based on toothed rings mounted at a shaft is very useful diagnostic signal source. Analysis of measurements carried out using the torque meter ETNP-8 enable to detect irregularity of engine work, and to show the tendency of changes. One has to realize that irregularity detection is very important, because any imbalance of combustion forces creates additional vibrations, and finally additional zones of barred rotational speed. Results of presented analysis are a justification of further development of the method of instantaneous angular speed (IAS) measurement based at a toothed ring and an optical sensor. Angular acceleration signal, after smoothing, is assumed as one most contributing and reflecting combustion process disturbances. The further investigations have to be focused on determination of relation between deviations of angular acceleration and Mean Effective Pressure pattern. It is obvious that proposed method can be acknowledged only in the way of long term analysis and requires bigger than two, population of object encompassed by investigation program.

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