Mathematical modelling malfunctions of marine diesel engine

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Abstract. The paper describes modelling methods of selected malfunctions in a four-stroke marine diesel engine. The model has been developed for purposes to assess methods of technical conditions selected elements of the engine structure. Modelling malfunctions allow to determine answers to energetic parameters of the faults. The paper is based on earlier publications, in which was carried out studies of the physical model of energetic processes in engine and additionally the mathematical model which was based on the developed physical model.

1 Introduction

The engines which are operated on the board of Polish Navy ships, most of them are supercharged, high speed, four-stroke engines. They are used as a main propulsion and an auxiliary engines both. The auxiliary engines drive electric generators acting together with diesel-generator (ZSE). Most of them they are not equipped with indicator valves, especially auxiliary engines [1, 2]. This is the main reason for using the TBO hourly strategy relative to this engines. This method of operation presents several problems:

- need to shut down an engine from service for maintenance. The combat readiness of the ship is low,
- high operational costs resulting from a replacement of components that could be used in the further. This illustrates the Wöhler curve (Fig. 1).

Fig. 1. The Wöhler curve [3].

Wöhler curve is a relationship between tension (periodically variable) and a number of load change cycles that could perform a part of machine until it will be destroyed due to fatigue. Wöhler curve is a statistical curve. An expected number of cycles must be under the curve. What is more, a problem is to estimate a load on an engine. As the result in most cases engine

components are changed to fit for further use. These factors make necessary to look for alternative strategies according to exploitation marine engines.

Another operating strategy is the exploitation of a technical condition which is free of mentioned disadvantages [4, 5]. This strategy method involves periodic implementation of diagnostic tests. This allows to determine a technical condition of an engine (the diagnosis). What is more it could be expected changes of a technical condition in a future (prediction). It allows that a part of engine construction could be replaced in the pre-damage moment [6, 7].

One of priorities of research in The Institute of Ships Construction and Operation (IBiEO) Polish Naval Academy (AMW) is development of technical condition of engines based on non-invasive methods. Mentioned methods are based on energetic parameters diesel's marine engines or electric generators. One of the ZSE's energetic parameters is interfacial voltage of synchronous generator which is driven by engine. Analysis of recorded waveform will determine fluctuations of crankshaft engine (shaft generator) angular velocity. Fluctuations of crankshaft engine angular velocity are the result of many factors. The main ones being:

- order of cylinder work (torques generated by gas forces),
- mass reciprocating and rotary movement,
- working cycle disruption as a result of structural engine's elements damage.

Fluctuations are repeated periodically and the period of four-stroke cycle engines is:

$$T = \frac{n}{2} \cdot N_{cyl} \quad (1)$$

where:

n – the rotational speed of engine's crankshaft [s^{-1}],
 N_{cyl} – the engine cylinders number.

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Fluctuations are the result from gas forces and mass moments of inertia. The Period of fluctuation rotation speed (four-stroke engine) is:

$$T = \frac{n}{2} \quad (2)$$

It results from working cycle disruption, which is connected with engine's damage.

2 Modelling of marine diesel engine's working cycle

Teams of scientists work on the problem of modeling processes in diesel engines in many countries in the world [8-10]. Most of the research is focused on a design of marine diesel engines and its environmental performance [11-13]. Many commercial programs are usually designed for this purpose. In most cases these programs are based on the finite element FEM and BEM boundary element method. Using them for diagnostic tests is often problematic. This is due to the fact that malfunctions typically are modeled as a change in the geometry of an engine structure. This approach is associated with the commercial models of a need to modify respective mesh elements. It is a very labor and time-consuming process. The source code of commercial programs are unavailable and users have only executable file. User does not have information about calculation methods and what simplifying assumptions have been applied. Therefore, it has been decided to develop a mathematical model of the physical processes in the marine four-stroke diesel engines. For this reason the model must fulfill several conditions, the most important of which are:

- versatility, must make possible of modeling all four stroke engines which are operated in Polish Navy,
- must be able to quickly and easily modify the structure parameters of selected structural engine components (eg. enable of changing the fuel delivery to each cylinder independently),
- performing rapid calculations for efficient and damaged engines both.

The algorithm of research methodology are shown on Fig. 2.

The object of the research is the ZSE – part of a ship's power plant. On a basis of a generating set the physical model of processes occurring in a marine engine is designed [15]. Based on the physical model is developed mathematical model of these processes [16].

3 Modeling fault conditions marine diesel engines

Marine engines is degraded differently in various states of operations (standby, running). This is a result of chemical and physical processes such as erosion, corrosion, friction or semi-dry friction, clogging, fatigue. The consequence of the engine's structure degradation is a change of condition and could be gradual or sudden. The state of condition changes from technical efficiency to the state of unfitness.

The model takes into account the ability to simulate changes in the technical condition of marine diesel engines. This is implemented by modifying the technical structure of engine. Modifications may concern elements comprising all or individual cylinder sections of engines. The modifications concern the structure of engine design (geometric dimensions) as well as the parameters of fuel and air supply. Modeled can be:

- change of fuel dose for each cylinder's sections (modeling of damage to the engine fuel supply),
- change fuel's chemical composition (for the whole engine),
- change timing injection (for each cylinder),
- change active cross-section area of intake and exhaust valves (for each cylinders),
- change of a flow resistance in exhaust channel (for whole cylinders),
- a leak in a piston-rings and cylinder (TPC) (for each of cylinders),
- change active cross-section area of injector holes (for each of cylinders).

The dose calculation of fuel is delivered during the engine cycle which is based on a value of the excess air ratio λ . By the fact that the parameter is easily measurable by exhaust gas analyzer this is the best way to determine the dose of calculation fuel.

The changing of the fuel chemical composition (in the model) is not a result of engine's technical condition. However, it is decided on the possibility of modifying this parameter. The calorific value is changed by the fuel composition, which shows the relation:

$$W = 340 \cdot C + 1017 \cdot H + 63 \cdot N + 191 \cdot S - 106 - 25 \cdot w \quad (3)$$

Fig. 2. Schematic implementation of research [14].

where C, H, N, S – are the percentages of the various chemical elements contained in the fuel. And w determines the moisture content of the fuel.

Changing the injection timing may concern the whole engine and its individual cylinders. Change of the injection advance angle for individual cylinders is a result of change injection pump shaft.

Changing the active cross-section area of the intake valves and exhaust can be modeled for the whole engine and each cylinders. Modelling of active cross-section area is performed by modifying the flow rate μ . Value μ can be between 0 and 1, as shown by the equation:

$$\dot{m} = w \cdot S \cdot \rho \cdot \mu \quad (4)$$

where: w – linear velocity, S – cross-sectional area of the valve, ρ – density factor, μ – flow rate.

Change pressure values anti-outflow of gases from the exhaust channel outlet are modeled for the all cylinders. This is realized by modifying the pressure p_2 at the outlet from the engine cylinders in the equation de Saint-Venant [17]:

$$w = \sqrt{\frac{2 \cdot \kappa_1}{\kappa_1 - 1} \cdot R_1 \cdot T_1 \cdot \left[1 - \left(\frac{p_2}{p_1} \right)^{\frac{\kappa_1 - 1}{\kappa_1}} \right]} \quad (5)$$

In equation 5 parameters marked with the subscript "1" refers to higher pressure (in-cylinder). Index "2" refers to a value at the output of a cylinder. Equation 5 is true, when the pressure inside a cylinder is higher than a pressure in an outlet channel, and when the linear velocity w is less than the speed of sound a which is determined by the equation [7]:

$$a = \sqrt{\kappa_1 \cdot R_1 \cdot T_1} \quad (6)$$

Modelling of leaks in a piston – ring – cylinder (TPC) is carried out for each cylinder separately. It is realized by specifying a value of a cross-section leaks in a TPC. It is calculated a value of the linear velocity (a leak) for each iteration. A value of the linear velocity w of the thermodynamic medium from a cylinder

(a pressure inside the cylinder is higher than in a crankcase pressure) is based on the de Saint-Venant relation (relation 5).

The thermodynamic medium outlet from a cylinder, the value p_1 replies to the pressure inside the cylinder. The pressure p_2 replies to the pressure inside the engine crankcase. Parameters such as the adiabatic exponent κ_1 , the individual gas constant R_1 and the temperature T_1 correspond with the parameters inside a cylinder. In case of a calculation all parameters are treated as variable and could be changed in every counting iteration (temperature, pressure, chemical composition). For modeling of engine failures, it is necessary to provide a constant of an indication power value for an engine in the fit state and the out of order.

In the model, this condition is fulfilled by being determined calculations engine's indicated power value for an efficient of engine. In the case of a damaged engine, calculations are repeated and in every iteration – the fuel feed rate (the excess air ratio) for an engine cylinders is modified. If a value of an indication power is less one percent (for damaged engine) then the calculation will be proceeded.

Exemplary results of carried out calculations (for full and partial technical condition of the engine) in the case of modification of fuel injection dose to one of the engine's cylinder are shown in Figures 3 and 4. Figure 3 shows the course of the indicated pressure as a function of the crankshaft's angle. Course "1" is obtained as a result of calculations for the engine in a state of full technical condition. Course "2" is corresponded to a 50% reduction in fuel supply to cylinder number 1.

Analysis of the figure shows that the speed regulator increased the fuel dose in the remaining cylinders to compensate indicate power loss due to reduction in the fuel dose in cylinder 1. For a fully engine-fit engine, the value of the excess air factor λ was 2.2. In the case of a damaged motor the excess air factor λ is 1.9. Indicative power for efficient engine was 405,182 kW and for damaged is 404,997 kW. The indicative power values of the individual cylinders for a fully engine-fit engine and damaged engine are shown in the Figure 4.

Fig. 3. The part of graph presents a pressure curve of an engine as a function of a crankshaft rotation angle, 1 – efficient engine, 2 – damaged engine.

Fig. 4. The graph of power indicated by individual engine cylinders: a) efficient engine, b) damaged engine.

Fig. 5. The graph of pressure as a function of a crankshaft rotation angle, 1 – efficient engine, 2 – damaged engine.

Fig. 6. The graph of power indicated by individual engine cylinders: a) efficient engine, b) damaged engine.

Another example of the research is a modification of an exhaust backpressure value in engine's exhaust duct. Figure 5 shows a process of indicated pressure as a function of the crankshaft rotation angle for an engine in full technical state and for a damaged. The back pressure (in exhaust duct) was doubled than nominal in simulation. As a result of the simulation the dose of fuel injected into the cylinder was increased (the result of the speed controller) and its combustion process was clearly elongated. The increase back pressure was caused an increase in unit fuel consumption from 105.25 to 111.02 g/kWh.

4 Summary

Damage modeling described in the article is one of the stages of method assessment of technical condition development of a marine engine with limited control susceptibility. Ability to simulate energy parameters of an damage engine allows both quantitative and qualitative assessment of their impact on it. The proposed model can also be used for research purposes: assess the energy efficiency of marine engines and assess impact of damage engine on emissions of toxic compounds.

The model is highly sensitive to a technical failures. Simulation of damage by reducing the fuel dose in one of cylinders caused about 30% indicated power drop from a damaged cylinder. Remaining cylinders increased the load by about 6%. The total power indicated by engine cylinders practically did not change due to a simulated technical state. In simulation, the change of flow resistance in an exhaust duct caused about 8% decrease in excess air factor. In addition, an increase back pressure caused an increase about 6%. The indicated power was not changed for this damage.

Currently the mathematical model is being verified by comparing the results obtained during experimental research on Sulzer type 6AL20/24 and Leyland type 6SW400 engines.

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