OPERATION OF DIESEL ENGINE IN DIRECT SHIP PROPULSION

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Abstract

In the paper an identification of low speed diesel engine operation in direct propulsion plant equipped with fixed pitch propeller during ship manoeuvring. It was starting of engine and gathering speed of ship. Analysis of engine operation was based on changes of engine torque and time of ship bring up to speed. Operation of reciprocating internal combustion engine consists in converting the supplied fuel energy and delivering it to ship propeller.

This condition implicates converting different amounts of energy in different time. The main attention was given to operation of engine caused by crank pin forces in wide range of revolutions and their influence on mechanical load of ship propulsion plant. The torque is the major component determining the engine load. As a matter of fact its mean value is low, but a passing torque can be four times higher than the rated torque.

The second important component of propulsion engine operation is the time of ship acceleration from one speed to another. It determines dynamic properties of the ship describing its reductional feature. This time is determined in dependence on other parameters characterizing operation of ship propulsion plant and ship motion by means of dimensional analysis.

These parameters were regarded as dimension quantities of three-dimensional space. Thus the three independent in dimension parameters can be noted in digital form in dimensional functions. The knowledge of operation parameters of ship propulsion plant and the knowledge of ship motion dynamics makes possible rational manoeuvring.

It increases safety of ship motion and failure-free operation of ship propulsion engine. The proper operation of engine requires delivery to the propeller such amount of energy, which ensure the motion of ship with required speed in given sailing conditions.

Keywords: *transformation of energy, engine performance, space-dimensional, the dimensional feature*

1. Introduction

Operation of low-speed diesel engine in direct drive of constant pitch ship propeller was defined in following conditions:

- starting the engine,
- increasing the speed of the ship.

These maneuvers are performed many times during normal ship operation. However, diesel engine performance depends on sailing conditions of the ship. It is based on the converting and transferring of fuel chemical energy from the engine into mechanical energy driving the propeller. This means that during engine manoeuvring operation it depends on the way of supplying engine cylinders with fuel and the way of processing and transferring energy to the propeller.

Operation of the ship propulsion engine while manoeuvring the vessel should cover working conditions without overload. This ensures a sufficiently long duration of action of the propulsion engine to its full load. Thus the excessive heat load of engine components as a result of increase of engine power is avoided.

Condition of the ship manoeuvring operation of the propulsion engine motor causes a fastchanging value of torque loads with high-amplitude fluctuations from negative to positive values. Such loads have a significant impact on the sustainability of individual elements of the propulsion system and engine.

Therefore, the identification of ship manoeuvring operation was carried out to evaluate the mechanical action of the engine. Such action is associated with tangential forces on the engine crankshaft, which in turn cause the torque on the shaft of the ship propeller.

2. Starting the ship propulsion engine

A typical course of engine the starting process is as follows: after forcing the starting air to the engine a pressure is built up in pipes supplying air to starting valves. Next the control air is directed through air distributor into starting valves placed on engine cylinders and opens them when the pistons are in the starting position i.e. in top dead centre (TDC). Compressed air pushing the piston gradually reduces the pressure after the manoeuvring valve (for the tested engine Sulzer 5RD68 the pressure drops from 0.3 MPa in the first period of starting to 0.2 MPa in final period). When the piston approaches the lower dead point (DMP) the starting air distributor closes the starting valve of cylinder [8]. This results in a dramatic stop of air flow which results in change of air kinetic energy into pressure potential energy. Therefore, at a starting air time diagram chart the peaks are observed. Number of peaks on the graph indicates the number of starting valves, which are opened up at engine starting time. Thus the starting air opening time can be read from the diagram. This time is a function of rotational speed of the engine crankshaft. At the beginning of start-up of tested low speed diesel engine Sulzer 5RD68 it was 0.2-0.25 sec.

After reaching the starting speed of the engine air intake is closed. This is shown in the chart time of starting air pressure as its immediate increase. It is caused by converting of the kinetic energy of air into the potential energy. This increase is much higher than during single cylinder valve closing, because the entire stream of starting air is stopped (for the tested engine, it amounts from 0.3 to 0.4 MPa).

Simultaneously with the interruption of starting air supply the shift of fuel adjustment lever is executed to the position corresponding to start-up dose of fuel. For the tested engine 5RD68 it is the position 5-6 much higher than required by instruction manual (3.5) [8].

During the starting period an observed air pressure after manoeuvring valve was lower than expected and ranging from 2.6 to 2.7 MPa.

In case the short time before the starting air entry the fuel lever was set to a given dose of fuel to ensure higher revolutions of engine in the first period of running. Faster gathering speed by engine can be explained by his earlier work on the fuel. The time of the air action during the start of the test engine was about 1.6 sec.

The average torque values are small in the process of engine starting. The maximum amplitude of the fluctuations in torque occurred in passing through a critical speed. It exceeds twice the nominal torque and tripled the amplitude in relation to the loads occurring at the rated speed and maximum values of torque [6, 7]. The time of passing through a critical speed was short, both in gatherings speed and its reduction. Despite short passing through the critical speed the instantaneous maximum torque values were high. After passing by the engine critical speed range the amplitude fluctuations of the instantaneous torque on the output shaft decreased.

During the starting the engine when the critical rotational speed is passed low average torque on the output shaft was observed.

Figure 1 shows a delayed movement of the fuel adjustment lever, which causes late delivery of fuel to the engine cylinders and consequently, the need to re-pass through the critical speed. It results in further increase of engine load, which is harmful for engine.

Starting of the engine can be executed from Engine Control Room, or by remote adjustment of manoeuvring lever on the bridge "Ahead" or "Astern".

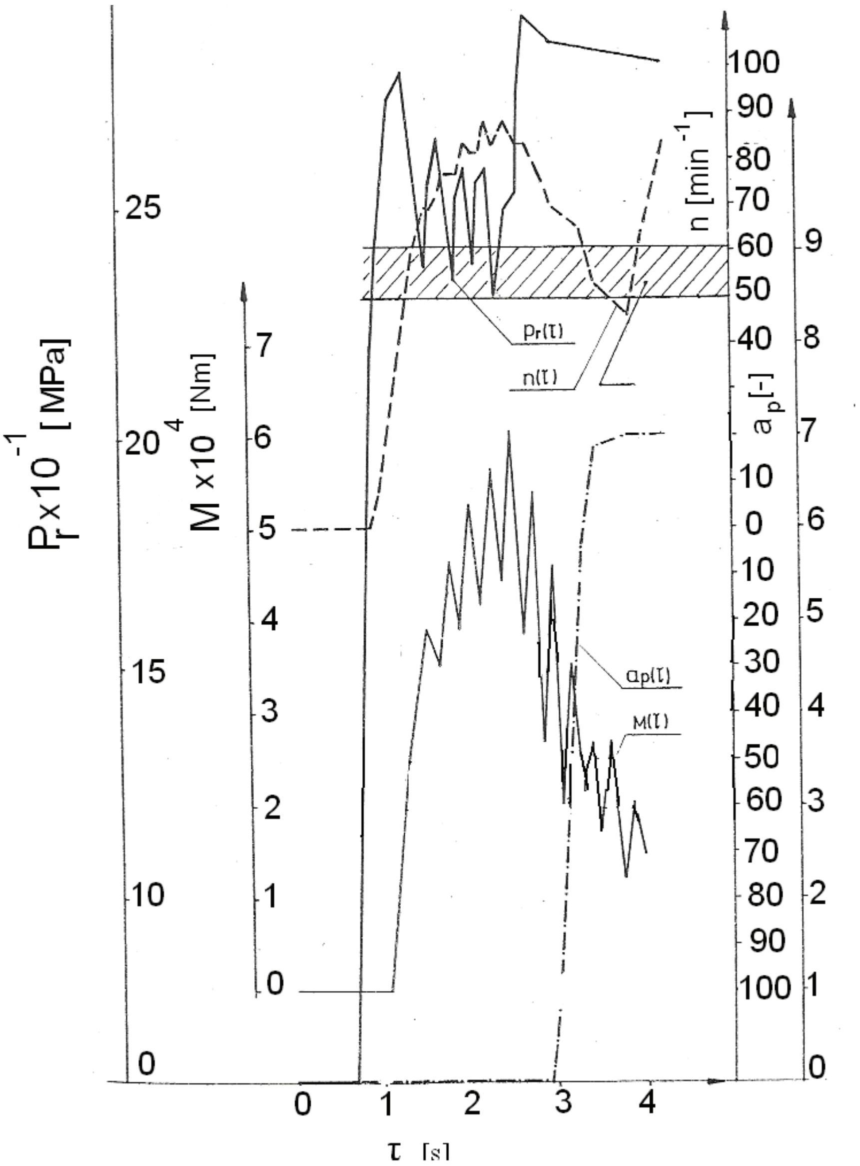

Fig. 1. Course of the operating parameters of engine propulsion type Sulzer 5RD68 during the riots at the start, "forward" Explanation: pr (τ) - starting air pressure, and p (τ) - Location of the fuel rail, n (τ) - engine speed, τ-time waveform parameters in the [s], A-critical range of engine speeds [7]

After reaching the ignition speed of the engine the control system acts as follows:

- stops starting air feeding,
- after excess of start air feeding time limit (set on the corresponding relay) gives information “engine running”’,
- changes over the fuel rate from starting dose to running dose according to the set rpm,
- opens the vent of air distribution,
- changes over the position of the fuel valve from starting position to emergency position.

When the engine does not reach the ignition revolutions the following is executed:

- information "start fail",
- restart of engine on emergency starting fuel dose.

On the contrary when the engine reaches ignition revolutions the relay prevents the next start. A second drop in engine speed below the ignition speed after an excess of time limit the information "start fail" is given by the relay [6]. The restart is possible if the control lever is set to

“Stop” position and next to position "Ahead" or "Astern".

3. Operation of propulsion engine during the ship speed acceleration

During the acceleration of the ship the propulsion system must produce an additional force of thrust, which will cause the acceleration of movement of the vessel and the additional torque to accelerate the rotation of the rotating masses. Usually acceleration of the ship starts on from propulsion engine speed equal to 0.8-0.9 rated speed. Increase of the vessel speed is connected with an increased activity of diesel engine by increasing the amount of fuel supplied. Engine performance is also related to the control of fuel supply the cylinders and the process and energy transfer to the propeller.

Acceleration of the vessel speed consists of two stages:

1. Increase the speed of the rotating masses of the shaft, propeller together with associated water, engine and related components at almost constant speed of the ship. This stage takes place in a very short time,
2. Slow growth of the ship speed. At this stage it is assumed that the engine torque is equal to the torque required by the propeller [7].

In the direct propeller drive the adjustable parameter is the ship's hull speed in the relation to water. The engine speed control is done manually or automatically. In both cases, increasing the speed of the vessel must be performed without overloading the propulsion engine. Therefore, the automatic control programs provide a long enough period to achieve full load of ship engine. In this way we avoid excessive thermal stress caused by rising temperatures of the engine. There are step by step changes of engine revolutions (each during ΔT time interval) in the whole range of engine speed. This time limits the acceleration of the vessel to ensure no overloaded operation of the propulsion engine [7]. Abrupt changes in engine speed may have the individual values of the different temporal changes for other parameters of the propulsion system. Changes in these parameters depend on**:**

- speed of fuel lever adjustment,
- the number of intervals of abrupt changes in propulsion engine speed,
- time of the propulsion engine running in interval between the step change of revolutions.

Changes of speed ranges of engine in time are characterized by torque and revolutions depend on way of control of fuel amount delivered to cylinders. If the increasing fuel lever adjustment is gentle the torque and revolutions are linear ascending functions. However, with abrupt stepped manual shifting of fuel lever the engine parameters are a function of:

- exponential in the case of speed,
- exponential with oscillations of amplitude in the case of torque.

Figure 2 shows the timing and course of propulsion engine parameters during acceleration of the ship speed after leaving the harbour. In the diagrams can be clear observed that after starting the engine began a gradual increase of revolutions up to 80-100 rpm. Vessel speed increased gradually, and after eight minutes was 12.3 knots, and after 3.5 hours reached a value of 14 knots. Average engine torques during such a acceleration are below rated torque and do not exceed 85% of the nominal engine torque. Instantaneous torques during acceleration is different. Fig. 2 indicates that at the higher the rotational speed of the propulsion engine the amplitude of the instantaneous changes in torque are lower. Amplitude changes in the instantaneous torque value decreases with increasing engine speed propulsion. This figure demonstrates that during the restart of the engine speed through the critical speed range there is higher instantaneous torque than during previous maneuvers. It is caused by longer than the previous run time of engine in the range of critical speed.

During the maneuvers, a ship propulsion engine is periodically subjected to cutting off fuel supply for a period of 1-2 sec thus decreasing and again increasing the revolutions. Such maneuvers because a rapid increase of instantaneous torque values during the course of engine speed by a range of critical speed. The engine speed during such maneuvers is not reduced to zero, because their time is short, and the speed of the vessel was constantly in the same direction. However, the torque fluctuations were very large. Within 10 minutes the amplitude of the torque ranged from a negative value, or close to zero to positive values about double the average value, and periodically the nominal values [6, 7].

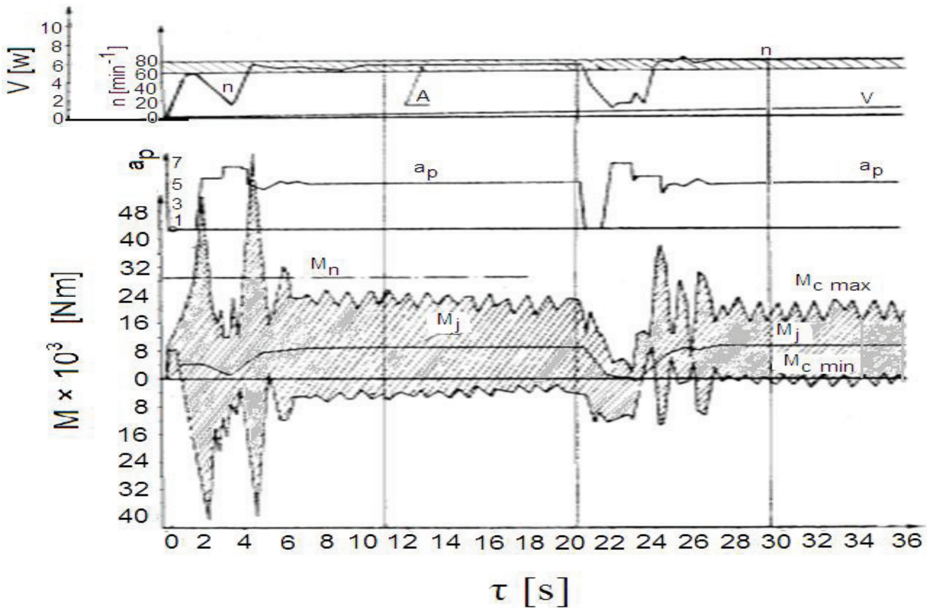

Fig. 2. Waveforms of parameters of engine propulsion type Sulzer 5RD68 after leaving the port during exercise the two maneuvers; Explanation: Mc - instantaneous torque on the output shaft of the ship, Mj-average value of torque , Mc max - the highest value of instantaneous torque, Mc min - the minimum torque value, Mn - nominal torque value, and p - the location of the fuel rail, n - engine speed, τ-time waveform parameters in the [s], v - velocity ship, the A-range of critical engine speeds [7]

4. The time of the ship speed acceleration

Real engine performance in the ship's propulsion system expressed described by increases of characteristic parameters in a wide range of sailing conditions may be different from the action requested by a given propeller characteristic [2, 3, 4]. Propeller characteristic determines the current load conditions depending on the hull and external factors. This allows obtaining changes in the value of the operating parameters of propulsion engine propulsion by informing about its performance.

The parameters of engine propulsion during maneuvers are:

- vessel speed v [m/s],
- torque on the propeller shaft of the vessel M [Nm],
- propeller speed n [rps],
- the weight of the vessel D in [kg],
- moment of inertia of the rotating masses of the propulsion system in [Nm],
- ship speed acceleration time t [sec] [2, 3].

These engine operating parameters are related to the dependence of dimensional function described in three dimension space. This allows describing the time of ship stoppage in the form following dimensional function:

$$t = \Phi (n, v, M, D, I), \tag{1}$$

where symbols as described above.

Form of the dimensional numerical function (1) can be estimated by dimensional analysis of an algebraic scheme constructed by S. Drobot [1]. Then replaced by the following numerical function

[3, 5]:

$$t = f\left(\frac{M}{D \cdot v^2}, \frac{n}{v}\sqrt{\frac{I}{D}}\right) \cdot \frac{1}{v} \cdot \sqrt{\frac{I}{D}}, \tag{2}$$

where symbols as in text.

Numerical function (2) was obtained by taking as a base the following dimensional parameters: the speed of the vessel v, the mass of the vessel D and moment of inertia of rotating masses of the propulsion system I. This base was chosen from among eight possibilities of choice. Database parameters are dimensionally independent of the other two-dimensional function parameters (1).

Assuming that the speed of the vessel during its acceleration varies proportionally to the time the numeric function (2) can be approximated by a linear form:

$$t = a \cdot \frac{1}{v} \cdot \sqrt{\frac{I}{D}} + b \cdot \frac{M}{v^3 \cdot D} \cdot \sqrt{\frac{I}{D}} + c \cdot \frac{n \cdot I}{v^2 \cdot D}, \tag{3}$$

where a, b, c are constant coefficients determined on the basis of measurement of parameters of the propulsion engine during ship acceleration using the least squares method and other symbols as in the formulas above.

Fixed coefficients a, b and c appearing in formula (3) were determined on the base of measurements of the parameters of propulsion engine during harbour leaving maneuvers.

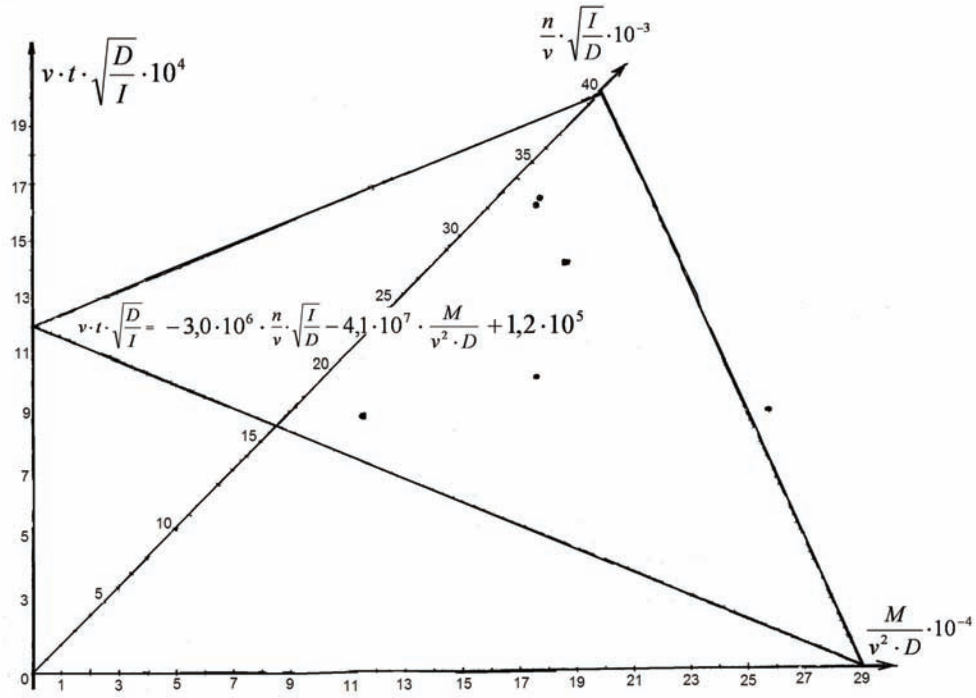

Fig. 3. Dimensional function arguments dimensionless acceleration of the ship together with their approximation to a linear function of two variables; *Explanation*: v-speed *vessel* [m / s], *M - torque on the output shaft of the vessel in* [Nm], *n - rotational speed of the screw* [r / s], *D - the weight of the ship in* [kg], *I - moment of inertia of the rotating mass of the propulsion system in* [Nm], t - *time in the acceleration of the ship [s]* [5]

The parameters are illustrated with numerical arguments, the dimensionless function (2) in figure 3. Based on these there was assumed the form of numerical linear function of two variables occurring in formula (2) and constant coefficients were set using the method of least squares.

Therefore, the following form to give the function of acceleration of the ship was obtained:

$$t = \left| -3{,}0 \cdot 10^6 \cdot \frac{n \cdot I}{v^2 \cdot D} - 4{,}1 \cdot 10^7 \cdot \frac{M}{v^3 \cdot D} \cdot \sqrt{\frac{I}{D}} + 1{,}2 \cdot 10^5 \cdot \frac{1}{v} \cdot \sqrt{\frac{I}{D}} \right|, \tag{4}$$

where designation as above.

The sign of absolute value in formula (4) was used because the negative values of the function have no physical meaning. Calculation of acceleration of the vessel using the formula (4) may be used only when its propulsion system is without a gear and has a constant pitch propeller.

5. Conclusions

Analysis of the ship propulsion engine during its start-up and acceleration the vessel speed allows making the following observations:

- operation of the engine in direct drive system of the ship during its start-up and passing through a critical speed fluctuations caused a very large positive and negative torque on the shaft, which affects its durability,
- the way of maneuvers executing automatic or manual maneuvers and their duration have an impact on the loads,
- during the test of the engine the differences between starting ahead and astern were not observed,
- a delayed move of the fuel lever causes the repeat passing through a critical speed range, causing a momentary overload of the propulsion engine,
- despite the short time of passing through the critical speed range during increasing or decreasing the engine speed the instantaneous torque is several times higher than its nominal value,
- operation of ship propulsion engine at low speed causes fluctuations in the instantaneous torque with an amplitude equal to the nominal torque,
- knowledge of the value of increments between the executed performance and required performance enables the assessment of the engine ability to adopt to loading conditions corresponding to the characteristics of the propeller,
- as the time of ship speed acceleration is longer the excess of the energy obtainable by the propulsion engine to the energy needed by ship sailing at a given speed is smaller,
- calculated time of ship speed acceleration according to formula (4) ranged from 90-100% of the time measured during the acceleration of ship speed, which confirms the usefulness of dimensional analysis to identify the ship propulsion engine performance,
- identification of ship propulsion engine performance allows to execute:
  - execution of optimum control of propulsion engine programme with avoiding the excessive load,
  - control of the degree of hazard of engine components brake-down due to the impact of the maximum instantaneous torque from the time of their occurrence,
  - assessment of influence of instantaneous torque on the durability of the propulsion system including the time of their impact in dependence on the quality of engine control.

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