MAKING USE OF STARTING THE ENGINE TO DETERMINE THE MOMENT OF INERTIA OF A SHIP PROPULSION SYSTEM

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Abstract

The article presents the method of determining the moment of inertia of a ship propulsion system while starting the engine which is based on torque and rotational speed measurements . The ship propulsion system in which the measurements were taken consisted of a slow – speed propulsion engine , shafting and fixed pitch propeller . The measurements mentioned above allow determination of a dynamics equation of a ship propulsion system which served the basis for determination of the moment of inertia . The specified method of defining the moment of inertia of a propulsion system is applicable to measurements in transient motion of the engine . This method is distinguished by simplicity of calculations and possibility of defining the moment of inertia of a propeller together with the water accompanying and requires taking measurements in transient motion of a ship .

1. Introduction

The course of starting torque of a ship propulsion engine recorded in time by means of a torque meter on a shaft can be used to determine dynamics of a propulsion system. Starting of the engine occurs after the crankshaft attains starting velocity. This requires supply of sufficient amount of energy via running gear from outer sources which will balance resistance losses of a starting process . For starting ship propulsion engines a pneumatic running gear is commonly used. In these devices air compression is used as a source of energy which while acting directly on a piston produces torque turning the crankshaft of the engine, so-called a starting torque equal to the anti-torque sum. A starting torque of the engine should attain acceleration and crankshaft velocity high enough to ensure the temperature in the cylinder capable to cause fuel self-ignition. In order to provide appropriate conditions for starting the engine, starting air is delivered to the cylinders in which the pistons are in starting position. Starting air admission lasts approximately 90 ÷ 100 ° (degrees of crankshaft revolution) from 1 ÷ 100 ° (degrees of crankshaft revolution) after TDC to 90 ÷ 100 ° (degrees of crankshaft revolution) after TDC at power stroke [3;4].

2. The course of starting a ship propulsion engine

The course of starting process of a two–stroke slow-slow speed propulsion engine which drives directly a fixed pitch propeller at re-steering ahead is shown in fig. 1 and astern is shown in fig. 2.
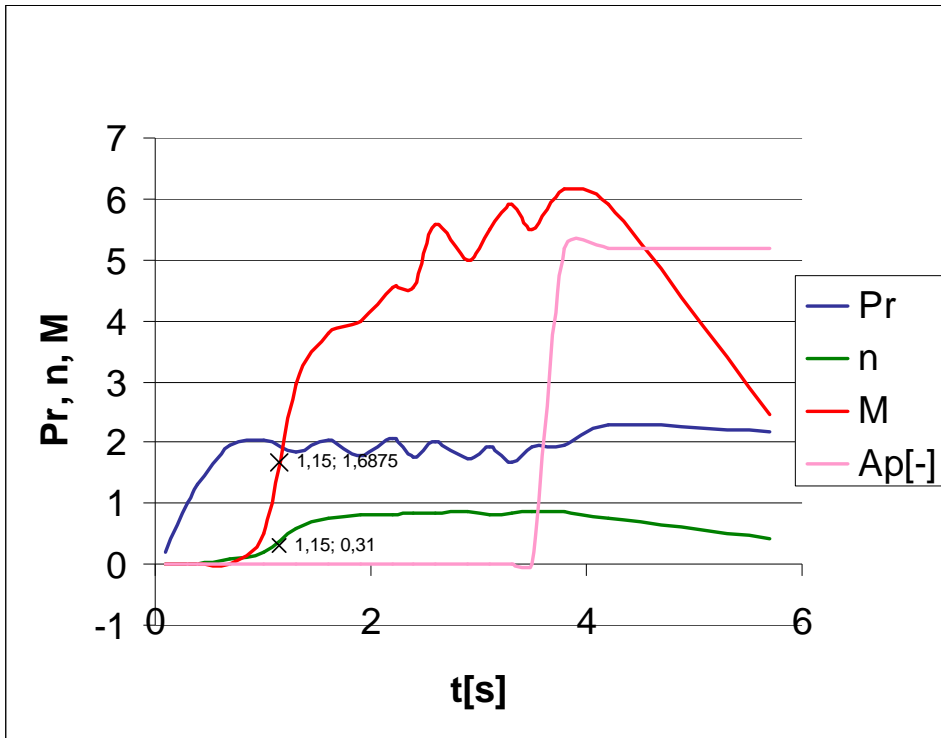
Fig. 1. The ahead course of starting a ship propulsion engine

Explanation:- Pr – pressure of starting air in [MPa], n – engine speed in [1/s], M – turning moment in [10^4Nm]
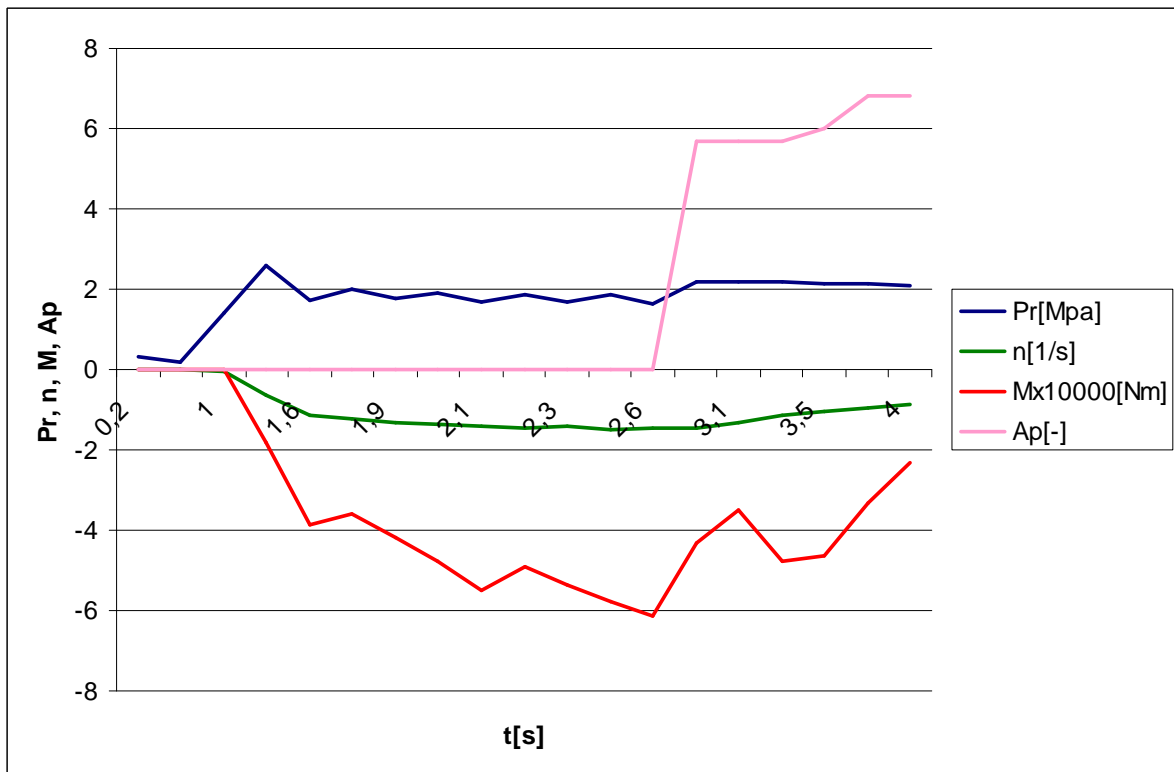Ap – setting fuel in [-]

Fig. 2. The astern course of starting a ship propulsion engine

Explanation:- Pr – pressure of starting air in [MPa], n – engine speed in [1/s], M – turning moment in [10^4Nm],
Ap – setting fuel in [-]

The process is as follows:- After directing the starting air onto the engine the pressure increases in pipelines which deliver the air to the starting valves. The steering air directed adequately by an air distributor opens the starting valves on the cylinders in which the pistons are in starting position. Compressed air while moving the cylinder expands by approx. 0.03 MPa at the first stage of starting and by approx. 0.02 MPa at the final stage of a starting process. When the piston is approaching BDC a starting air distributor makes a starting valve close. Speeding air stream is rapidly stopped and its kinetic energy is converted to potential energy of the pressure. As a result of such a starting process the diagram of a pressure course in time Pr(t) obtains characteristic sawtooth shape (fig. 1). The number of peaks in the diagram indicates how many starting valves opened at the time of starting. The diagram allows as well the readout of the time of starting air valve opening . This time will be a rotational speed function of a crankshaft. At the beginning of starting when a rotational speed is rather low it amounts to approx. 0.2 ÷ 0.25 sec. When rotational speed of a crankshaft reaches the value of starting speed a starting air admission to the engine closes . The diagram shows clearly almost immediate increase in pressure by approx. 0.03 ÷ 0.04 MPa caused by converting kinematic energy of air stream to potential energy of pressure. In this case the increase in pressure is much higher than for one starting valve because the whole air stream is subject to stop. Simultaneously with the air inflow stop the fuel linkage is shifted to the position corresponding to a fuel starting dose. The way of starting the engine with compressed air and the quantity of a fuel ignition dose affect the course of pressure alteration in the cylinder beginning from the first ignitions until the engine steady running is attained . In general the starting fuel dose amounts to from 30 to 50 % of a nominal dose [2]. The time of starting air effect at the time of starting the engine came to 1.6 sec.

3. The method of determining the moment of inertia of a ship propulsion system based on starting the main engine

The moment of inertia should be big enough to cause such an angular acceleration of a crankshaft which during the first rotation sets its angular velocity conditioning self-ignition of the injected fuel and its stable burning at the further phase of starting [2;3].

This is expressed by the following equation:

$$M(t)=M_r=M_I+M_T+M_S \qquad\qquad (1)$$

where:-

$$M_I = I \cdot \frac{d\omega}{dt}$$ - the moment of inertia of moving mass of the engine , propeller shaft , propeller and the mass of the water whirling behind the propeller in [Nm] ;

I – polar moment of inertia of reduced masses on the axis of a crankshaft involved in rotating movement in [Nm s²] ;
- angular acceleration of a crankshaft at starting in [rad/s²];

$$M_T = (0,01+0,02 \cdot \frac{n}{n_{nom}}) \cdot M_{nom}$$ - the moment of friction forces of a propulsion system in [Nm];

n – engine speed in [1/s] ;
n_{nom} – nominal engine speed in [1/s] ;
M_{nom} – nominal moment of inertia of a propulsion engine in [Nm];

$M_S = k_M \cdot \rho \cdot D^5 \cdot n^2$ - hydrodynamic moment demanded by a propeller in [Nm] ;

kM – non-dimensional coefficient of the moment in [-] ;

ρ – density of sea water in $\left[\dfrac{N \cdot s^2}{m^4} \right]$;

D – diameter of propeller circle field in [m] ;

n– rotational speed of a propeller in [1/s] ;

$M(t) = M_r$ – measured starting torque in [Nm] .

The equation (1) can be converted to the form:

$$ I = \frac{M(t) - M_S - M_T}{2\Pi \cdot \dfrac{d\omega}{dt}} \qquad (2) $$

where: -

-   designations as in the formula (1)

The formula (2) makes sense only in transient states i.e. $\dfrac{d\omega}{dt}$ when is different from zero. This condition is met well in the state of starting the propulsion engine, where the rotational speed and the torque on the propeller shaft increase from zero up to big values in a short time. By measuring the courses of rotational speed and the torque on the propeller shaft at the time of starting the engine they can be defined mathematically in a time function. Their form is the likeliest to be found in the time function where the ship propulsion system is treated as an inertia object of the second order [1]. In this case the input signal is the starting air pressure and the output signals are the rotational speed and the torque on the propeller shaft. The response of such an object to a step function as it is starting the propulsion engine by means of air can be presented in the form:

$$ y(t) = k \cdot \left(1 - \frac{1}{1-b} \cdot e^{\frac{-t}{T_1}} + \frac{b}{1-b} \cdot e^{\frac{-t}{b \cdot T_2}} \right) \qquad (3) $$

where : -

y(t) - response of the object to a step function;

k - gain coefficient of the object signals;

$b = \dfrac{T_1}{T_2} > 1$ - coefficient defining the ratio of the two time constants T1 and T2;

T1 , T2 - time constants of the inertia object of the second order ;

t – the time of the signal occurrence in [s].

By registering the courses of the rotational speed and the torque on the shaft while starting the propulsion engine we can calculate all the components of the equation right side (2), thus calculate the moment of inertia I. The courses of the rotational speed and the torque on the propeller shaft at the initial moment of starting can be approximated by straight lines. Then in this time interval [t1; t2] the derivative $\dfrac{d\omega}{dt}$ can be replaced with the increase $\dfrac{\Delta\omega}{\Delta t}$; which simplifies considerably

calculations of the proposed method. By choosing from this time interval the instant t_0 on the basis of the formula (2) we will receive:-

$$I = \frac{M(t_o) - M_S \cdot [n(t_o)] - M_T \cdot [n(t_o)]}{2\Pi \cdot \dfrac{n(t_2) - n(t_1)}{t_2 - t_1}} \tag{4}$$

where:-

$t_1 < t_o < t_2$ - chosen time instant in [s];
- other designations as in the formula (2).

By substitution of the expressions defined in the equation (1) to the formula (4) we will receive the final form which allows the calculation of the moment of inertia of the part of the propulsion system from the place where measurements of the torque and the rotational speed were taken up to the propeller with the accompanying water .

$$I = \frac{M(t_O) - k_M \rho D^5 n^2(t_O) - \left[a + b \cdot \dfrac{n(t_O)}{n_n}\right] \cdot M_n}{2\Pi \cdot \dfrac{n(t_2) - n(t_1)}{t_2 - t_1}} \tag{5}$$

where:-

- designations as in the formulas (1) and (2) .

All the values which appear in the equation (5) can be determined on the basis of a propulsion system documentation and the measurements taken on a ship. The coefficient of the moment k_m can be determined from the hydrodynamic characteristic of a propeller e.g. from Dankwardt diagrams when knowing the advance coefficient.

The specified method of determining the moment of inertia of a part of a ship propulsion system was illustrated on the example of a direct drive. A propulsion engine at nominal revolutions n_n = 135 rev/min = 2.25 rev/sec attained the torque of M_{nom} = 291800 [Nm]. It drove the propeller screw of a diameter D = 4.55 [m]. At starting the speed ship was low which allowed determination of a moment coefficient from the hydrodynamic characteristic equal to:-

$$k_M(I_p) = k_M(0) = 0,0311$$

From the measurements of the courses of the rotational speed and the torque on the shaft at the initial instant t_o=1,15[s] of starting the following values were received:-

$M(t_O)$=16875[Nm]
$n(t_O)$=0,31[1/s]

the courses of these values at starting are shown in fig. (1). On the basis of numerical data according to the formula (5) the moment of inertia of the part of the propulsion system which was equal to:-

$$I = 8855{,}8[\text{Nms}^2]$$

The value of the moment of inertia of an appointed part of the propulsion system was compared with the value of this part which was received on the basis of a documentation of torsional vibration calculations. Assuming 25 % of water fraction the moment of inertia in torsional vibration calculations was equal to:

$$I = 8253{,}1\ [\text{Nms}^2]$$

The comparison of the values above points to satisfying accuracy of the method proposed.

4. Summary

The more the values of the function derivative of the rotational speed after time $\left(\dfrac{d\omega}{dt}\right)$ will differ from zero, the more the moment of inertia of a propulsion system determined by the proposed method will be close to a real one.

The moment of inertia depends on the engine design and the way of the power transmission onto the screw i.e. the quantities of rotational masses and the instant angular acceleration of the crankshaft.

The proposed method of determining the moment of inertia has its advantages and drawbacks. The advantages are following: simple calculations and the possibility of determining the moment of inertia of a propeller together with the accompanying water. The drawbacks of the proposed method involve its restriction to existing propulsion systems and the necessity of taking measurements.

References

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