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On the Relationship of Torsional Vibrations and Breakdown Torque of Marine Diesel Engines

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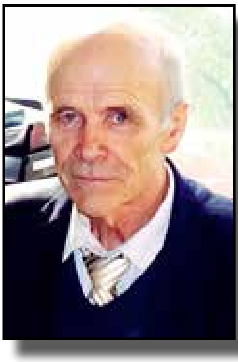

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ABSTRACT

The article provides an overview of the conditions necessitating the calculation of torsional vibrations and disturbing moments relevant for their calculation as for marine diesel engines followed by an analysis of the effect of torsional vibrations on the breakdown torque of the engine. The forces arising in the crank mechanism of the engine due to torsional vibrations are illustrated by a diagram. Formulas are suggested for calculating the breakdown torque caused by torsional vibrations of the crankshaft of a multi-cylinder engine and the total breakdown torque. It is recommended to consider the influence of moments caused by torsional vibration on the unevenness of rotation and vibration of the engine.

The results of calculation of the total torque of the engine previously performed by group of researchers, considering the influence of torsional vibrations, are quoted for DGR A 100/750 diesel generator with an effective power of 100 kW at a nominal speed of 750 rpm with a 6L 18/22 engine.

Based on the results of the analysis, suggestions are given on the need to consider the moments arising from torsional vibrations when diagnosing the engine.

Keywords: water transport, torsional vibrations, marine engine, breakdown torque, shaft line, ship power plant.

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INTRODUCTION

The transport in Russia is developing rapidly, and water transport is no exception. The introduction of information technologies and automation for water transport allows not only to improve the quality of management and control of parameters, but also to ensure constant monitoring of the technical condition of installations and units.

Series of research works are dedicated to that issue. They particularly note that comprehensive support of a ship's power plant (SPP) «as of a highly dependable object» provides for «cloud technologies for storing large amounts of data and reliable communication via secure channels between the ship, equipment manufacturers and coastal services» [1].

But «during operation of marine internal combustion engines (ICE), wear and aging of their components and assemblies naturally occur, inevitably causing a deterioration in the machines' environmental, economic and efficiency performance» [2].

For SPP of unmanned ships, the requirements for reliability, efficiency, survivability, and environmental friendliness will be even higher. Autonomous ships will require an advanced maintenance and diagnostic system. «In places where the autonomous fleet stops (ports, roadsteads), the presence of repair and diagnostic teams will be required to inspect, check, and maintain SPP and ship automation systems. Along the routes of autonomous vessels, access will be required for emergency response teams using helicopter transport» [3].

With increasing load and decreasing metal consumption of mechanisms, the importance of dynamic calculations of the system increases. As the unevenness of the torque increases, there is an increase in vibrations of the engine installed on the supports and an increase in noise in the engine room of the vessel.

Torsional vibrations in the motor-shafting-propulsion system can create a real danger. In resonant operating modes of the power plant, the probability of fatigue failure of the most loaded parts increases. Identification and suppression of a strong source of vibration is an equally important method for increasing the reliability of SPP [4].

However, due to the complexity and high cost of equipment for studying torsional vibrations, the importance of being able to use indirect control methods is increasing.

The objective of the study is to analyse the relationship between torsional vibrations and breakdown torque of marine diesel engines.

Tasks of the study include review of disturbing moments during torsional vibrations, drawing up a diagram of the forces and moments arising in the crank mechanism of the engine due to torsional vibrations, computational study of the overturning moment from torsional vibrations, assessment of the impact of the moment of breakdown torque arising due to torsional vibrations on the diagnostic parameters of the SPP.

The work was carried out using theoretical research *methods*, such as analysis and synthesis, content analysis of research data from open sources.

RESULTS

The torsional oscillating motor-shafting-propulsion system is a system of interconnected shafts. Besides the moment of mechanical energy transmitted to the consuming unit and the perception of axial force, shaft line is influenced by many additional loads. A special place among them is occupied by torsional vibrations, since the tangential stresses arising during their resonance can be several times higher than all other acting loads.

Based on that, the motor-shafting-propulsion system should be considered one of the most critical and stressful parts of a power plant, despite the apparent simplicity of the design.

Torsional vibrations were first described at the very beginning of the 20th century in connection with some features of the shaft line of a ship's steam power plant, particularly by Hermann Frahm. However, even in our time, shaft failures are repeatedly observed due to this dangerous phenomenon.

Torsional vibrations are vibrations in which all points of the system perform reciprocating movements along circular arcs around a fixed axis.

Calculation of a system regarding torsional vibrations is one of the most complex and voluminous calculations when creating or modernising a SPP. According to the rules of the transport supervisory authorities, calculations for torsional vibrations and verification of the calculation results with the help of torsion recording are carried out when re-equipping, modernising, renewing, updating or reclassifying a vessel[1]. For the experimental study of torsional vibrations, special devices are used – torsiographs (recording torsion meter), including domestic ones, which have proven themselves quite well [5–7]. Conditions under which torsional vibration testing is necessary include:

• Replacing the main engine of the power plant or changing the parameters and/or structural elements of the previous engine.

• Replacing flywheel or changing its design.

• Replacing torsional vibration damper/anti-vibrator.

• Replacing elastic coupling.

• Replacing propeller or changing its design.

• Installation, replacement or removal of an additional energy consumer or source (pump, shaft generator, power turbine, etc.).

• Change in shaft diameter by more than 2 %.

• Changing the parameters of anti-vibration joints.

• Installation of additional concentrated masses (flywheel, clutch, etc.).

• Modernisation of the unit with replacement of the main elements of the system.

The moments that are considered when calculating torsional vibrations of power plants include [8]:

• Moments arising due to the forces of inertia and gravity of moving masses in the crank mechanisms of piston engines.

• Moments arising due to steam or gas pressure forces in the cylinders of piston engines (or air in the cylinders of compressors).

• Constant component of the torque transmitted from the source to the energy consumer (average torque).

• Variable component of the torque created by the propeller, due to the uneven velocity field of the passing water flow (when the propeller operates behind the ship's hull).

• Variable component of the torque created by the winged propeller, due to the cyclic operation of the propeller blades.

• Some other types of disturbing moments caused by design features or inaccuracy in the manufacture of the installation in question (cushion joints of shafts, inaccuracy in the manufacture of gear joints).

But the main source of torsional vibrations of the system are variable moments from the action of various forces in the crank mechanisms.

To calculate the power plant's forced torsional vibrations, it is necessary to get the values of all moments as a function of the angle of rotation of the shaft.

The sources of forced vibrations of a marine diesel engine on supports comprise unevenness of the breakdown torque due to gas forces and inertia forces, imbalance of the shafting, breakdown torque arising from the resonance of torsional vibrations.

The torque and breakdown torque acting in the crank mechanisms are obtained by decomposing, according to the classical scheme, the total force from the gas pressure and the inertia forces of the moving masses of the crank mechanisms. This process is discussed in the kinematics section of any textbook on internal combustion engines.

Moments due to torsional vibrations are periodic functions of the crankshaft rotation angle (CRA).

The occurrence of torque from torsional vibrations is described as follows. If at some point in time the amplitude of the vibration of the shaft crank reaches the maximum value, to which the crank has turned in a counterclockwise arc of a circle, then, when the crank in its oscillatory motion turns back, each time a pair of equal in magnitude and oppositely directed forces T_i applies in points O and B (Pic. 1).

The torque from torsional vibrations of the crankshaft arises from the action of a pair of tangential forces T_i.

As a result of decomposition of one tangential force from the crank shaft, acting in the connecting crankpin, into components K along the crank and P_{shi} along the moving parts of the connecting rod-piston group. The transfer of the force P_{shi} along the line of action to point A gives the components of the vertical inertial force P_i and horizontal normal force N_i.

Another tangential force from the crank shaft, acting in the crankshaft neck, is decomposed into components K along the crank and P_{shi} parallel and oppositely directed force P_{shi} from the moving parts of the connecting rod-piston group. In turn, P_{shi} force represents the vertical P_{shi} and horizontal N_i components. As can be seen from Pic. 1, a pair of forces N_i form a breakdown torque due to torsional vibrations.

The force K with which the crank acts on the support (point O), as well as on the oppositely directed reaction of the support, tends to shift the engine in the direction of the force.

[1] Manual R.009–2004 «Calculation and measurement of torsional vibrations of shaft lines and units», Russian River Register, Moscow, 2016.

$$M_{entorcrank} = A_r \bullet \omega^2 \bullet \sum_{i=1}^{n} I_i a_i \times$$
$$\times \left(\begin{array}{l} \left(k^2+1\right) \times \left(\begin{array}{l} \sin\left(\phi+\delta_i\right) - 1,25\lambda \sin\left(2\left(\phi+\delta_i\right)\right) \cdot \sin\left(k\phi+\varepsilon_k\right) - \\ -k\left(\cos\left(k\phi+\varepsilon_k\right) + \lambda\cos\left(2\left(\phi+\delta_i\right)\right)\cos\left(k\phi+\varepsilon_k\right)\right) \end{array} \right) \times \\ \times \left(\dfrac{\left(4-3\lambda^2\right)\sin\left(\phi+\delta_i\right) + 2\lambda\sin\left(2\left(\phi+\delta_i\right)\right) + 2\lambda^2\sin\left(3\left(\phi+\delta_i\right)\right)}{1-0,25\lambda^2\left(1-\cos\left(2\left(\phi+\delta_i\right)\right)\right)} \right) \end{array} \right), \text{ kN•m} \quad (1)$$

or according to the simplified dependence:

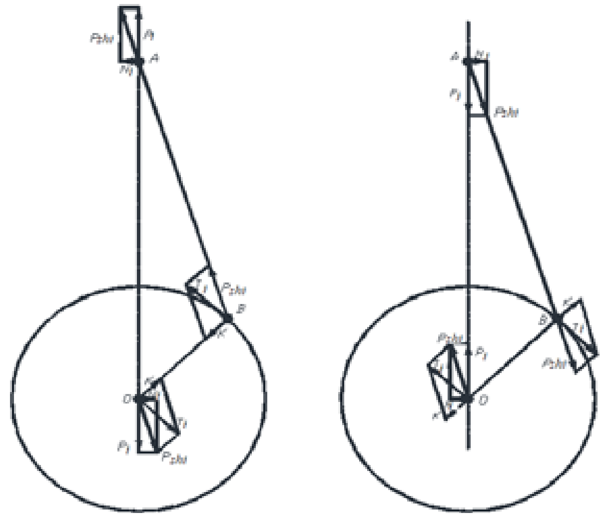
$$M_{entorcrank} = 0,5 \bullet A_r \bullet \omega^2 k^2 \sin\left(k\phi+\varepsilon_k\right) \bullet \sum_{i=1}^{n} I_i a_i \times$$
$$\times \left(1-\cos\left(2\left(\phi+\delta_i\right)\right) + K\lambda\sin\left(\phi+\delta_i\right)\sin\left(2\left(\phi+\delta_i\right)\right)\right), \text{ kN•m} \quad (2)$$

where A_r – resonant amplitude of torsional vibrations, rad;
ω – angular speed of the shaft, rad/s;
k – harmonic order of torsional vibrations;
λ – constant of the crank mechanisms;
I_i – moment of inertia of the crank mechanism, kg*m^2;
a_i – relative amplitude of the i-th mass of torsional vibrations;
φ – crank angle;
δ_i – crank wedge angle;
ε_k – initial phase of the k-th harmonic of torsional vibrations;
K – correction for the influence of the constant of the crank mechanisms;
n – number of compartments (cylinders).

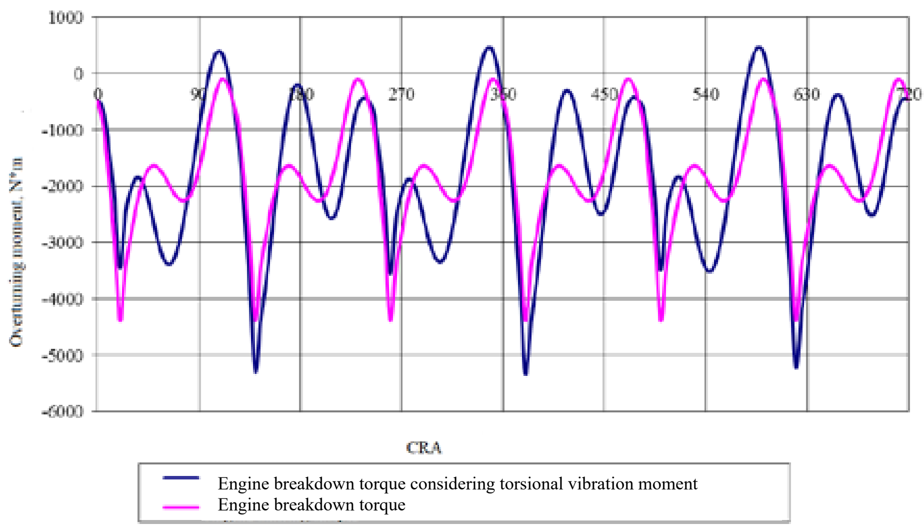
According to Pic. 1 it can be seen that the breakdown torque due to torsional vibrations of the crankshaft makes a certain contribution to the current breakdown torque arising from the total force. «The energy from gas forces, partially spent during the power stroke on development of vibrations, causes an increase in the load on the connecting rod and the occurrence of a breakdown torque due to torsional vibrations, which affects the breakdown torque due to the total gas and inertial forces» [9].

It should be noted that the breakdown torque is equal in magnitude and opposite in direction to the torque, but due to the fact that they are applied to different bodies (motor housing and shaft line) they are not mutually balanced.

The derivation of formulas for calculating the breakdown torque due to torsional vibrations of the crankshaft of a multi-cylinder engine is given in [10]. Here we will limit ourselves to formulas that are suitable for an in-line marine engine (1; 2).



Pic. 1. Diagram of forces arising in the crank mechanisms from torsional vibrations [performed by the authors].



Pic. 2. Dependence of the breakdown torque on the crankshaft rotation angle (CRA) during the working cycle [performed by the authors].

Dependences (1) and (2), considering the amplitudes of oscillations of the motor masses, can be used to determine the total influence of the breakdown torque due to torsional vibrations and breakdown torque of the engine.

The total moment will be equal to:

$$M_{\Sigma} = M_{en} + M_{entorcrank} = \sum_{i=1}^{n} M_{tg} + M_{entorcrank}, \text{kN} \cdot \text{m} \qquad (3)$$

where M_{en} – engine breakdown torque;

M_{tg} – breakdown torque of one engine compartment.

When calculating the total torque, it is necessary to know the initial phase of the harmonic component of the *k*-th order torque, which excites torsional vibrations.

Calculations were carried out using these formulas for DGR A 100/750 diesel generator with an effective power of 100 kW at a nominal speed of 750 rpm with a 6CH 18/22 engine. The results were reported by their authors at the All-Russian Scientific and Technical Conference on Automatic Control and Regulation of Thermal Power Plants at Bauman MSTU in 2014 and 2015, the abstracts of which were published in [11, 12].

The calculations showed that torsional vibrations of the shaft line affect the breakdown torque of the entire engine. For clarity, Pic. 2 shows the characteristic calculated dependences of the breakdown torque M_{Σ} on the angle of rotation of the crankshaft φ, considering the moment from torsional vibrations with sixth harmonic resonance and without those vibrations during the operating cycle. The graph shows that the torque amplitudes have increased, which leads to development of dangerous stresses in the shafting and vibrations in the engine room.

If there is a resonance, moments from torsional vibrations will affect the operation of the entire torsionally oscillating system. Therefore, to ensure operability of the power plant, it is necessary to monitor the parameters of ship internal combustion engines (main and auxiliary) under operating conditions.

For in-place automatic technical troubleshooting of the systems, among others, the following parameters are promising to be checked: engine torque, crankshaft rotation speed, vibration in the area of the cylinder covers (vibration velocity/vibration displacement), vibration in the crankshaft area (vibration velocity/vibration displacement) [13]. They may be affected by the influence of resonant torsional vibrations.

The uneven rotation of the shaft line is another important diagnostic parameter. One of the reasons contributing to the occurrence of uneven rotation is the presence of torsional vibrations of shafts and shaft lines [14].

«Modern diagnostic systems have the functions of automatic failure detection, automatic diagnostics, as well as automatic troubleshooting of main ship engines, as well as of other types of ship equipment located in the engine room [1; 15]. If a universal platform with open software is used, then it becomes easier to consider the influence of moments arising due to torsional vibrations when diagnosing a torsionally oscillating engine-shafting-propulsion system.

CONCLUSIONS

Following the analysis of referenced sources and results of previous authors' research it is possible to draw some summarising conclusions.

The engine-shafting-propulsion system is one of the most critical and stressful parts of a ship's power plant. And the calculation of a system regarding torsional vibrations is one of the most complex and voluminous calculations when developing a power plant, which must be checked by torsion metering.

Several types of disturbing moments must be considered in the calculations of torsional vibrations of power plants, but the main source of torsional vibrations of the system are variable moments from the action of various forces in the crank mechanisms.

According to the considered diagram of forces in the crank mechanisms and following the calculations carried out using the given dependencies for the DGR A 100/750 diesel generator, it becomes clear that torsional vibrations of the shaft line affect the breakdown torque of the entire engine.

When diagnosing a torsionally oscillating engine-shafting-propulsion system, it is important to consider the influence of moments arising from torsional oscillations since under operating conditions this can allow maintenance personnel to prevent the occurrence of possible accidents.

Further research is required dedicated to search for increase in efficiency of technical diagnostics with the use of digital tools and communication means allowing to eexchange big data.

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