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Enhancing operational characteristics and technical-economic indicators of vessels through the application of new toothed coupling designs

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Abstract. This study demonstrates the potential for improving the operational characteristics and technical-economic indicators of vessels operating under conditions of misalignment of the axes of connecting shafts of marine power plants and their elements by using toothed coupling constructions with enhanced operational characteristics. The proposed couplings are designed in a way that makes them almost insensitive to the misalignment of the axes of connecting shafts, thus operating like an ideal hinge. The application of toothed couplings allows reducing the likelihood of unscheduled docking of the vessel, which, in turn, helps save significant costs for realignment and payment in case of the loss of the vessel's transit capacity.

1 Introduction

Reducing costs in the creation of the final product, lowering the construction and maintenance costs of a ship, updating outdated production facilities, and implementing new technologies and equipment are priorities for shipbuilding in Ukraine. Improving the technical and economic indicators of ship power plants operating under conditions of shaft misalignments in ship units (turbogear or diesel-reduction gear) through the use of high-performance gear couplings in the "engine – gear coupling – intermediate shaft – gear coupling – reducer" section is a relevant task, the solution of which determines the further development of modern shipbuilding. This task is an integral part of the existing programs and tasks of shipbuilding in Ukraine, which produces systems and units of power plants in accordance with the Law of Ukraine "On state support of shipbuilding."

However, in modern ship power engineering, issues such as increased fuel consumption, deterioration of reliability, and environmental indicators (including vibrations and noise) of ship power plants remain unresolved. The most dangerous and inevitable problems affecting the reliability and, consequently, the decrease in the technical and

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economic indicators of ship power plants are the misalignments of the axes of connecting shafts of ship units. These misalignments negatively affect the transmission of effective power from the engine to the reducer through the coupling node "gear coupling – intermediate shaft – gear coupling." The magnitudes of shaft misalignments during the operation of vessels depend on a whole range of design, technological, and operational factors.

Misalignment represents a violation of the coaxiality of shafts, i.e., deviation from the nominal axis placement in any direction. These deviations are called displacements and, in turn, are divided into longitudinal, radial, angular, and combined. Angular displacements are also called tilts or deflections. Displacements and tilts of axes are converted into angular misalignment, not exceeding, according to the value of $\psi = 8{,}7 \cdot 10^{-3}$rad, which is equivalent to 0,5º.

The specified misalignments significantly overload the output and input shafts of the engine and the reducer, respectively, the intermediate shaft, as well as the bearings. This negatively affects the reliability, durability, and repairability of marine power plants, leading to unplanned maintenance stops. This, in turn, reduces the operational reliability of the vessel, increases the likelihood of emergency situations, and raises repair costs [1-5].

2 Materials and methods

In writing this paper, the authors used an analytical method, with the help of which the studied problems were considered in their unity and development. Taking into account the goals and objectives of the study, the structural and functional method of scientific research was used. The theoretical research was based on the fundamental principles of tribology in general and shipbuilding, utilizing theoretical mechanics approaches, machine components, and principles of design.

3 Results

Analysis of operational characteristics and technical-economic indicators of marine power plants indicates that the misalignments of the shafts, expressed in terms of shifts and fractures, increase and exceed the established alignment standards by 2-6 times or more. Currently, the issue of eliminating the negative impact of misalignments of the shafts of marine units is solved in two ways: either by realigning the shafts of these units, which requires a complete stop of the vessel, or by using compensating devices, including traditional gear couplings.

In the first method, to bring the increased norms of misalignments of the shafts in accordance with permissible standards, it is necessary to carry out from four to five realignments throughout the entire ship's operation. This not only requires material costs ranging from 25,000 to 55,000 US dollars for each realignment but is also accompanied by vessel downtime and a significant reduction in their operational capability.

The second method is based on the use of compensating devices, including traditional gear couplings consisting of bushings with external and sleeves with internal teeth. They are intended not only for transmitting torque and rotational frequency but also for compensating misalignments of the shafts of marine units, due to the presence of guaranteed radial and lateral clearances between the teeth. However, traditional designs of gear couplings are characterized by several significant drawbacks.

Firstly, due to the instantaneous application of load on the meshing tooth pairs during misalignments of the axes, which also changes from zero or a minimal value to a maximum value, there is an impact loading on the teeth, significantly deteriorating the vibroacoustic characteristics.

Secondly, overloading of the meshing tooth pairs, in the case of misalignment of the connecting shafts' axes, leads to an increase in contact stresses, significantly reducing the load capacity under these stresses.

Thirdly, the occurrence of flexible torsional moments in the gear coupling due to friction forces and unbalanced efforts negatively affects the intermediate shaft, as well as the output and input shafts of the connecting machines and mechanisms, which overall has a negative impact on their efficiency.

Lastly, during the operation of gear couplings under conditions of misalignment of axes, where an extremely uneven distribution of forces between the engaged tooth pairs is observed, the lubrication conditions of their friction surfaces deteriorate. This leads to an increase in power losses due to friction and a decrease in the coefficient of useful action, resulting in a deterioration of the technical and economic indicators of the equipment in which they operate.

The above has led to the need for the development of new technical solutions for gear couplings, insensitive to misalignments of the connecting shafts' axes, operating as part of marine power plants. In connection with this, the introduction of new designs of gear couplings with enhanced operational efficiency is proposed [6-17].

Increasing the efficiency of gear couplings is associated not only with their design but also with the influence of lubrication, friction, and heat generation and should be implemented through the development of new technical solutions that foresee not only an increase in their load-bearing capacity but also compensatory capability. In the course of theoretical research designs of gear couplings with longitudinally modified external and internal teeth [6-17], it has been proven that these gear couplings, when subjected to misalignment of the connecting shafts of marine power plants (MPP) under load, are characterized by a practically uniform distribution of forces between the mating pairs of teeth. Taking this into account, their use in marine power plants allows solving a range of tasks aimed at a significant improvement in the operability of the main power unit.

According to the Ukrainian Ship Register, scheduled docking of vessels is carried out every four years. In this context, ensuring the operability of the main turbo gear units between planned dockings can be achieved by using gear couplings of increased operational efficiency. This will help avoid unscheduled downtime for repairs and ensure reliable vessel operation.

Thus, the assessment of the performance of gear couplings, taking into account the misalignment of the connecting shafts of the main turbo gear units, should be carried out based on the information provided below.

The calculation of the toothed couplings for contact endurance should be carried out based on the expression:

$$(\sigma_{cs})_{n}^{6} \cdot \alpha_{c} = (\sigma_{cs})_{t}^{6} \cdot \alpha_{0}, \tag{1}$$

where $(\sigma_{cs})_n$, $(\sigma_{cs})_t$ are the contact stresses acting on the teeth of new and traditional designs of toothed couplings, $\alpha_c = 60nT_c$, $\alpha_0 = 60nT_0$ - the number of load cycles for new and traditional designs of toothed couplings, respectively, T_c, T_0 - the service life of new and traditional designs of toothed couplings in hours, n - rotation frequency, rev/min.

On the basis of Hertz's formula, the ratio $[(\sigma_{cs})_t/(\sigma_{cs})_n]^6$ takes the form:

$$\left[\frac{(\sigma_{cs})_{t}}{(\sigma_{cs})_{n}}\right]^{6} = \left(\frac{F_{n\max}^{t}}{F_{n\max}^{n}}\right)^{3}, \tag{2}$$

where $F^{\mathrm{t}}_{n\max}$, $F^{\mathrm{n}}_{n\max}$ are the maximum forces acting on the teeth of traditional and new designs of toothed couplings, respectively.

Based on the provided expressions (1) and (2), the relative durability of the new design is determined as follows:

$$T_{\mathrm{n}} = \frac{T_{\mathrm{c}}}{T_0} = \left(\frac{F^{\mathrm{t}}_{n\max}}{F^{\mathrm{n}}_{n\max}}\right)^3 .$$

If the teeth are designed for shear strength, then the dependence of the operational capability (service life) of the new construction of the coupling will take the form:

$$T_{\mathrm{n}} = \frac{T_{\mathrm{c}}}{T_0} = \left(\frac{F^{\mathrm{t}}_{n\max}}{F^{\mathrm{n}}_{n\max}}\right)^6 .$$

However, the operational capability of toothed couplings is determined not by the magnitudes of contact and bending stresses acting on the teeth, but by wear resistance. The wear of traditional and new designs of toothed couplings is determined by the formulas:

$$i_{\mathrm{t}} = c_1\left[1 - \frac{c_2}{(F^{\mathrm{t}}_{n\max})^{k1}}\right]^2 \cdot (F^{\mathrm{t}}_{n\max})^{k2}; \qquad i_{\mathrm{n}} = c_1\left[1 - \frac{c_2}{(F^{\mathrm{n}}_{n\max})^{k1}}\right]^2 \cdot (F^{\mathrm{n}}_{n\max})^{k2},$$

where c_1 and c_2 are coefficients taking into account the mutual influence of lubrication, technology, and the dimensions of the toothed couplings on wear resistance; k_1 = 0,58 and k_2 = 1,13 are exponent values.

The wear value i_{t} corresponding to shaft misalignments is equivalent to $2\cdot10^8$ cycles, and it is directly proportional to the service life of the toothed coupling in hours. Thus, the relationship for the relative durability of the toothed coupling, taking into account tooth wear, will be expressed as:

$$T = \left(1 - \frac{1 - c_2/(F^{\mathrm{t}}_{n\max})^{0,58}}{1 - c_2/(F^{\mathrm{n}}_{n\max})^{0,58}}\right)^2 \cdot \left(\frac{F^{\mathrm{t}}_{n\max}}{F^{\mathrm{n}}_{n\max}}\right)^{1,13} . \tag{3}$$

Increasing the efficiency of the high-performance toothed couplings, based on the dependence (3), with an error not exceeding 3.5%, should be determined by the relationship:

$$T = \left(\frac{F^{\mathrm{t}}_{n\max}}{F^{\mathrm{n}}_{n\max}}\right)^{1,215} . \tag{4}$$

Thus, increasing the load capacity of the toothed couplings, based on the above expressions and the relationship (4), is equivalent to improving their efficiency.

The operational capability of the traditional toothed coupling, whose lifecycle is $i\cdot10^8$ cycles, should be calculated taking into account the rotation frequency of the shaft. Since one cycle equals one complete revolution of the toothed coupling (during which the teeth are subjected to maximum force twice), based on the above, the operational capability of the traditional toothed coupling (in hours) is determined by the formula

$$T_{\mathrm{t}} = \frac{i \cdot 10^8}{n}. \quad (5)$$

Table 1. Improvement in the operability of the proposed designs of gear couplings compared to traditional constructions under misalignments of connecting shafts

The angle of misalignment of the shafts $\psi \cdot 10^{-3}$, radians	Maximum forces in the toothed coupling		Increase in operational efficiency T_{p}, times.
	traditional $F^{\mathrm{t}}_{n\max}$, H	proposed $F^{\mathrm{n}}_{n\max}$, H	
2,5	5188,68	4299,69	1,2565
5,0	7855,65	4299,69	2,0780
7,5	12300,61	4299,69	3,5862
8,7	15065,73	4299,69	4,5881

Based on equation (5) and knowing the rotation frequency of the output shaft of the main engine, determining the increased operational efficiency (in hours) of the proposed gear couplings under shaft misalignments does not pose complications.

Taking the above into account, gear couplings with a combined longitudinal modification of external and internal teeth under shaft misalignments in the main turbo gear units can rightfully be called gear couplings of increased operational efficiency, as their performance is significantly higher than traditional ones.

4 Discussion

The application of the developed designs of toothed couplings [6-17] allows for: ensuring reliable transmission of mechanical energy from one shaft to another in machines and mechanisms; providing even distribution of forces among all engaged teeth, thereby practically eliminating their breakage; compensating for misalignment of the axes of connected shafts in assemblies; reducing the magnitudes of contact stresses and, consequently, significantly increasing the load-carrying capacity under specified stresses; increasing the operational lifespan of toothed couplings by eliminating unplanned replacements, thereby reducing downtime and associated labor and equipment adjustment costs;

It's worth noting that these technical solutions can be applied in various sectors of the economy, including shipbuilding, mechanical engineering, aviation, automotive manufacturing, agricultural machinery, drilling equipment, rolling mills, and other industrial sectors in Ukraine.

5 Conclusions

1. Improving the operational characteristics and increasing the technical and economic indicators of ship power plants is possible by reducing the negative impact of misalignments in the axes of connected shafts in marine units, through the use of high-performance toothed couplings. 2. Designs of high-performance toothed couplings are characterized by an increase in operational efficiency, ranging from 1,25 to 4,59 times compared to traditional ones, at angles of misalignment of the shafts $\psi = (2{,}5\text{-}8{,}7)\cdot 10^{-3}$ rad. 3. The application of the investigated toothed couplings in conditions of misalignment of the axes of connected shafts in main marine units allows for a reduction in material costs by

$125-225 thousand USD for aligning the shafts and hundreds of thousands of dollars due to the absence of the need for unscheduled docking of the vessel, depending on its type, cargo, and operating conditions.

References

1. Popov A.P. Contact strength of gear mechanisms [Text] / A.P. Popov - Nikolaev: NUK Publishing House, 2008. - 580 p.
2. Popov A.P. Toothed mechanisms with point contact of teeth [Text] / A.P. Popov - Nikolaev: Izd - in Atoll, 2010. - 774p.
3. Popov A.P., Mironenko A.I. 2012. Tooth part transmission with point tooth engagement. Bulletin of the National Technical University "ХПІ". Kharkiv. No. 27, 133-141.
4. Spitsyn V.E., Popov A.P., Mironenko A.I., Dzyatko S.A. 2011. Results of the first tests of gears with initial point contact of teeth. Kharkiv: Visnik National University "KhPI". Vol. 24, 76-83.
5. Popov A.P., Mozgovoy M.G. 2013. Contact durability of gears with precise tooth engagement. Bulletin of NTU (KhPI). Kharkiv: Collection of scientific papers. No. 40, 108–116.
6. Patent No. 25103 Ukraine. IPC F16H1 1/00. Toothed clutch [Text] / O.P. Popov, O.I. Savenkov – u200703132; filed on 23.03.2007; published on 25.07.2007. Bulletin No. 11.
7. Patent No. 25111 Ukraine. IPC F16D1 1/00. Toothed clutch [Text] / O.P. Popov, O.I. Savenkov – u200703132; filed on 23.03.2007; published on 25.07.2007. Bulletin No. 11.
8. Patent No. 51954 Ukraine. IPC F16D1 1/00. Toothed clutch [Text] / O.P. Popov, O.I. Savenkov – u201000897; filed on 29.01.2010; published on 10.08.2010. Bulletin No. 15.
9. Patent No. 55634 Ukraine. IPC F16D1 1/00. Toothed clutch [Text] / O.P. Popov, L.O. Popova, O.I. Savenkov – u201004688; filed on 20.04.2010; published on 27.12.2010. Bulletin No. 24.
10. Patent No. 55771 Ukraine. IPC F16D1 1/00. Toothed clutch [Text] / O.P. Popov, L.O. Popova, O.I. Savenkov – u201007003; filed on 07.06.2010; published on 27.12.2010. Bulletin No. 24.
11. Patent No. 61719 Ukraine. IPC F16D1 1/00. Toothed clutch [Text] / O.P. Popov, O.I. Savenkov – u201100468; filed on 17.01.2011; published on 25.07.2011. Bulletin No. 14.
12. Patent No. 62922 Ukraine. IPC F16D1 1/00. Toothed clutch [Text] / O.P. Popov, O.I. Savenkov – u201100858; filed on 26.01.2011; published on 26.09.2011. Bulletin No. 18.
13. Patent No. 64856 Ukraine. IPC F16D1 1/00. Toothed clutch [Text] / O.P. Popov, L.O. Popova, O.I. Savenkov – u201103737; filed on 28.03.2011; published on 25.11.2011. Bulletin No. 22.
14. Patent No. 69705 Ukraine. IPC F16D1 1/00. Toothed clutch [Text] / O.I. Savenkov – u201112523; filed on 25.10.2011; published on 10.05.2012. Bulletin No. 9.

15. Patent No. 78089 Ukraine. IPC F16D1 1/00 F16D1 11/00 F16H1 1/00. Toothed clutch [Text] / O.P. Popov, O.M. Medvedovsky, L.O. Popova, O.I. Savenkov – u201209687; filed on 10.08.2012; published on 11.03.2013. Bulletin No. 5.
16. Patent No. 81556 Ukraine. IPC F16D1 1/00. Toothed clutch [Text] / O.P. Popov, O.M. Medvedovsky, L.O. Popova, O.I. Savenkov – u201212902; filed on 13.11.2012; published on 10.07.2013. Bulletin No. 13.
17. Patent No. 84863 Ukraine. IPC F16J 9/00. Piston with liquid sealing [Text] / O.P. Popov, O.M. Medvedovsky, O.I. Savenkov, D.A. Volik – u201301593; filed on 11.02.2013; published on 11.11.2013. Bulletin No. 21.