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Behavior Tests of a New Form of Propulsion After Ship Reconstruction

Enis Dauti [1)]
Dragan Trifkovic[2)]

The subject of this paper is a detailed qualitative analysis maneuvering and propulsion characteristics of a special purpose river vessel „КОЗАРА“ River war flotillas of the Serbian Army, after reconstruction and modernization. With the modernization of the ship, among other things, the old propulsion group with a classic diesel engine propulsion was replaced by a new diesel electric propulsion. In order to assess the justification of this replacement from the aspect of expected improvements of shunting and propulsion characteristics of the ship, it was necessary to develop and implement a test program and compare the results with available test results of the ship with the old propulsion group in earlier periods of ship operation. The results of measuring the basic maneuvering characteristics: ship speed, stopping distance and turning circle diameter, as well as propulsion characteristics: propeller shaft power, axial and torsional vibrations after six years of operation of the new propulsion confirmed all the advantages of diesel electric propulsion over classic diesel engine propulsion. However, certain problems have been noticed in terms of maintaining this complex plant, and proposed measures to overcome them.

Key words: **ship propulsion, shunting and propulsion characteristics of the ship, examination of maneuvering and propulsion characteristics of the ship.**

Introduction

THE development of technology and increasingly stringent requirements for improving the maneuvering characteristics of warships lead to the need to modernize them. The modernization of a warship primarily means the modernization of the propulsion group as one of the vital ship systems.

Given the decline in performance of the old propulsion group of the ship "KOZARA", the declining reliability of its systems and significant maintenance costs, it was necessary to consider possible ways to reconstruct the ship in order to modernize and improve its characteristics.

Taking into account the tactical and technical requirements that the ship needs to meet after modernization and considering the best possible solution that will provide better performance, it was decided to replace the classic diesel engine as part of the ship's reconstruction with a diesel electric group.

Remotorization as part of the modernization of the ship was carried out in 2011 when the propulsion hood with diesel propulsion was replaced by a new design in the form of diesel-electric propulsion (DEP).

The main difference between the two mentioned forms of drive groups is that in the classic diesel drive, the propeller drive is realized by direct drive, ie. motor, and in diesel electric drive, the propeller is driven by an electric motor. Electric motors are powered by generators powered by diesel engines.

Ship operating characteristics before modernization

Before the modernization, the propulsion group of the ship "KOZARA" consisted of two four-stroke, six-cylinder diesel engines of the RVB M-345 type, both with a power of 298kW. In this drive group, the motors were connected directly to the propeller shaft without a coupling, so the change in the direction of rotation of the propeller was done by changing the direction of rotation of the motor. The command was of the manual type.

The transmission of power from the diesel engine to the propeller was done using two shafts. Both shafts consisted of 3 shafts interconnected by a rigid connection, where a bronze propeller was connected to the last part. The transmission of the propeller propulsion force to the hull was performed by means of thrust bearings.

Fig.1 shows a schematic representation of the ship's propulsion group before modernization.

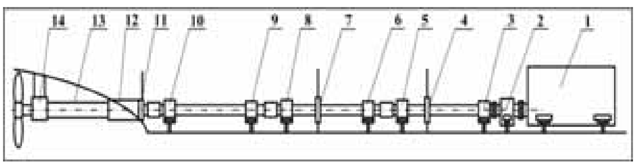

Figure 1. Schematic representation of the old propulsion group of the ship "Kozara"

The positions in Fig.1 are: 1 - diesel engine; 2 - thrust bearing; 3 and 5 - bearings of the first part of the propeller shaft; 4 - passage through the watertight barrier I; 6 and 8 -

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1) Serbian Army, River Flotilla Command, address: 1300 kaplara 11, Novi Sad, SERBIA
2) University of Defense in Belgrade, Military Academy, Pavla Jurisica Sturma 33, Belgrade, SERBIA
Correspondence to: Enis Dauti; e-mail: dautienis1907@gmail.com

bearings of the second part of the propeller shaft; 7 - passage through watertight barrier II; 8 - bearing of the second shaft; 9 and 10 - bearings of the third part of the propeller shaft; 11 - passage through watertight barrier III; 12 - stand tube with two propeller shaft bearings; 13 - sock; 14 - bed in step.

Thanks to the preserved results of the first measurement during the examination of the propulsion and maneuvering characteristics of the ship performed on September 19, 1963. year on the Danube, you can see the performance of the ship "KOZARA" with the old diesel propulsion group.

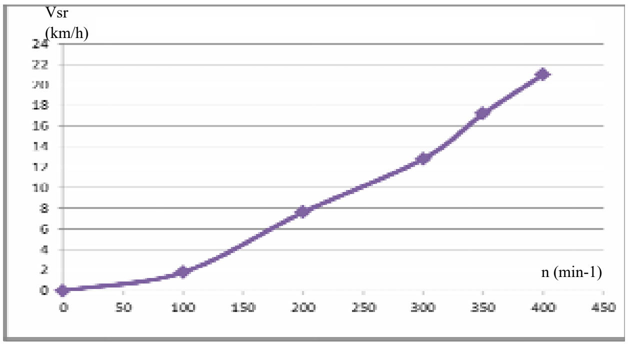


Diagram 1. Dependence of the average speed of the ship on the number of revolutions of the propeller

As part of the first examination of the maneuvering characteristics of the ship "KOZARA" realized on September 19, 1963. year, under the same conditions, the measurement of the stopping distance (upstream and downstream navigation) was realized, with the then diesel propulsion group.

Table 1. Ship launch downstream

1268-1269km fairway	FEED		
	slowly 100 o/min	with half the power 200 o/min	full power 360 o/min
	STOP ROAD		
slowly 100 o/min	400 m	200 m	120 m
	3 min i 26 s	1 min i 36 s	1 min i 5 s
with half the power 200 o/min	600 m	350 m	140 m
	4 min and 35 s	2 min and 18 s	1 min and 22 s
full power 360 o/min	800 m	450 m	300 m
	4 min and 16 s	2 min and 15 s	1 min and 35s

Table 2. Ship launch upstream

1268-1269km fairway	FEED		
	slowly 100 o/min	with half the power 200 o/min	full power 360 o/min
	STOP ROAD		
slowly 100 o/min	80 m	50 m	20 m
	42 s	35 s	15 s
with half the power 200 o/min	110 m	95 m	70 m
	1 min and 2 s	58 s	48 s
full power 360 o/min	225 m	145 m	105 m
	1 min and 49 s	1 min and 3 s	1 min and 2 s

Selection of a new ship drive group

Electric propulsion of ships first appeared in the middle of the 19th century, and its development was realized first in the military industry. With the introduction of electric propulsion, the percentage of utilization of the cargo space of the ship increases significantly, due to its simple installation, small dimensions and propulsion safety.

Precisely this type of propulsion, which enables continuity in operation and achieving better performance while reducing fuel consumption, was chosen for the new form of propulsion of the ship "KOZARA".

Replacing the old classic drive group with a new diesel electric group also required the selection of appropriate drive electric motors. When choosing an electric motor, it was necessary to determine the required power delivered to the propellers. The power supplied to the propeller, in the case of a classic diesel drive, is calculated by the formula:

$$P_D = P_n \cdot \eta_w = 294 \cdot 0,93 = 273,43 \text{ kW} \qquad (1)$$

where P_n- nominal power of the diesel generator.

In the case of diesel electric drive on board the "KOZARA", the degree of efficiency of the reducer with a thrust bearing is taken into account $\eta_R = 0,98$ and the degree of efficiency of the return line η_w which has five bearings in its system and one passage through a watertight bulkhead, on the basis of which its value is determined $\eta_w = 0,97$.

After that, the calculation of the required power of the electric motor was started according to the formula:

$$P_{EM} = \frac{P_{DEM}}{\eta_w \cdot \eta_R}(kW) = \frac{273,42}{0,97 \cdot 0,98} = 287,6\,(KW) \qquad (2)$$

Based on the obtained value, typical asynchronous electric motors with a power of 250 kW were selected from the catalog, which were estimated to provide the required speed of the ship because the fact that the ship will have a smaller displacement after reconstruction was taken into account.

The new motor drive of the ship now consists of two electric motors that drive one propeller each and the transfer of power from the engine to the propellers is done via a reducer.

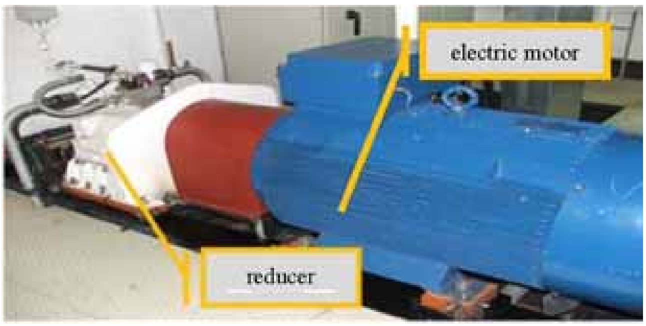


Figure 2. Selected electric motor behind the reducer

The regulation of the speed of rotation of the propulsion motors on board is performed by means of selected voltage-frequency converters of four-square shape.

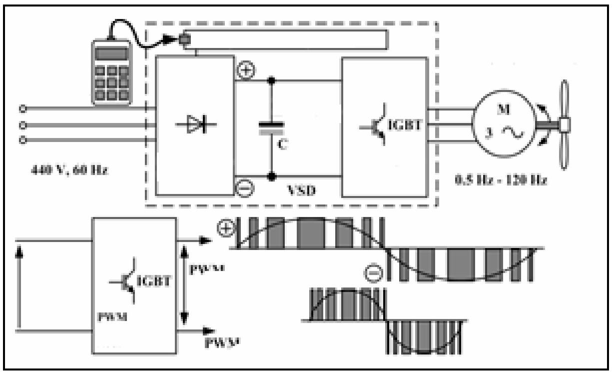


Figure 3. PWM voltage frequency converter

After choosing the propulsion electric motors, the next step was to select the generator to power the ship's network. Based on the calculation of the peak load of all electricity consumers on board, the required installation power of the electricity source is determined. The basic power supply of the ship is performed by means of two selected synchronous self-excited non-contact generators of the ship's construction with a power of 400 kW. These generators are air-cooled and designed to operate in parallel. To drive the generator within the diesel unit, diesel engines were selected and installed, the technical characteristics of which are shown in Table 3:

Table 3. Basic characteristics of diesel generators

Characteristics of diesel aggregates			Generator characteristics		
	Manufacturer	CATERPILLAR		Manufacturer	CATERPILLAR
	Type	C18 i6 four-stroke diesel		Model	OLYMPIAN
	Nominal power	492 kW		Type	OLY00000KE4B01298
	RPM	1500 o/min		Nominal power	64 kW
	Exhaust show	IMO/EPA Tier I CCNR		RPM	1500 o/min
	Volume	18.1 L (11006 cu. in.)		Voltage / Frequency	400 V/55Hz
	Weight dry	1630 kg		Current	88 kVA
	Protection type	Protects against overload		Protection type	Protects against overload

The drive is controlled by a counter built into the wheelhouse, on which the remote control equipment is located. Fig.4 shows the disposition of the shaft line of the new type of drive.

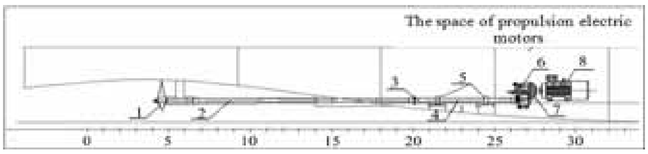


Figure 4. Disposition of the return line of the new type of drive

Testing of the ship "KOZARA" after modernization

The testing of the ship "KOZARA" after the modernization was preceded by the development and definition of a test program that should include testing the propulsion and maneuvering characteristics of the ship, determining the value of torque on the return line and recording performance and measuring axial and torsional vibrations.

Examination of the propulsion and maneuvering characteristics of the ship included:

1. Measuring the speed of the ship,
2. Measuring the ship's stopping distance and
3. Measuring the diameter of the ship's turning circle.

The measurement of the speed of the ship "KOZARA" with the new diesel-electric propulsion group was performed during the first and second tests, according to the conditions given in Table 4.

Table 4. Test conditions

Conditions at first examination		Conditions during the second examination	
Deplacement of the ship	530 t	Deplacement of the ship	564 t
Medium draft of the ship	1.11 m	Medium draft of the ship	1.17 m
Water depth	10 m	Water depth	до 15 m
Speed of river flow	3.43 km/h	Speed of river flow	2.24 km/h
Meteorological conditions	no wind and waves	Meteorological conditions	wind 5 m/s no waves

The measurement of the diameter of the ship's turning circle was performed within the second test on the part of the waterway in the area of Veliki Gradište and Donji Milanovac.

Measurement of the ship's stopping distance was performed under conditions of steady rectilinear movement at constant speed at 100% propulsion mode while the sailing course was chosen so that the vessel sailed downstream in the middle of the fairway after which the propulsion was switched to full stern navigation. The measurement of the stopping distance was interrupted after the ship reached a reversing speed of 0.25 m / s. For the needs of measuring the time and the distance traveled until the beginning of the stern navigation, the ship's GPS system was used.

Part of the obtained characteristic results of propulsion and maneuvering characteristics of the ship are given in Table 5.

Table 5. Results of measuring the propulsion and maneuvering characteristics of the ship

Propulsion and maneuverability characteristics	**SAILING REGIME**			
	Both engines forward (o/min)	**CRASH-STOP maneuver**	**Coup**	**Coupling and bow thruster**
Medium speed (km/h)	1490 o/min			
	22,14 km/h			
	1550 o/min			
	22,87 km/h			
Stop road (m)		downstream		
		2,8 m		
		upstream		
		1,6 m		
Diameter of turn circle (m)	1000 o/min		1000 o/min full rudder deflection	1000 o/min,full rudder deflection ,bow thruster 980 o/min
	234 m		102 m	73 m
				1000 o/min , rudder in the middle , bow thruster 980
				270 m

Torque measurement on the shaft line

The measurement of the torque on the return line of the ship was performed within the first test, on the part of the waterway from Novi Sad to Belgrade. The measurement was performed on the part of the shaft behind the reducer of the left shaft line of the ship.

Table 6. Results of torque and power measurements

Se. number	Shaft speed (min^{-1})	Torque (Nm)	Power P (kW)
1	101.0	510.7	5.4
2	202.0	1925.3	40.7
3	301.0	4123.5	129.9
4	375.0	6425.7	252.2
5	393.0	6758.6	278.0

The obtained measurement results confirm the value of the power of the propulsion electric motors as well as the fact that the propulsion motors can work overloaded by a value of 10% for a period of one hour.

Measurement of torsional oscillations of shaft lines

Measurement of torsional oscillations on the shaft line of the ship "KOZARA" after modernization was performed within the first test, as part of the torque measurement. Determination of the oscillation value was performed on the left propeller shaft at given propeller speeds.

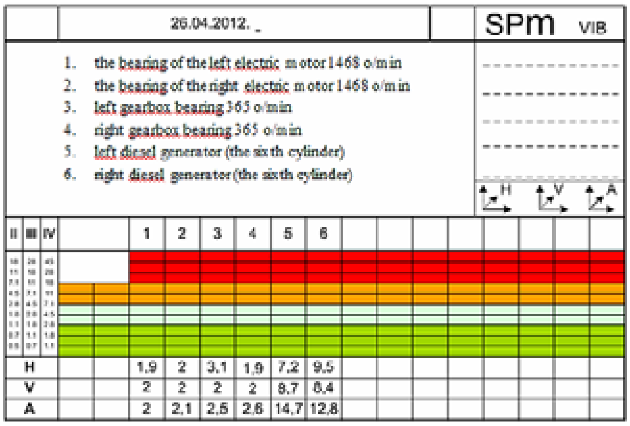
Table 7. Results of torque and calculated tangential stress

Se. number	Propeller speed (min^{-1})	Measured torsional moment (Nm)	Torsional stress of the shaft (N/mm^2)	
			measured maximum stress values	maximum allowable value
1	101	510.68	1.2	41
2	375	6512.29	15.5	32

Measurement of linear structure oscillations

The measurement of linear oscillations was performed with the Vibrometer VIB-10 device, on the bearings of electric motors, reducers, on the sixth cylinder of the diesel generator and on the front and rear bearing of the second part of the return line.

Table 8. Results of linear oscillation measurements



Testing of modernized ship drive after six years of operation

After six years of operation of the modernized ship "KOZARA", and in order to form an objective assessment of the current state of the ship's propulsion complex and the formation of a database with measurement results during the operation of the ship, control measurements were realized. These diagnostic measurements were preceded by the fact that during the regular operation of the ship, the left propeller was damaged, so it was necessary to consider both the consequences and the proposed overhaul. The testing of the ship was realized on April 7, 2016 by the Technical Testing Center on the part of the waterway Belgrade-Veliko Gradiste on the river Danube.

Propeller power measurement

The measurement was performed while driving upstream, at different speeds.

Table 9. Power values passed to the propeller

min^{-1}	P_{vrl} [kW]	P_{eml} [kW]	P_{emd} [kW]
201	25.11	28.75	21.34
252	64.85	72.50	55.12
302	133.70	142.50	118.28
338	210.40	222.50	174.63
350	245.06	250.00	196.05

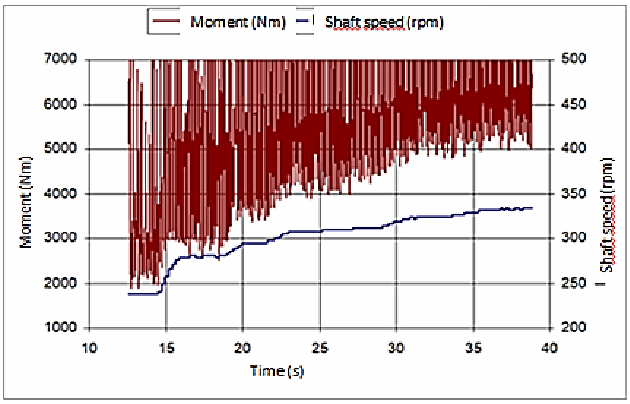
where are they:
P_{vrl} – measured power delivered to the propeller,
P_{eml} – power of the left drive electric motor,
P_{emd} - power of the right drive electric motor,
n – number of turns of the left shaft line.

Based on the obtained results, it follows that the increased load of the left drive electric motor is caused by the condition of the propeller (damaged).

Measurement of torsional vibrations

A damaged propeller inevitably causes the appearance of increased oscillation of the torsional torque value at stationary modes of operation of the propulsion engines, which can be seen on the basis of the torque timing diagram.

Diagram 2. Time record of torque and speed



Comparative quantitative technique according to the ISO 18434-1 standard was used for thermographic recordings. Thermographic imaging showed a difference in the temperature of the housing of the electric motor of the left and right shaft water, which averaged 13.5°C in the fourth imaging. During thermographic recordings and monitoring of the operation of electric motors and frequency converters during navigation, the permitted temperature values of operation of these devices were not exceeded.

Analysis of measurement results performed after six years of operation

The analysis of measurement results is based on the comparison of measured values with permissible values defined by appropriate standards and technical instructions of the manufacturer, as well as on the comparison of measured values with values measured during test run performed after overhaul and reconstruction of the ship "KOZARA" in 2012.

Based on the measured linear oscillations and operating parameters of the diesel electric generator, no values deviating from the valid standards and technical documentation were observed.

Measurement of linear oscillations of diesel generators

Measurements of linear oscillations were performed using a portable vibrometer SPM type VIB-10, in order to establish the level of oscillations and to compare the measured values with those allowed according to ISO8528-9: 1995.

According to the measured values of diagnostic parameters, it was concluded that all measured values of oscillations of diesel generators are in the range allowed by the standard. The read values of the operating parameters of the diesel engine do not indicate malfunctions or symptoms of possible failures.

Thermographic tests of devices and systems

Thermographic recordings of ship devices and systems were performed before navigation and several times during navigation.

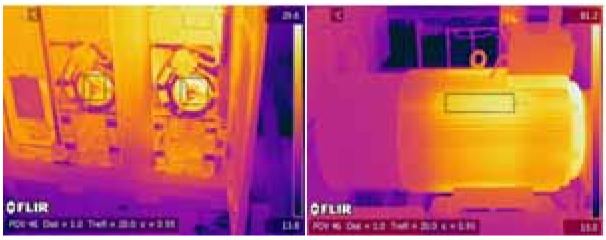


Figure 5. Temperature monitoring area on EM and frequency converters

The power diagram shows that at each speed the left drive electric motor works at a significantly higher load than the right (approximately 20%). This results in slightly higher measured temperatures of the left electric motor housing, and ultimately increased fuel consumption.

By measuring the power delivered to the propeller, it was unequivocally confirmed that the left electric motor was overloaded due to the condition of the propeller. The propeller is damaged, ie all three wings of the propeller are deformed due to the impact and worn along the edges.

The measured values of torsional oscillations of the left propeller shaft are at the level of up to 30% of the allowed, but they are also about three times higher than those measured during test runs in 2012 (the increase is directly caused by the damaged propeller).

The linear oscillations are within the permitted limits with respect to the recommendations prescribed by ISO 10816-3.

The control of roller bearings was done by the method of shock impulses and it is concluded that the controlled roller bearings are in the area of so-called good condition. According to above given facts, it can be concluded that the critical point in the propulsion system is the left propeller (damaged and deformed).

A potential problem, which could not be noticed under the conditions of this ride, is the high value of the fuel consumption temperature.

The assumption is that under stricter sailing conditions (summer period, multi-day rides) this problem will come to the fore.

In order to solve the problem caused by damage to the left propeller and to restore the performance of the ship to its original condition, the following works have been proposed:

- dock the ship and then repair the left propeller,
- after completion of the repair, be sure to perform static balancing of the propeller,
- check the condition of the bearings in the steps, ie measure the gaps in them,
- solve the problem of elevated temperature of the diesel fuel supply generator (consider the possibility of installing a fuel cooler or solve the problem in another technically acceptable way).

After these realized measurements, all the proposed works by the TOC were realized and the control measurements after the completion of the docking of the ship show that in the process of docking the ship irregularities in the propulsion system were eliminated. It is also concluded that the electric drive motors are equally loaded and that the difference during driving does not exceed the value of 3%.

The occurrence of unauthorized heating of the left electric motor bearing, as an indirect consequence of propeller damage, has been eliminated. All measured values of linear oscillations and temperatures are within the permitted standards and manufacturer's instructions.

The built-in coolers in the fuel consumption system of the diesel generator are in operation.

Conclusion

The warships of the River Flotilla, which have been in use for many years, require a certain type of modernization and equipping with modern equipment in order to keep up with the basic purpose and keep up with the basic requirements that are set before them.

Based on the comparison of the test results of the ship after the reconstruction with the test results of the ship before modernization, it can be concluded that the modernization of the ship has improved the maneuverability and navigability of the ship.

Improving the maneuverability and navigability of the ship is reflected in the following:

4. The new form of propulsion of the ship increased the average speed in free navigation to 22.25 km/h, by about 5%.
5. The new diesel electric group enabled the modernized ship to reduce the stopping distance to 191m, ie by about 47%.
6. The measurement established a difference in the drastically reduced diameter of the ship's turn by using the coupling of the electric motor and the bow thruster, which significantly improved the maneuvering characteristics.

The successfully modernized ship gained an increase in operational capability, provided a significant cost-effective solution to the cost of the new ship, and thus provided reliable propulsion for the next two to three decades.

Based on the test results after six years of operation of the ship, it can be concluded that in that period there was no deterioration in the performance of the new propulsion group, except in the case of damage and failures.

As failures and damage to the ship's propulsion system (in this case damage to the propeller) have a negative impact on the performance of the propulsion group, it is necessary to timely diagnose the observed work irregularities and take measures to eliminate them.

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Ispitivanja ponašanja novog pogona nakon rekonstrukcije broda

Predmet ovog rada je detaljna kvalitativna analiza manevarskih i pogonskih karakteristika rečnog broda posebne namene „KOZARA“ Rečne ratne flotile Vojske Srbije nakon izvršene rekonstrukcije i modernizacije. Modernizacijom broda je, između ostalog, stara pogonska grupa sa klasičnom dizel motornom propulzijom zamenjena novom dizel električnom propulzijom. Kako bi se ocenila opravdanost ove zamene sa aspekta očekivanih poboljšanja manevarskih i pogonskih karakteristika broda bilo je neophodno izraditi i sprovesti program ispitivanja i dobijene rezultate uporediti sa dostupnim rezultatima ispitivanja broda sa starom pogonskom grupom u ranijim periodima eksploatacije broda. Rezultati merenja osnovnih manevarskih karakteristika: brzine broda, njegovog zaustavnog puta i prečnika kruga okreta, kao i pogonskih karakteristika: snage na propelerskom vratilu, aksijalnih i torzionih vibracija nakon šest godina eksploatacije novog pogona potvrdili su sve prednosti dizel električne propulzije nad klasičnom dizel motornom propulzijom. Međutim, uočeni su i određeni problemi u pogledu održavanja ovog kompleksnog pogona, te predložene mere za njihovo prevazilaženje.

Ključne reči: **pogon broda, manevarske i pogonske karateristike broda, ispitivanje manevarskih i pogonskih karakteristika broda.**