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Determination of Critical Values of Parameters for Practical Application of Express Method of Diagnosing the Technical State of Shipboard Diesel Engines

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Abstract

This paper substantiates the feasibility and advisability of developing a new express method of diagnosing the state of diesel engines of combat boats based on the analysis of readings through on-board instruments of the information system for controlling and monitoring the boat's powerplant. This express method will enable combat boats' (ships') crews to employ the predictive maintenance of shipboard mechanisms to promptly identify degradation processes during their operation and minimize the risk of unexpected failures (breakdowns) while performing the combat missions. The essence of the new method lies in constructing a model of diagnosing shipboard machinery based on the analysis of empirical criteria for the rates of change of the current values of the determining parameters in singled-out time ranges during engines heating-up. As a result of full-scale tests, the determining parameters were defined and their limiting normalized rates of change were established, exceeding which could lead to emergency situations.

Keywords: shipboard diesel engine; determining parameter; heating-up mode; current values.

1. Statement of the problem in general

The introduction of martial law in Ukraine has not changed the requirements for the operation, maintenance, and repair of ships and their technical equipment. On the contrary, it has imposed additional burdens on the technical operation of the ships and boats of the Ukrainian Navy. At the same time, the conditions for ensuring and maintaining the established technical readiness of the ships and boats have changed. Specifically, the processes for ensuring the trouble-free operation of technical equipment and their timely maintenance have become more complex, and the capabilities of the ship repair and technical support system have deteriorated. Consequently, the requirements placed upon ships' (boats') crews have increased in terms of their specialized training, their ability to make sound decisions and fully perform their duties in difficult conditions, their ability to learn from positive and negative experiences, and their ability to incorporate these lessons into their work.

Under complicated combat conditions of operation, any failure or malfunction of the ship's (boat's) emergency alarm and control systems in combination with the insufficient level of crew's training in the maintenance of powerplants leads to delays in taking timely and adequate measures of responding to changes in technical state of shipboard machinery The crew's insufficient knowledge regarding the methods and techniques for localizing and

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repairing combat and emergency damage of technical equipment can lead to serious consequences, including the loss of combat capability by the ship (boat), a death threat to the members of the crew, and, in extreme cases, the wreck of the ship (boat).

In everyday situations, the cost of a belated detection of the values deviation of determining parameters from normalized values or an operational error by crew during the working of a modern ship's (boat's) technical equipment can be very high as well. Accidents can reach such a scale that moderating their consequences will require significantly greater effort and financial expenditures than simply the direct costs of restoring the technical resources and operability of such equipment. In world shipping practice, global environmental disasters as well as serious political consequences by reason of accidents at sea have taken place.

An analysis of technical failures on Ukrainian Navy ships (boats) shows that these failures most often occur as a result of influence of two common factors: (1) design and technological drawbacks (due both to the exhaustion of technical resources and to imperfections in the processes of scheduled inspection and restoration); (2) the accompanying human factor.

The main causes of breakdowns on ships (boats) of the Ukrainian Navy are as follows:

1) The obsolete and exhausted service life of a significant portion of the technical equipment, including equipment received as part of the logistical support.
2) Discrepancy within the chemical compositions of oils, lubricants, and process liquids in comparison with the established reference standards of the manufacturer.
3) Lack of spare parts, special tools, and instruments.
4) Abridged quantity of hours for performing the maintenance of shipboard machinery, and as a result, a low level of quality of work performed by the maintenance and repair department personnel.
5) A low level of quality of repair work and maintenance of watercraft in state-owned and private enterprises (companies).
6) Irregularity of ships' (boats') goings to sea, which leads to the crews losing their practical skills in operating shipboard technical equipment.
7) A low level of quality of incoming inspection of fuels, lubricants, and process liquids by crews.
8) Limited access to modern technical diagnostic tools and their use, as well as an insufficient number of instruments (including auxiliary ones) for technical monitoring.
9) Limited use of nondestructive express diagnostic methods and insufficient qualifications (technical awareness) of crews to carry out routine monitoring and prompt diagnostics of the technical state of shipboard machinery on the high sea.

Thus, the search for ways to further improve the operation of the ships' (boats') powerplants of the Ukrainian Navy under the martial law regime, in particular routine monitoring of the technical state, as well as forecasting and preventing possible failures of marine diesel engines, is an extremely pressing problem given the transition of the Ukrainian Navy to NATO standards for the operation of military equipment.

2. Analysis of recent research and publications

Ensuring the serviceability, reliability, and safe operation of ships (boats) requires the introduction of effective diagnostic tools, among which nondestructive testing (NDT) methods play a leading role. During the operation of technical equipment on the high sea, when maintenance is carried out in limited space and time conditions, and access to specialized laboratories is limited, the correct choice of NDT method becomes a serious condition that directly affects the operability of shipboard machinery.

When deciding on an NDT method for technical diagnostics of machinery, based on ship-repair practice, the following five key areas should be taken into account:

1) Analysis of the physical nature of the defect or property being tested, during which the type of object (hull parts, shafts, gearboxes, pipelines, welds, etc.) and the nature of possible damage as typical for the marine environment (cracks, corrosion, delamination, decompaction, etc.) are determined.

2) Knowledge of the physical principles underlying a specific NDT method. This is necessary to determine the capabilities and limitations when testing steel, aluminum, composite, or anti-corrosion coated objects to be diagnosed.
3) Evaluation of the interaction of a testing medium with the material of a part (assembly). For example, ultrasonic methods require the use of a wetting medium, which may be unacceptable for certain types of ship's equipment (electronics, high-precision components).
4) Analysis of the technical potential of the equipment, the measurement capabilities, and the reliability of the results obtained, taking into account the conditions on shipboard: vibration background, temperature conditions, spatial restrictions of the engine room, the presence of electromagnetic interference, etc.
5) Taking account of regulatory, economic, financial, organizational, and logistical factors for the feasibility of using a specific NDT method, which is related to the cost of maintenance, the speed of inspections, the requirements of marine classification societies (IACS, ABS, DNV, BV, etc.), as well as compliance with environmental requirements (including during stays in port or at anchor).

For example, ultrasonic or magnetic particle testing methods can be used to detect cracks in main engine crankshaft and connecting rod components, such as the crankshaft or connecting rods. Ultrasonic thickness testing is used to check for erosion and corrosion damage in cylinder liner walls, water jackets, or bores. In each of these cases, it is necessary to take into account not only the compliance of an NDT method with the physical characteristics of the object being tested, but also the internal operating conditions of the engine (high temperatures, limited access to components, the presence of lubricant residues, and the possibility of performing the testing without dismantling the components) and external ones (exposure to seawater, high salinity, and corrosive activity).

It should be noted that the equipment sensitivity values specified by manufacturers in their data sheets and operating instructions may differ from the actual parameters under operating conditions of a ship (boat) during a real combat situation. That is the reason why the competence of the personnel performing the testing and adherence to standardized testing procedures are of particular importance.

Thus, the optimization of NDT methods in the maintenance of ships (boats) of the Ukrainian Navy should be based on a deep understanding of physical, technological, and operational factors, which will ultimately allow not only the timely detection of defects and the prevention of emergency situations, but also ensure full compliance with the requirements of international standards for their operation.

It is clear that reliability evaluation of technically complex objects (machinery and their components) using NDT methods plays a significant role both when designing and manufacturing, and when operating and maintaining them. Currently, about a dozen different NDT methods are used: electrical, radio-wave, thermal, acoustic, vibroacoustic, optical, with penetrants, eddy-current, magnetic, radiative. All the NDT methods are categorized by their areas of application, as each has certain technical limitations [1].

At the present time, in the theory of technical diagnostics in relation to shipboard machinery, three groups of methods have received the greatest distribution: (1) the methods of diagnosing by the parameters of working processes (based on determining the technical state of machinery through monitoring the dynamics of changes in their operating parameters); (2) the methods of diagnosing by the parameters of accompanying processes, which indirectly affect the operation of technical equipment (based on the analysis of the indicators of thermal field, noise, vibroacoustics, etc.); (3) the methods of diagnosing by structural (geometric) parameters, which directly characterize the technical state of the units and assemblies of powerplant (based on the evaluation of objective geometric parameters (gaps, backlashes, free plays, displacements, etc.) [2], [3].

Diagnostic objectives, the means and methods for measuring diagnostic parameters, and the physical nature of the processes underlying the operation of the units and components being diagnosed are key factors when choosing a method for diagnosing the technical state of shipboard machinery. For example, when performing a standard technical diagnostics of individual systems and components of a marine diesel engine, as well as its diagnostics as a single unit of equipment, a good deal of diagnostic operations must be performed, which ultimately leads to significant time losses and, therefore, such a diagnostics is lengthy and ineffective.

It is clear that the solution of the problem of early warning of a high probability of failure, whether it is a single complex mechanical system (diesel engine, gearbox, generator, etc.) or individual simple components (injector, bearing, valve, etc.), depends on the availability of possibility to conduct a prompt evaluation of their technical state during operation. One of the key factors that can be singled out among others affecting the reliability of a component (or a mechanism) during operation is the quality level of current monitoring its technical state, which is conducted in the course of its intensive working.

In recent years, several innovations have become known in global practice for the technical diagnostics of complex systems—some enterprises (companies) have introduced so-called deep learning models in production, which ultimately increase the service life of these systems [4]. In dozens of countries, predictive maintenance systems are being added to production, which is associated with the implementation of the so-called smart factory at the Industry 4.0 level [5], [6]. Also highly reasonable is the attempt by Chinese researchers to create standard databases for diagnosing the malfunctions (failures) of technical equipment in order to prevent repetition of their research [7].

According to paper [8], the authors investigated a method for improving the efficiency of parametric diagnostics of marine engines based on the analysis of indicator diagrams and heat release characteristics. The method for diagnosing the quality of the combustion process in a marine internal combustion engine is based on measuring the pressure within cylinder as a function of the crankshaft angle (CA) during engine operation under typical operating conditions. The resulting indicator diagrams allow one to determine a number of indicator parameters (maximum combustion pressure, pressure at the beginning and end of combustion, average indicator pressure, etc.), the analysis of changes in which enables one to identify deviations in the operation of systems that form the combustion process, in particular the fuel injection system, the gas exchange system, and the "piston–piston rings–cylinder" assembly. The advantages of this method are its non-invasiveness (no need to stop the engine), as well as the speed of obtaining results and the ability to directly evaluate the technical state of the engine's functional systems based on physically substantiated indicators of the combustion process.

According to paper [9], the use of new-generation high-performance microcontrollers with wireless interfaces and integrated analog-to-digital converters (given their low overall power consumption) makes it possible to solve the problem of comprehensive diagnostics of marine diesel engines. And this, in turn, makes it possible to develop a portable system for technical diagnostics of the parameters of marine engines, which operates in real time. Such a system can be installed on well-known devices with Android or iOS mobile platforms, which receive information from sensors via Bluetooth system, after which they perform the necessary calculations and display diagrams and data (in real time). The proposed system uses a combination of a gas pressure sensor in the working cylinder and a vibroacoustic sensor, which expands the diagnostic capabilities of marine diesel engines in operating conditions. The presented method allows one to calculate the irregularity indicators of engine working in real time and introduces the integral CII criterion for evaluating the stability of operating cycles, thereby ensuring an accurate determination of the indicated power and providing a possibility of optimizing the settings of engine systems during operation.

Recently, there has been a clear trend in the modernization of marine technical equipment toward the active introduction of artificial intelligence into control and monitoring systems for shipboard machinery. The use of modern machine learning and big data processing technologies significantly improves the reliability of statistical information on the technical state of a ship's powerplant and auxiliary systems. And this, in turn, minimizes the probability of errors when evaluating the parameters of equipment working and ensures the timely detection of process deviations from standard operating modes. For a ship's tending squad, such intelligent solutions become decision support tools that reduce the complexity of understanding complex technical processes and contribute to the transition of the ships' (boats') crews from a reactive approach to the tending of shipboard machinery (i.e., passively responding to external events occurring with machinery) to a proactive approach (i.e., anticipating the failures of machinery in advance through predictive maintenance). In other words, a crew of a modern ship (boat) must have the ability to fully understand technical faults that unexpectedly arise during the operation of shipboard machinery on the high sea, and be able to use their knowledge to take further measures to operate the ship in accordance with the objective reality of the current state of the mechanisms.

In paper [10], the researchers described a new model of artificial intelligence based on a multi-scale attention transformer (MSAT) that can automatically detect faults in marine diesel engines by sensor data (e.g., cylinder pressure). Its unique feature is that it simultaneously recognizes fine signal details (local variations) and the overall picture of engine working (global dependencies). To ensure fast and accurate training of the model, they used an improved optimization algorithm. The testing showed very good results—the model correctly identifies faults even in the presence of significant interference (noise). The study substantiates the advisability of the integration of MSAT into on-board control and monitoring systems of marine engines as a decision support tool for predictive maintenance of ships' powerplants. And this means that such an approach can be applied directly on shipboard to continuously monitor the technical state of an engine and to provide early prevention of potential faults. The authors of this study believe that for developing an express method for diagnosing the diesel engines of fast-moving surface platforms, the method based on the parameters of accompanying processes is the most practicable.

According to paper [11], a passive thermal monitoring method based on the study of bearing heating rates was proposed for the prompt evaluation of the technical state of rolling bearings. A distinctive feature of this approach is the evaluation of the technical state of friction assemblies using the empirical criterion of heating rate as an indirect criterion of bearing operability by thermal state. This paper also took into account the results of bench tests [12], during the analysis of which the issue of shifting the period of prompt evaluation was examined in detail when starting up a unit (mechanism).

Under the conditions of combat operations, the problem of conducting the prompt diagnostics of shipboard diesel engines is particularly pressing. The intensive operation of ships and boats of the Ukrainian Navy at near-maximum operating modes occurs amid active enemy's counteraction and is accompanied by significant physical and psycho-emotional exhaustion of crews. Under such conditions, the known diagnostic methods used, including those based on empirical criteria of accompanying processes (heating rate when shifting the period of prompt evaluation when starting up the units), do not provide complete and reliable information about the actual technical state of the engine precisely at the moment of starting up, as the most critical and vulnerable mode of its operation. And this, in turn, creates the risk of hidden failures and sudden breakdowns, which directly impacts the combat readiness and survivability of ships (boats) [13].

One of the key prerequisites for ensuring the trouble-free operation of the main and auxiliary mechanisms of ships' powerplants during combat and special missions is effective current technical monitoring of critical operating parameters of engines and auxiliary equipment. The possession of reliable information about current changes in the values of these parameters in real time allows the crew to quickly respond to changes in the technical state of the powerplant, duly identify the initial signs of hidden defects and monitor degradation processes, as well as duly warn the maintenance and repair department about potential threats. Based on the data received from the crew, maintenance and repair department specialists can organize unscheduled diagnostic measures (using special instruments and tools) and, based on an analysis of the current values of the measured parameters, make substantiated decisions about the need for unscheduled maintenance or repair of specific assemblies (parts) of the powerplant.

The implementation of express methods of diagnostics based on the analysis of data through the digital display panels of on-board instruments will ensure the timely forestalling of emergency situations while ships are on the high sea. Given the crew's limited access to information about the technical state of shipboard machinery, and having only data coming from standard on-board control and monitoring systems, it is advisable to create an algorithm for the crew's actions and a database with a formalized description of procedures in the event of situations where, during technical diagnostics, an excessive increase in the rate of degradation processes occurs (by extremely high values of the determining parameters). This requires a clear determination of diagnostics objectives, formalization of monitoring procedures, optimization of the selection of critical parameters and establishment of standards for indicators characterizing the oncoming of the technical state of the powerplant to the critical one, as well as taking account of distinction in the use of a direct or indirect mode of measuring the values of the determining parameters.

In paper [14], we described the development of an express method for predicting the development of degradation processes based on a series of full-scale experiments to determine the most informative parameters for the prompt evaluation of the technical state of the diesel engines of boats' powerplants, the values of which vary over time. Using an improved diagnostic technique based on an empirical criterion for the rate of change of determining parameters over a fixed period of time, particularly during the unit heating-up stage, we analyzed data obtained through on-board instruments of the control and monitoring system. This made it possible to establish intermediate values for the rate of change of operating parameters and determine ways to obtain the boundary limits of critical values. As a result of the conducted research, we made a substantiated conclusion that nearing these limits indicates an increased probability of loss of operability of the shipboard diesel engine, which, in turn, increases the risk of the ship (boat) losing her capability to perform combat missions.

Taking into account the aforesaid, there is a need to develop a relatively easy-to-use and physically understandable (for ship's crew) express method of diagnosing the actual technical state of the engine, which allows for the advantages and disadvantages of other methods and provides crews with an effective tool for promptly evaluating the operability of powerplants in real time. Such a method must be technologically simple when introducing, be adaptable to standard technical instruments for measuring the parameters being monitored, ensure rapid acquisition of diagnostic data, and also minimize the influence of human error. Its use will significantly improve the effectiveness of decision-making by the crew under complicated operating conditions (including combat operations), when the combat readiness and survivability of a ship (boat) depend on the failure resistance and timely response to malfunctions.

3. The goal and tasks of the study

The goal of the study is to develop a new express method of diagnosing the technical state of diesel engines of powerplants on shipboard of high-speed combat boats of the Ukrainian Navy directly at the initial stage of engines working, in particular during their heating-up.

Practical application of the new express method by the crews of ships (boats) must ensure the timely detection of early signs of degradation processes in the functional systems of engines, which will enable one to take preventative measures and, consequently, to stave off probable failures in the future. At a later time, this will significantly reduce the probability of operability loss by ships' (boats') powerplants during combat missions on the high sea and will lay the foundation for implementing the concept of predictive maintenance (i.e., maintenance based on actual technical state) into the operational practices of the Ukrainian Navy.

According to paper [14], the model of the express method of diagnosing is based on the evaluation and analysis of the indicators generated by the on-board instruments of the control and monitoring system (with the shifting of period of the prompt evaluation during the engine startup stage and singled-out phases of its heating-up). Taking into account the results of full-scale experimental tests, which were conducted on shipboard diesel engines, and the conclusions from the analysis of the interdependence of the parameters of the on-board instruments of the control and monitoring system, as well as the forecast of the possibility of obtaining the boundary limits of critical values, the following scientific research tasks can be defined that require fulfillment:

1) Calculation of critical values of determining parameters, nearing which increases the probability of loss of engine operability and reduces the combat capability of the ship (boat), taking into account the dynamics of changes during engine startup in heating-up mode.
2) Obtaining confirmation of the specified normalized critical values of determining parameters and the rates of their change within specific time intervals through full-scale experiments on existing diesel engines of ships' powerplants.
3) Development of a new express method of diagnosing the technical state of diesel engines based on the readings through on-board instruments of the control and monitoring system of ship's powerplant, with the possibility of using the method as an auxiliary monitoring tool between scheduled maintenance dates.

4. Materials and methods of the conducted study

Modern military ships and boats are equipped with on-board electronic control and monitoring of the technical state of shipboard machinery with different degrees of informativeness and diagnostic capabilities. Large-displacement ships (frigates, corvettes) are equipped with complicated systems that enable their crews to diagnose the individual mechanisms, autonomous engine groups and the entire propulsion system of the ship (Fig. 1). These systems are distinguished by a wide range of monitoring functions and diagnostic parameters, which is ensured, in particular, by the use of modern diagnostic technologies: sensors and instruments, on-board information and control panels (ECU, EMU, EIM), data collection, storage and display systems (MTS, LOP, LOSDE/GT), software for diagnostic and analysis system, communication and integration modules (CCG, PIMs), information support tools for ships' tending squads [15] with the corresponding visualization of data transmitted to the digital display panel of control and monitoring of the ship's powerplant (Fig. 2).

However, the excessive complexity of up-to-date electronic control and monitoring systems for shipboard machinery, the high cost of their installation and operation, the need for specialized training for ships' tending squads, as well as limited access to spare parts and a small number of maintenance and repair centers, pose significant limitations to their effective use, especially on small military boats of the Ukrainian Navy. In connection with this, there is a need to introduce simpler, more reliable, and more cost-effective control and monitoring systems that provide a sufficient level of monitoring and diagnostics of the technical state of ship machinery, and thereby simplifying tending and reducing operating costs on small vessels.

Fig. 1. Modular hardware for monitoring and diagnostics of modern diesel engines (MTU Co.).

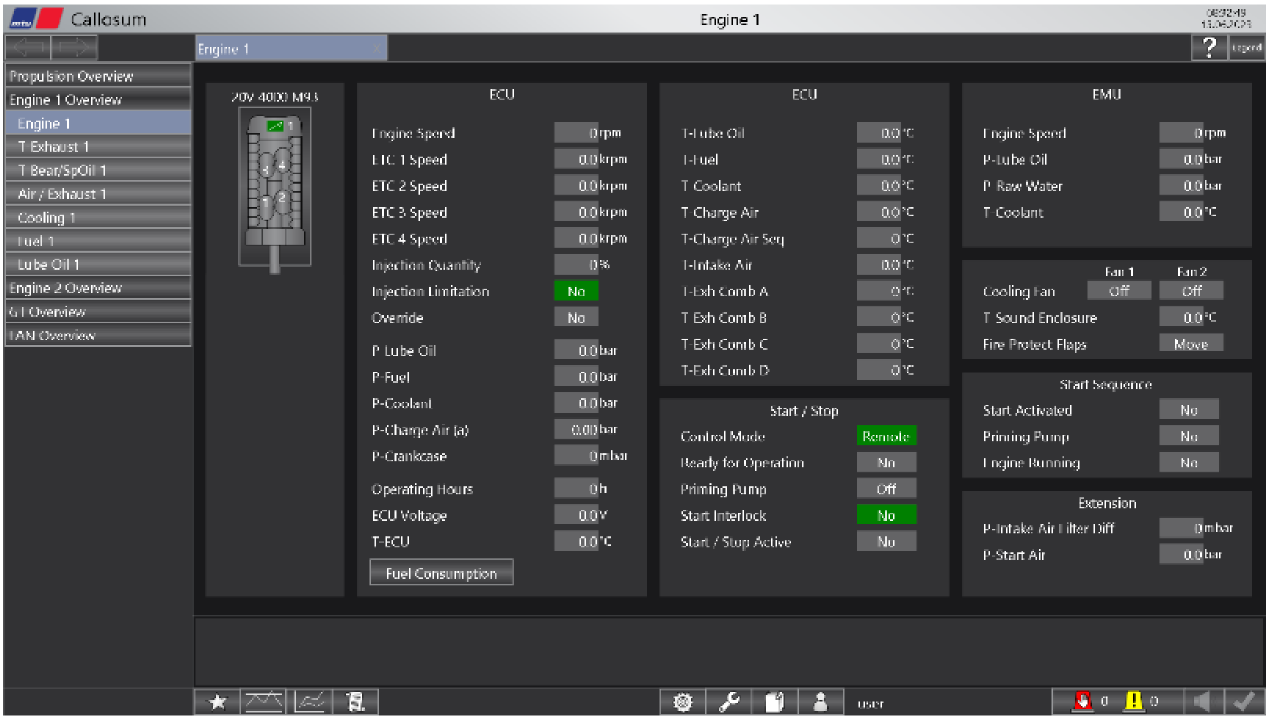

Fig. 2. Visualization of current values of determining parameters on the digital display panel.

Currently, small combat and specialized self-propelled marine and river platforms (boats, launches, inflatable boats, etc.) utilize relatively simple control and monitoring systems of powerplants working, which provide the data transmission of minimum necessary but supremely important operating parameters of the main and auxiliary diesel engines to the digital display panels of on-board instruments. The values of these operating parameters indicate the current technical state of the shipboard machinery of powerplant in various operating modes (Fig. 3).

Caterpillar's CAT18 ACERT engines, which were the subject of research in paper [14], exemplify the application of simplified information systems on marine vessels. These engines are equipped with the ADEM A3 control system, which provides a sufficient degree of integration of control, protection, and technical state monitoring functions. The system also supports the functions of diagnostics and fault codes display via the Cat Electronic Technician (ET) interface.

Fig. 3. Types of digital display panels of on-board instruments for controlling and monitoring the powerplant.

The disadvantage of this information system is that the specialists of maintenance and repair department can gain access to information on the state of the machinery only after the ships' return to their home ports. On the high sea, only the ship's (boat's) crew members are present, and they are not sufficiently trained in analyzing and deciphering the coded monitoring results from the ECU (electronic control unit). In addition, in cases where only generally accepted maintenance schedules are in effect on ships, the specialists (of maintenance and repair department) retrieve information from the ECU at fairly long intervals (according to the schedule), or after an emergency situation not provided for by the maintenance schedule has already occurred. It is at preventing and reducing to zero the risk of such unforeseen emergencies on the high sea that the implementation of the new express method is aimed.

At the same time, simple control and monitoring systems of ship's powerplant have certain advantages: (1) the use of simple systems makes it possible to reduce acquisition and maintenance costs, which is critical for military boats with limited funding; (2) reduced complexity of the systems simplifies the procedures of diagnostics and repair, which, in turn, reduces downtime and dependence on specialized personnel; (3) the use of standard components and techniques provides easier access to spare parts and maintenance.

Therefore, adapting simplified on-board electronic control and monitoring systems, such as the CAT18 ACERT™ engine monitoring systems, can be an effective solution for small military boats, which will provide the necessary level of monitoring and diagnostics while reducing the costs and moderating the complexity of maintenance as a whole.

5. Presentation of the main material

As part of the ongoing research, the values of the determining parameters that change their values during the operation of the ship's powerplant in various operating modes with a measurement interval of 3 minutes have already been calculated [14].

Lubricating oil pressure measurements were conducted using a Caterpillar 304-5668 type stationary sensor (Sensor GP-Pressure), which is designed for continuous monitoring of pressure in the lubrication system of a C18 series marine diesel engine. The sensor converts mechanical oil pressure into a standardized electrical signal transmitted to the ECM for indicating and diagnosing the technical state of the system. This sensor has a sealed housing with a threaded connection; it is resistant to vibration and high temperatures, and its operating range of 0–1.8 MPa and fast response time of 5–20 ms ensure instantaneous detection of pressure changes during engine operation and timely activation of automatic protection systems.

Coolant temperature measurements were taken using a Caterpillar 256 6453 type stationary resistive sensor, which is applied on Caterpillar C18 marine diesel engines. The sensor changes its resistance depending on the coolant temperature, transmitting a signal to the ECM to accurately determine the engine temperature, to diagnose and protect the system. This sensor's operating range is 86–99 °C; when the temperature reaches 106 °C, an alarm is activated, preventing overheating. The sensor's response time is 20–100 ms, allowing the ECM to instantly monitor coolant temperature changes and maintain the safe operating mode of engine.

The time interval was recorded using a FLOTT FS 8200 digital stopwatch, a high-precision instrument with an accuracy rating of ±0.01 s. It has a three-line LCD display and memory for 200 readings, which enables one to simultaneously measure and record the current values of all the determining parameters of working engine. The stopwatch ensured reliability under real-world operating conditions, while its resolution and accuracy rating enabled us to precisely monitor the time during experimental measurements of diesel engine operating parameters, in particular when recording rapid changes in operating modes and evaluating the dynamics of powerplant performance.

A preliminary analysis of experimental data showed that the starting mode of heating-up of diesel engine (at no load) is the most informative for forecasting its overall technical state and early detection of faults. This operating mode makes it possible to effectively evaluate the state of engine at the expense of the clearly expressed dynamics of key parameters. On the basis of these circumstances, the following indicators were selected for prompt diagnostics, directly reflecting the thermal and mechanical stress of the engine: (1) coolant temperature (Coolant Temp); (2) oil pressure (Oil Pres); (3) fuel consumption (Fuel Rate). Changes in these three parameters over time during engine heating-up are noticeable indicators, which makes it possible not only to analyze the current state, but also forecast the onset or acceleration of degradation processes, as well as anticipate potential faults before their critical manifestation in the form of a breakdown. This methodology formed the basis for developing an express method as the basic platform for a system for monitoring the current technical state of engines.

Based on experimental data obtained during engines operation in the starting mode of heating-up (the phase of regular heating-up), graphical dependencies were constructed by criteria of the rates of change of the current values of the determining parameters of diesel engines working over time (for two main starboard diesel engines of two boats). These graphical dependencies are presented in Figures 4–7, where the different colors of the jogged lines and the corresponding numbers correspond to the quantity of measurements (tests) performed on two combat boats.

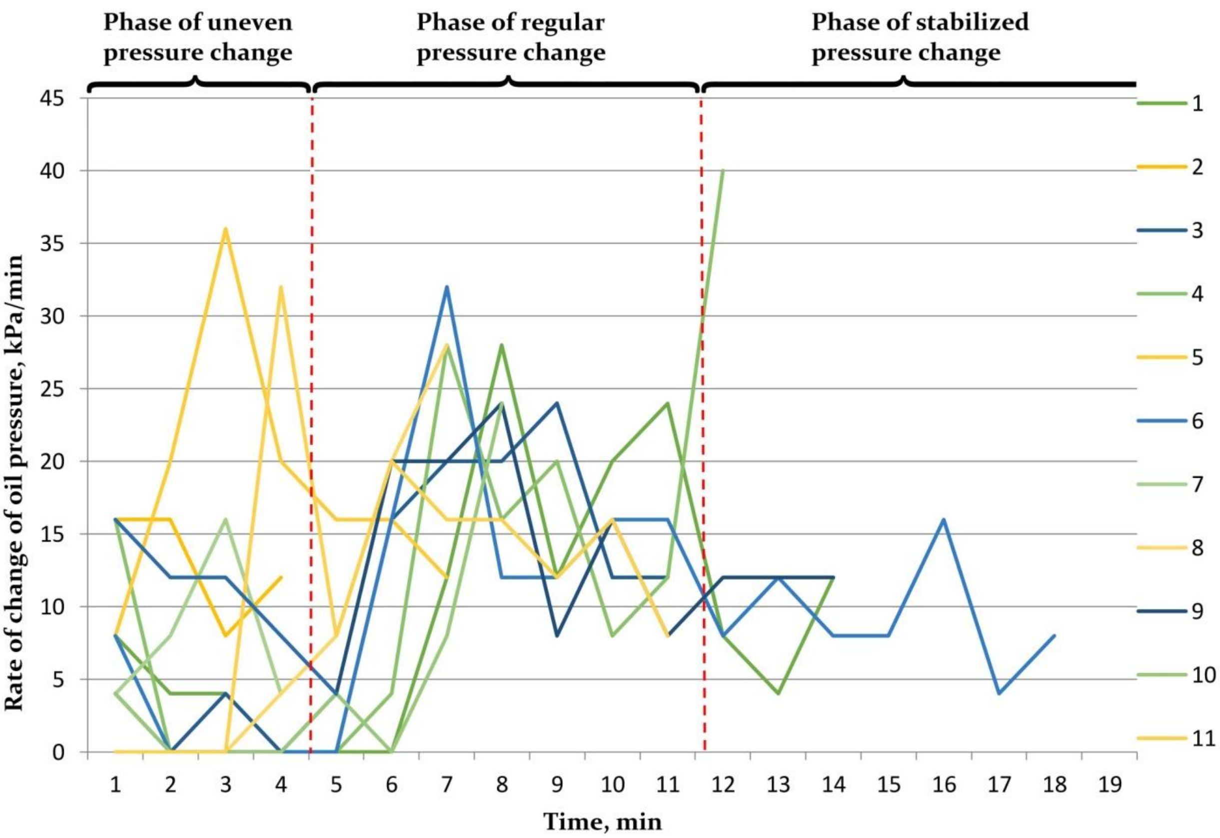

Fig. 4. Boat No. 1: Rate of change in the values of oil pressure in the heating-up mode of engine.

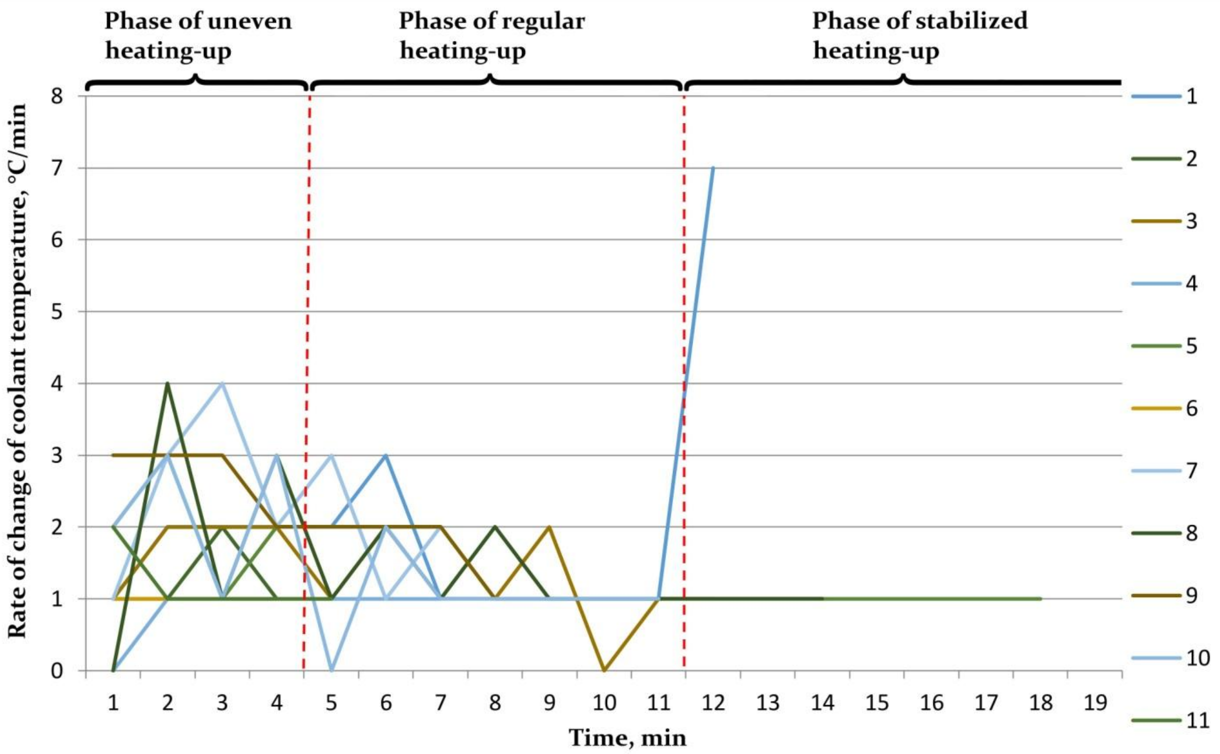

Fig. 5. Boat No. 1: Rate of change in the values of coolant temperature in the heating-up mode of engine.

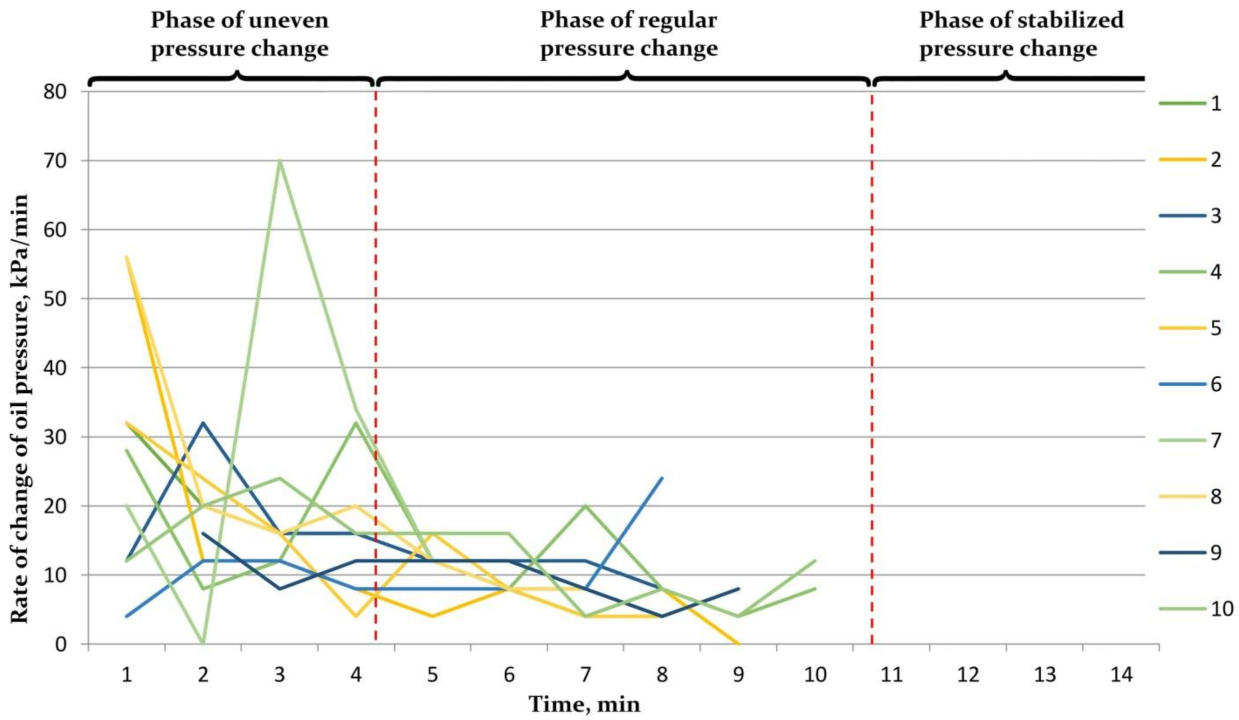

Fig. 6. Boat No. 2: Rate of change in the values of oil pressure in the heating-up mode of engine.

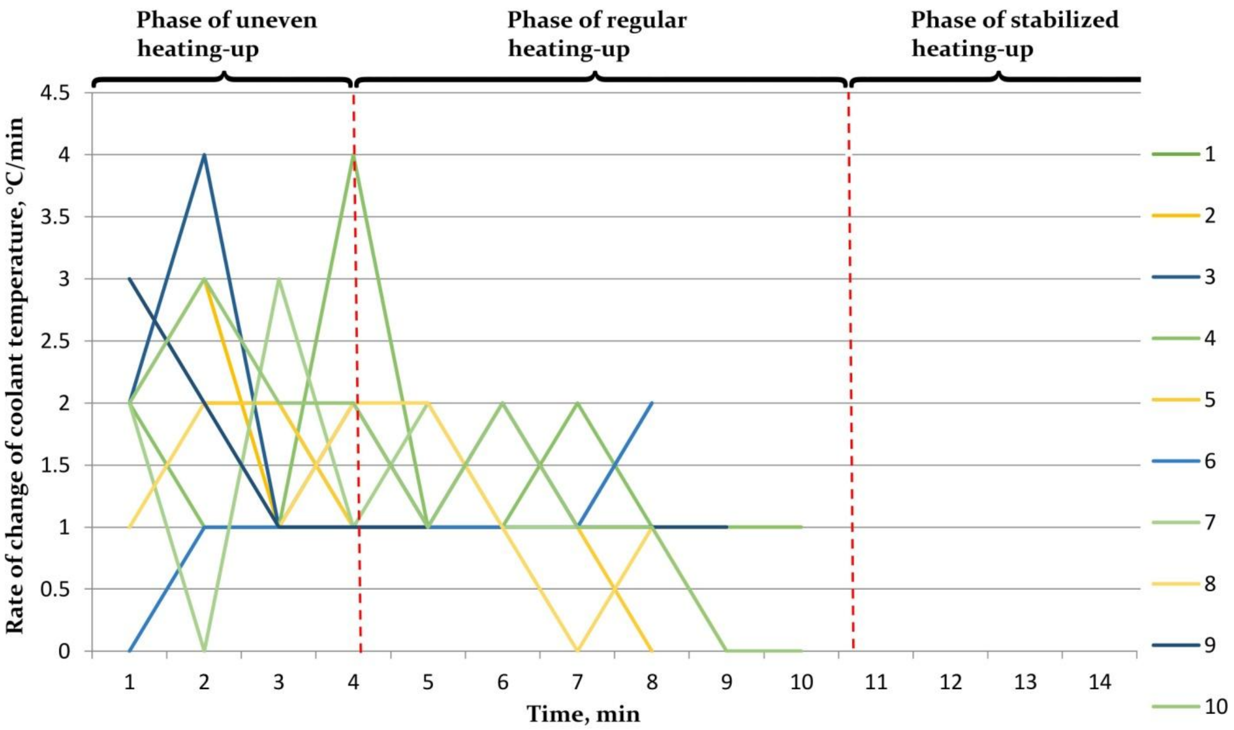

Fig. 7. Boat No. 2: Rate of change in the values of coolant temperature in the heating-up mode of engine.

Further research into the starting mode of the diesel engine showed that, under identical constant loads and rotation speeds of the drive shaft of the engine, the regularities of change in the operating parameters take place, especially the thermal indicator. The cooling mode efficiency of the diesel engine, as a key thermal indicator, has a direct impact on the strength and deformation characteristics of its components, as well as on the quality of lubrication of friction surfaces. Insufficient removal of heat (overheating state) significantly reduces the tensile strength of materials, especially in thermally stressed areas (cylinder heads, pistons, and cylinder liners). This can lead to thermal fatigue, plastic deformation, and, ultimately, breakup of components. An elevated temperature in the cooling system, manifested as engine overheating, is extremely dangerous for the lubrication system and can lead to rapid degradation and sudden failure. At the same time, excessive cooling (low operating temperature) increases engine oil viscosity, which impairs pumpability and lubrication efficiency, increases hydrodynamic friction, and accelerates corrosive wear. Optimal thermal conditions make possible maintaining the necessary oil viscosity to form a strong oil film, and thus minimize friction and wear, and prevent material degradation and structural changes that are critical to engine longevity.

From the moment of starting diesel engines, three time phases of their thermal state can be distinguished: (1) the phase of uneven (chaotic) heating-up; (2) the phase of regular heating-up; (3) the phase of stabilized heating-up. During these phases, changes in the above-mentioned determining parameters (the most informative) occur. From an analysis of the graphical dependencies of the current values of the parameters of diesel engines in the starting mode of heating-up without load (i.e., from the moment of starting a "cold" engine to the phase of stabilized heating-up), it was determined that the main changes in the parameters occur up to the 11th min. of engine operation, which makes it possible to predict engine failure with sufficient probability and quickness, which means to anticipate an imminent emergency situation at the very initial stage of the operation of the ship's powerplant.

Moreover, it can be visually determined that after engine startup, from the first to the fourth minute of operation, a disordered change in all operating parameters is observed, characterized by instability in the thermal and mechanical load conditions on the engine. This time interval is not taken into account when analyzing changes in the values of the determining parameters (for diagnostics).

Between the 4th and 11th min. of engine operation, regular surges take place, and changes in operating parameters have corresponding peak zones, corresponding to a transient state during the increase in operating parameter values.

This phase of engine operation is the most informative (and valuable) component, which is of immediate interest in our study.

The final phase (the 3rd one), from the 11th min. onward, is characterized by a steady increase in operating parameters and indicates stabilization of the engine's operating process. This period of time is also not taken into account when analyzing changes in the values of the determining parameters (for diagnostics).

Further research into the graphical dependencies of the rates of change of oil pressure and coolant temperature parameters within the main diesel engines and analysis of the results showed that the maximum values of these rates in the time interval from the 4th to the 11th min. can be adopted as normalized values for the express method of diagnosing technically faultless engines. All other values of the determining parameters (rates of change of oil pressure and coolant temperature) that exceed the established normalized values can be considered as critical ones for main diesel engines, and which are associated with accelerated degradation processes during the period between scheduled maintenances.

To normalize the critical values of the defining parameters, it is quite appropriate to proceed from the reliability coefficient set by the manufacturer separately for each component of the engine system (lubrication system, coolant system, fuel system). In the technical and operational documentation for CAT18 ACERT engines, which are produced by the famous American company Caterpillar Inc. [16], the minimum and maximum permissible values of the main operating parameters for each separate system are defined. Therefore, to select determining parameters, the excess of which will indicate a deviation from normal operation and signal the presence of a fault, one can use the technical instructions given in Table 1 from the manufacturer.

Table 1. Performance Analysis Report (PAR) data during sea trials (system format) for diesel engine C18 DITASWACTESTSPEC 371-7544 EFFS/NJLE05142ADVPWR 1135 BHP (840 BKW) @ 2300 RPMPERFREFEM0260.

Code Number	Check Parameter	Nominal	Value	Unit
Circulating Water System (of Cooling System)				
922	Circulating water inlet temperature (from cooler)	Max.	92	°C
921	Circulating water pressure from cooling system	Min.	Note 1	kPa
933	Circulating water inlet temperature (to cooling system)	Max.	103	°C
901	Circulating water outlet temperature (before regulator)	Max.	103	°C
918	Circulating water outlet pressure (before regulator)	Min.	Note 1	kPa
902	Circulating water temperature (after water pump)	Max.	103	°C
Delta T	Circulating water (outlet–inlet)	Max.	10	°C
Lubrication System				
914	Oil pressure at low idle	Max.	600	kPa
914	Oil pressure at low idle	Min.	100	kPa
914	Oil pressure at full load	Max.	600	kPa
914	Oil pressure at full load	Min.	275	kPa
927	Oil filter inlet pressure	Min.	Note 15	kPa
928	Oil filter outlet pressure	Min.	Note 15	kPa
Heat Removal				
Overall Cooling System (see Note 5)		Max.	556	kJ/min
Notes				
Note 1	This value is based on an external limitation that is not known during engine manufacturing. This datum is subject to determination during sea trials by a certified expert.			
Note 5	Size the system so that the overload factor is 5 %.			
Note 15	The pressure drop must not exceed 35 kPa across the filter and housing at rated speed.			

The first significant parameter for diagnostics is lubricating oil pressure. The Performance Analysis Report (PAR) during sea trials for a diesel engine contains Note 15 at the very bottom line, which states that at rated speed, the pressure drop across the filter and housing must not exceed 35 kPa. Thus, we have a permissible critical value for the rate of oil pressure change when measured in the time interval from the 4th to the 11th min., which corresponds to the phase of regular rate of change of the first determining parameter, when the oil pressure difference for a faultless engine must not exceed $P/\Delta t \leq 35$ kPa/min. Therefore, the ratio of pressure changes in fixed time intervals should be adopted as the first determining parameter for diagnosing diesel engines, which we have laid down as the basis for constructing a model of our new express method.

The second important parameter for diagnostics is the temperature of the fluid in the circulating water system, along with the overall cooling system. The well-known formula for calculating the amount of heat (Q) required to change the temperature of a body is as follows:

$$Q = c \cdot m \cdot \Delta T \text{ [kJ]} , \quad (1)$$

where c is specific heat capacity of the body [coolant] (in kJ/(kg · °C) or kJ/(kg · K)); m is the mass of the body; ΔT is the change in temperature (in °C or K) as the difference between the initial and final temperatures.

Formula (1) allows us to calculate the quantity of heat required to heat or cool a body of a certain mass with a certain specific heat capacity by a certain number of degrees.

Furthermore, the line for Heat Removal of the PAR form states "Overall Cooling System (see Note 5)" and also indicates a maximum value of 556 kJ/min (i.e., maximum heat removal capacity). According to Note 5, the overall cooling system must be sized to provide a 5% overload factor. This is an indicator of the permissible difference in loading when extracting the amount of thermal energy with time (heat removal capacity), and therefore, we have the following condition for the operability of the overall cooling system (i.e, the normalized heat removal capacity):

$$\Delta Q = \frac{Q_{out} - Q_{in}}{\Delta t} \le 556 \text{ [kJ/min]} , \quad (2)$$

where Q_{in} is the amount of thermal energy that the fluid has in the system at the engine inlet (kJ); Q_{out} is the amount of thermal energy that the fluid has in the system at the engine outlet (kJ); Δt is the time interval (duration) of measurement (min).

According to data of the PAR form for the Circulating Water System (of Cooling System), the maximum circulating water temperatures are 92°C at the inlet (from the cooler) and 103°C after the water pump. The maximum temperature difference ΔT of the circulating water (outlet–inlet) is 10°C. Therefore, the permissible critical value for the circulating water temperature difference is $\Delta T \le 10$°C. However, the overall cooling system is quite inertial, and therefore such a difference will be characteristic for long-term monitoring of changes in the absolute value of temperature.

It is quite obvious that for a short-term prompt diagnostic interval of 7 minutes (from the 4th to the 11th min.), the derivative of the temperature parameter function with time $\Delta T/\Delta t$ (°C/min) will be more informative, rather than its absolute final value ΔT (°C). On this basis, the second determining parameter for diagnosing diesel engines should be the rate of change of the difference in the temperature of the circulating water in the measurement time interval, which we have laid down as the basis for constructing a model of our new express method.

To clearly define the permissible critical value of the rate of temperature change, it is appropriate to start from the permissible overload factor of the circulation system of 5% and the maximum temperature of the circulating water (after the water pump) of 103 °C, and assign the permissible critical value of the change in temperature difference with time as 5% of 103 °C, i.e., the difference between the measured temperature values in the time interval from the 4th to the 11th min., which corresponds to the phase of regular heating-up of the faultless engine, must meet the condition $\Delta T/\Delta t \le 4.9$ °C/min.

Thus, based on the readings (current values) through the on-board instruments of the ship's powerplant control and monitoring system and the analysis of these readings, we propose a constructed model of our new express method for diagnosing diesel engines at the initial stage of their heating-up from the 4th to the 11th min., taking into account the monitoring of two determining parameters at fixed time intervals:

1) Change in oil pressure $\Delta P/\Delta t \le 35$ kPa/min.
2) Change in the temperature difference of the circulating water in the cooling system $\Delta T/\Delta t \le 4.9$ °C/min.

Based on the information received from the tending squad regarding two determining parameters and normalized criteria, the ship's captain makes a substantiated decision on the possibility of the ship's going to sea to carry out a combat mission or notifies the maintenance and repair department of the presence of a fault, which sends authorized specialists (with specialized equipment and tools) to the ship to find the defective assembly (part) and eliminate the fault by conducting unscheduled maintenance or repair.

The express method being proposed for diagnostics is very simple to use. During the initial heating-up mode of the diesel engines, the ship's tending squad record the current values and the difference in lubrication pressure (ΔP) every minute (Δt) for 7 minutes, starting from the 4th to the 11th min., and compare them with the normalized value $\Delta P/\Delta t \leq 35$ kPa/min. The current values and the difference in temperature of the circulating water in the cooling system ΔT are similarly recorded and compared with the normalized value $\Delta T/\Delta t \leq 4.9$ °C/min. Based on the information received from the tending squad regarding two determining parameters and normalized criteria, the ship's captain makes a substantiated decision on the possibility of the ship's going to sea to carry out a combat mission or notifies the maintenance and repair department of the presence of a fault, which sends authorized specialists (with specialized equipment and tools) to the ship to find the defective assembly (part) and eliminate the fault by conducting unscheduled maintenance or repair.

It is quite obvious that the process of measuring current values, calculating and comparing the results being obtained with the normalized critical values of the determining parameters should preferably be automated using mobile devices (tablet, cellphone, etc.) in order to avoid subjective influence (human factor) on the final results of diagnostics, so we will continue research work in this direction.

As a visual example, it is worth demonstrating the application of the express method being proposed for diagnosing two diesel engines from different boats using empirical data (see Fig. 4–7) for two determining parameters (oil pressure change and circulating water temperature difference in the cooling system). Based on the analysis of the constructed graphical dependencies, several substantiated conclusions can be drawn.

According to ten test measurements of two diesel engines, which were carried out at different times of day and under different ambient temperature values, they did not exceed the permissible normalized values for the determining parameter of oil pressure change with time, namely:

- Engine #1 has maximum values within the range of $\Delta P/\Delta t = 24–32 \Rightarrow < 35$ kPa/min (Fig. 4).
- Engine #2 has maximum values within the range of $\Delta P/\Delta t = 12–20 \Rightarrow < 35$ kPa/min (Fig. 6).

A similar situation was observed in test measurements of changes in the temperature difference of the circulating water with time, namely:

- Engine #1 has maximum values within the range of $\Delta T/\Delta t = 2–3 \Rightarrow < 4.9$ °C/min (Fig. 5).
- Engine #2 has maximum values within the range of $\Delta T/\Delta t = 2 \Rightarrow < 4.9$ °C/min (Fig. 7).

During the comparative analysis of identical experimental diesel engines, for which the first scheduled maintenance period is set at 3,000 hours of operation time, the following was established: main diesel engine #1 with a total operation time of 2,236 hours, which was confirmed by the data of digital display panel of the electronic control unit of the boat's powerplant parameters (photo recording of the "Engine Hours" indicator at the 2,236 hours mark), the service life of which was approaching the first scheduled maintenance, was characterized by a more deteriorated technical state than that of engine #2 due to its operation time of 2,236 hours. In turn, main diesel engine #2 with a total operation time of 3,112 hours, which was confirmed by the data of digital display panel (photo recording of the "Engine Hours" indicator at the 3,112 hours mark), 112 hours of which were operated after the scheduled maintenance, having reached the 3,000 hours mark, showed a better technical state than engine #1.

The conducted comparison of the current technical states of identical diesel engines with different operating hours "before" and "after" maintenance has confirmed the effectiveness of the new express method being proposed of prompt diagnostics, which makes it possible to quickly evaluate the current technical condition of a ship's powerplant in a short period of 7 minutes (from the 4th to the 11th min.) and can serve as an indicator of confirmation of the fact of maintenance fulfillment and the level of its quality. The foregoing example clearly demonstrates the practical value of the new express method for crew members as well as specialists of maintenance and repair department as an additional tool for monitoring changes in the current state of engines, which provides a high degree of technical informativeness during the interim period between the dates of conducting scheduled maintenance.

6. Conclusion

Monitoring the temperature of the circulating water in the cooling system and the lubricating oil pressure is a mandatory and critical requirement for the operation of a shipboard main diesel engine. Deviations from the nominal values of these parameters have a very direct impact on thermal stability, lubrication reliability, fuel efficiency, and the service life of the unit as a whole. A belated detection of deviations in these determining parameters from the normalized values, as well as ignoring such deviations, may lead to unpredictable emergency situations, such as a sudden shutdown (failure, damage) of the ship's powerplant.

Other operational parameters (related to the air intake system, fuel system, exhaust system, engine speed and power, fuel physicochemical properties, etc.) are not critical to the engine's ongoing operation, as changes in these parameters do not result in its unlooked-for shutdown. In this case, if necessary, the ship (boat) can suspend the execution of her combat mission and return to the home port to carry out urgent troubleshooting of these systems by force of the authorized maintenance and repair department.

The express method being proposed should be considered as an auxiliary source for the prompt evaluation of current information, which makes it possible to improve interaction between a ship's (boat's) crew and the maintenance and repair department regarding the current technical state of engines and making appropriate decisions on the possibility of further safe operation of the ship (boat) or the pressing need for performing the unscheduled maintenance and, consequently, her time-urgent return to the home port. In a sense, the constructed model of our express method acts as a kind of "safety net" against unexpected failures, which in practice makes it possible to prevent emergency situations and reduce the risk of sudden breakdowns of the shipboard mechanisms to zero.

The implementation of this express method significantly increases the responsibility of maintenance and repair departments, since the results of their troubleshooting and work as a whole can be quickly verified in practice, which ultimately contributes to an increase in the combat readiness of the ship (boat) before going to sea.

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Визначення критичних значень параметрів для практичного застосування експрес-методу діагностики технічного стану суднових дизельних двигунів

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Анотація

У цій статті обґрунтовується технічна можливість та доцільність розробки нового експрес-методу діагностики стану дизельних двигунів бойових катерів на основі аналізу показань бортових приладів інформаційної системи керування та стеження за силовою установкою катера. Цей експрес-метод дозволить екіпажам бойових катерів (кораблів) використовувати прогнозне обслуговування суднових механізмів для швидкого виявлення деградаційних процесів під час експлуатації та мінімізації ризику непередбачених відмов (поломок) при виконанні бойових завдань. Суть нового методу полягає в побудові моделі діагностування суднового машинного обладнання на основі аналізу емпіричних критеріїв швидкостей зміни поточних значень визначальних параметрів у виділених часових діапазонах під час прогріву двигунів. В результаті натурних випробувань були визначені визначальні параметри та встановлені їх граничні нормалізовані швидкості зміни, перевищення яких може призвести до аварійних ситуацій.

Ключові слова: судновий дизельний двигун; визначальний параметр; режим прогріву; поточні значення.