UDC 623.85/623.826

K. Boriak, DSc., Prof.,
O. Ihnatenko
Institute of Naval Forces of the National University "Odessa Maritime Academy", Didrikson Str. 8, Odesa, Ukraine, 65029;
e-mail: tangi7501@gmail.com

AN EXPRESS METHOD OF FORECASTING THE DEVELOPMENT OF DEGRADATION PROCESSES IN SHIP'S MECHANISMS USING CURRENT INFORMATION THROUGH ON-BOARD INSTRUMENTS

К. Боряк, О. Ігнатенко. **Експрес-метод прогнозування розвитку деградаційних процесів в корабельних механізмах з використанням поточної інформації з бортових приладів.** Пропонується на показах вимірювальних приладів панелі бортової системи управління та контролю експлуатаційних параметрів експлуатації енергетичної установки бойового катеру побудувати новий експрес-метод оперативної оцінки поточного технічного стану цієї установки. Експрес-метод діагностування пропонується в якості допоміжного джерела поточної технічної інформації, яка надається членами екіпажу сервісному технічному персоналу при поверненні в гавань. Експрес-метод не може замінити інструментальний метод діагностування із застосуванням сервісними інженерами спеціальних технічних приладів з метою отримання корисної інформації, який здійснюється на березі під час стоянки корабля біля причалу, а скоріш служить допоміжним до нього, і виконує роль сигнального запобіжника виникнення непередбачуваних аварійних ситуацій в морі в проміжку часу між сервісними інтервалами технічного обслуговування. Проведено ряд натурних експериментів з метою визначення найбільш інформативних параметрів, для оперативної оцінки технічного стану складових частин енергетичної установки, значення яких змінюються в часі. Зроблено оцінку та аналіз параметричних показників, що видає бортова система контролю технічного стану, зі зміщенням періоду проведення оперативного контролю на етапі прогріву агрегату чи механізму, з використанням удосконаленої методики діагностики за емпіричним критерієм швидкості зміни визначальних параметрів у фіксований період часу. Отримані проміжні значення швидкості зміни певних експлуатаційних параметрів та визначені шляхи отримання граничних меж критичних значень, наближення до яких збільшує імовірність втрати працездатності судового дизельного двигуна та ризик спроможності корабля виконувати свої завдання.
Ключові слова: оперативна оцінка технічного стану, моніторинг експлуатаційних параметрів, швидкість зміни у часі параметрів, бортова система контролю дизельного двигуна

K. Boriak, O. Ihnatenko. **An Express Method of Forecasting the Development of Degradation Processes in Ship's Mechanisms Using Current Information through On-Board Instruments.** The article proposes a novel express method for the prompt evaluation of the current technical condition of a combat boat's powerplant to forecast the development of degradation processes in the assemblies (mechanisms) of this powerplant during operation in order to prevent the occurrence of unforeseen failures when the boat performs her combat missions, as well as to adjust the timing of maintenance (repairs) based on the analysis of the monitored values of the determining parameters. One of the key roles in the method proposed is played by the control panels of the on-board system for monitoring the operating parameters of the boat's powerplant. It is supposed that the developed diagnostic express method of will become an auxiliary source of current technical information that is provided by the ship's (boat's) crew members to the maintenance and repair department personnel for further analysis and decision-making when the boat comes back to the harbor. The article presents the results of full-scale experiments conducted to determine the most informative parameters for the prompt evaluation of the technical condition of the components of a ship's powerplant, the values of which change through time. A detailed analysis of the parametric values generated by the on-board technical condition monitoring system is shown, taking into account the shift in the period of the prompt evaluation to the stage of heating-up of the unit (mechanism) using an improved diagnostic technique based on the empirical criterion of the rate of change in the values of the determining parameters in a fixed period of time. The obtained intermediate values of the rate of change in certain operational parameters are presented and ways of obtaining the limits of critical values are determined, approaching which increases the probability of loss of operability of the diesel engine and therefore increases the risk of the ship's inability to perform her tasks.
Keywords: prompt evaluation of technical condition, monitoring the operational parameters, rate of change in parameters through time, on-board monitoring system of diesel engine

1. Introduction

The Decree of the President of Ukraine "On the decision of the National Security and Defense Council of Ukraine" dated July 17, 2024 approved the "Maritime Security Strategy of Ukraine". This Strategy is based on certain principles, in particular on the "development principle" – expanding, strengthening, and enhancing the state's maritime and river potential with the aim of reliably ensuring national interests and ensuring maritime security, on the basis of which the priority of tasks was formulated – "Transforming Ukraine into a powerful maritime and river state, expanding the naval potential sufficient to deter potential aggressors in maritime and river directions, restoring and developing the

DOI: 10.15276/opu.2.70.2024.15

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

maritime and river potential of Ukraine". The implementation of this priority is impossible without maintaining and building up the potential of the naval forces, in particular the ship and boat composition.

Russia's full-scale aggression against Ukraine, as well as the hybrid components and technological nature of modern wars, have forced many design organizations, scientific institutions, and scientists to take a new look at the problem of the trouble-free operation of ship's technical equipment.

On the one hand, there was a loss of individual ship-repair capacities of the state (as a result of the seizure of individual territories of Ukraine or partial destruction of ship-repair capacities, as well as by reason of the impossibility of performing the scheduled maintenance and repair work in the zone of active combat operations and a high degree of missile danger for existing enterprises), which led to a change in the conditions and circumstances of performing the scheduled maintenance and repair work. On the other hand, there was an intensive use of the ship and boat composition in conditions of limitation of logistic chains for the technical operation system of the Navy of the Ukrainian Armed Forces by reason of a shortage of qualified technical personnel for the maintenance and repair of ship's technical equipment. Here we can also add the factors of physical and psycho-emotional exhaustion of personnel and changes in the requirements for the level of professional training of navy sailors in conditions of uncertainty and rapid change in the combat situation, which ultimately increases the risk of accidents and breakdowns of technical equipment associated with errors by the crew or defense industry workers.

Thus, the search for ways to further improve the processes of technical operation of ship's technical equipment (including boats) of the Ukrainian Navy under the conditions of the martial law legal regime, in particular, improving solutions to the problems of monitoring the current technical condition, forecasting, and preventing possible failures of ship's technical equipment including marine diesel engines, is an extremely urgent problem.

2. Analysis of Published Data and Statement of the Problem

The development of the theory and the preparation of methods and tools for diagnostic monitoring are directly related to the complexity of the processes occurring in the units and mechanisms of the ship's powerplant (including marine diesel engines), as well as the influence of other factors on their operability – namely, physical wear of parts and mechanisms as a result of the impact of natural processes associated with friction, corrosion, and other physical and chemical processes; loss of initial properties of materials (metal fatigue, reduction of elastic properties of rubber products, etc.); violation of the mating of individual elements and assemblies (inconsistency of the parameters of the mutual arrangement of the shafts of the mechanisms standardized by the operating documentation, etc.); human error (insufficient professional training, physical and psycho-emotional fatigue, etc.).

An important factor in the creation and operation of vital products and objects, components, and structures is the evaluation of their reliability using nondestructive methods. Today, at least ten different types of nondestructive evaluation of the technical condition of an object are known: acoustic, vibroacoustic, eddy-current, magnetic, optical, with penetrants, radiative, thermal, electrical, radio-wave [1]. Each of the listed methods has its own area of application and inherent disadvantages, which means that there is no universal method of nondestructive evaluation of the technical condition of an object.

Currently, in the theory of diagnostic monitoring of technical equipment, three groups of methods are most widely used: the diagnostic methods by the parameters of working processes, the diagnostic methods by the parameters of accompanying processes, the diagnostic methods by the structural (geometric) parameters that directly characterize the state of the units and assemblies of the powerplant [2, 3].

The diagnostic methods by the parameters of working processes (1st group) are based on determining the technical condition of a mechanism through observing the dynamics of changes in its operating parameters, such as the temperature of exhaust gases or coolant under various operating modes, pressure values, and oil quality. The use of these parameters directly characterizes the state of units and mechanisms, which is an advantage of such methods. In the methods of this group, the simulation of fast and load modes of operation of technical equipment, determination of initial parameters under given conditions and subsequent comparison of their values with reference ones are applied. At the same time, despite a certain simplicity of technical implementation of these diagnostic methods and the facility of measuring the parameters controlled, their general disadvantage is the analysis of only individual processes occurring in a diesel engine – namely, processes occurring in plain bearings and combustion processes of the fuel-air mixture, which does not fully allow evaluating the actual state of the entire engine.

The 2nd group of diagnostic methods by the parameters of accompanying processes expands the possibilities of the methods of the 1st group at the expense of the analysis of indices (by thermal field, noise, vibroacoustic processes, etc.) that indirectly affect the operation of technical equipment, in particular units and assemblies of a marine diesel engine and thereby they form the subset of internal processes. These methods have become a certain symbiosis of several separate subcategories of nondestructive evaluation – namely, diagnostic methods for the tightness of work objects; thermal methods; diagnostic methods for units and systems by the parameters of oscillatory processes; methods that allow evaluating the condition of units and assemblies by the physical and chemical composition of exhaust gases and materials used. Each of the listed components of these methods involves monitoring a specific unit or assembly, in particular the cylinder-piston groups of internal combustion engines, the fuel injection equipment of diesel engines, the lubrication system of internal combustion engines, etc. The main advantage of these methods is the evaluation of the condition of not only individual units and assemblies, but also the analysis of the processes occurring in them by the corresponding parameters. From the point of view of the universality of the diagnostic system based on these methods and its adaptability to monitoring the actual state of diesel engines, it is not universal for diesel engines of all types (low-speed, medium-speed and high-speed). And from the point of view of technical implementation, such a diagnostic system for a single diesel engine, in particular a marine engine has a large number of sensors that differ in their operating principle and design, which in turn requires a solution to the issue of the reliability of such a system and the elimination of errors.

The 3rd group of methods is based on the evaluation of objective geometric parameters (gap, slackness, free play, offset, etc.) which directly character the state of the unit or mechanism. Despite the simplicity of such methods, the diagnostic operations used in them suppose the consideration of certain design features of technical equipment, which are associated with solving the problem of accessibility and ease of conducting the direct measurements on certain assemblies subject to diagnostics.

The choice of one or another method of diagnostics of the technical condition of ship’s mechanisms and equipment depends primarily on the tasks of diagnostics, measuring means, and ways of measuring parameters controlled, as well as the physical nature of the processes on which the operation of the assemblies controlled is based. In addition, determining the technical condition of both the engine as a whole and its individual systems and mechanisms requires a significant number of diagnostic operations, which leads to significant losses of time and is unacceptable from the point of view of diagnostics efficiency.

The capability to conduct an operational evaluation of the technical condition of both a complex diagnostics system (diesel engine, gearbox, generator, etc.) and simple objects (injector, bearing, valve, etc.) makes possible warning about highly probable failures during their operation. In order to increase operational time and prevent unexpected breakdowns within complex systems associated with fault detection and diagnosis, some enterprises have implemented application of so-called deep learning models [4]. To implement a so-called smart factory at the Industry 4.0 level, in many countries, predictive maintenance systems are introduced into production [5, 6], and in China, for example, scientists have attempted to create standard databases for fault diagnostics to avoid repeating studies [7].

The author of dissertation [8] investigated diagnostic methods based on measuring and analyzing those parameters, the changes of which characterize the engine condition to the greatest extent. The essence of such methods is that in order to check the performance of a diesel engine, it is necessary to control only two parameters – temperature and smoke content of exhaust gases. Then the author determined that the most advanced method for diagnosing wheeled vehicles under operating conditions is the method based on the dependence of the speed of sound on the temperature of gases. In this case, the dependence is instantaneous in nature and acoustic temperature sensors are most suitable for its determination, which allow recording instantaneous values of the exhaust gas temperature at the outlet section of the exhaust pipe.

The authors of paper [9] showed that the solution to the scientific and practical problem of complex diagnostics of marine diesel engines can be realized through the use of modern high-performance microcontrollers with wireless interfaces and built-in analog-to-digital converters with low overall power consumption, which makes it possible to develop a portable parametric diagnostics system for marine engines that operates in real time. Such a system is based on the use of modern devices with Android or iOS mobile platforms, which receive information from sensors via Bluetooth system, and then perform the necessary calculations and display current data and diagrams. In addition, this real-time diagnostic system makes it possible to conduct the optimal adjustment of the relevant mechanisms and control of the result of their adjustment during operation. In the working principle of such a system, a combination of a gas pressure sensor in the working cylinder and a vibroacoustic sensor is applied, which expands the diagnostic capabilities of marine diesel engines under operating conditions.

After studying various diagnostic methods, we came to the conclusion that the most practical solution for constructing an express method for diagnosing diesel engines of high-speed floating platforms is a parametric diagnostic method by the parameters of accompanying processes.

The authors of paper [10] proposed a method of passive thermal control for the prompt evaluation of the technical condition of rolling bearings, which is based on studying the heating rate of the bearing. The advantage of this approach is the assessment of the technical condition of friction assemblies by the empirical criterion of the heating rate and the shift of the period of the prompt evaluation when starting the unit or mechanism as an indirect criterion of the operability of bearing by its thermal state [11].

However, despite the improvement of the diagnostic method by the parameters of accompanying processes based on the empirical criterion of heating rate and the shift in the period of prompt evaluation during the start-up of a unit or mechanism, it does not allow obtaining complete information on the actual state of a marine diesel engine during start-up as the most unfavorable operating mode of the engine, since in conditions of intensive use of diesel engines of the ship and boat composition of the Ukrainian Navy (often under conditions of extreme loads), active counteraction by the enemy, as well as physical and psycho-emotional exhaustion of the crew, it is necessary to find a reliable design solution for the problem of creating the system for prompt evaluation of the actual state of the operating engine [12]. Such a solution should be relatively inexpensive and easy to use, as well as take into account the advantages and disadvantages of existing diagnostic methods and their design solutions.

An analysis of the latest published researches has shown that the task of predicting the development of degradation processes in the main ship's diesel plant using standard on-board information systems remains insufficiently studied and disclosed from the point of view of prompt evaluation of the operating parameters of the engine and its servicing systems, especially during the most unfavorable transient operating modes.

3. The Purpose and Tasks of the Research

The purpose of the research is to forecast and study the dynamics of the development of degradation processes in a marine diesel engine during its operation as part of a ship's powerplant, which will allow reducing the probability of its failure during the performance of a combat mission by a ship (boat) and subsequent loss of her operability, as well as to lay the foundation for the implementation of a strategy of predictive maintenance by the actual current condition in the maintenance and repair system departments of the Ukrainian Navy.

One of the most important prerequisites for ensuring the no-failure operation of the main and auxiliary mechanisms of ship's powerplants (including boat's ones), especially when they perform combat and special missions, is monitoring and technical evaluation of the determining operating parameters. Availability of information on the current values of the defining parameters of ship's mechanisms during operation allows the crew to promptly respond to changes in the technical condition of the powerplant, track the emergence of hidden defects and monitor the progress of degradation processes, as well as timely notify technical maintenance and repair departments about any technical problems identified.

Based on operational technical information provided by the ship's crew, specialists from the technical maintenance and repair department conduct unscheduled (before the scheduled maintenance date) instrumental diagnostics of the mechanisms and, after analyzing the results of measuring the determining parameters, make a decision on the need for conducting the maintenance or repair of a specific unit in the ship's powerplant. The availability and application of such an express method of forecasting in practice will allow avoiding unpredictable emergency situations when ships are in the open sea. Since the ship's crew members have free access only to information from on-board digital panels, which is transmitted from measuring instruments, it becomes logical to build this express method using the available data through the panel of on-board information systems for monitoring and controlling the ship. To achieve this, it is necessary to develop appropriate algorithmic support and a formalized description of degradation phenomena during technical diagnostics of a powerplant. In addition, there is a need for a conditioned formulation of the tasks to be performed, formalization of diagnostic procedures, as well as optimization of the choice of determining parameters and standardization of the readings of the critical technical condition of the powerplant by direct or indirect methods of their measurement.

To develop the express method of forecasting based on the prompt evaluation and analysis of parametric values generated by the on-board technical condition monitoring system (with a shift in the period of prompt evaluation to the stage of heating up the unit or mechanism), as well as an improved diagnostic technique by the empirical criterion of the rate of change of determining parameters in a certain period of time, the following set of research tasks to be performed was singled out:

– Studying the interdependence of the readings on the on-board display panels of the measuring instruments of operational parameters with each other, choosing the determining parameters that are traced by the dynamics of changes through time, linking these changes with the degradation processes monitored (preferably with the specification of the main assemblies of the ship's powerplant).

– Determining the critical limit values, approaching which increases the probability of loss of operability of the ship's diesel engine and the risk of the ship's inability to perform her missions.

– Conducting full-scale experiments with the aim of confirming and refining the critical values of the operability of mechanisms by the criterion of the rate of their change in fixed time intervals with the involvement of specialists from the maintenance and repair department of the ship's powerplant for the possibility of introducing the developed express method into the practice of current monitoring of the technical condition as an auxiliary source of technical information during the interim period before conducting the scheduled maintenance.

4. Materials and Methods of the Research

Modern combat ships (boats) are equipped with on-board information systems for controlling and monitoring the technical equipment. The values of operational parameters that reflect the technical condition of the participating mechanisms of the powerplant during operation are generated on the screens of digital displays of the ship or boat's control and monitoring panel (see Fig. 1).

Fig. 1. Digital displays of the control and monitoring panel of the powerplant, which are installed on modern high-speed combat boats

The powerplant of the small armored artillery boat of project No. 58155 with two main diesel engines of the CAT 18 ACERT type from Caterpillar Co. was chosen as the object of the scientific research. To control and monitor the powerplant, the ship (boat) is equipped with an on-board integrated information system.

The main component of the system is the electronic engine control module (ECM) with a hardware and software complex for conducting the technical diagnostics of engines. This module conducts the evaluation of the technically sound functioning of the components of the main powerplant (MPP) – namely, main engines, diesel generators, auxiliary mechanisms and systems, gearboxes; performs monitoring of the technical condition of the object by a binary indication (direct and indirect); solves the problem of recording violations of the normal operation of the MPP. Subsequently, based on the results of the evaluation of all the information tracked, specialists from the maintenance and repair department develop recommendations for the prolongation of operation or perform the control actions to change the operating modes of the MPP.

The disadvantage of such a monitoring system is that the maintenance and repair department personnel gain access to information about the state of the mechanisms only after the ship returns to her base, and in the open sea the ship's (or boat's) crew is not sufficiently knowledgeable in the analysis

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

and interpretation of the coded results of monitoring from the ECM, which is very important when performing a combat mission. In addition, in the practice of applying scheduled maintenance to ships, the maintenance and repair department takes information from the ECM at fairly long intervals: usually between the time intervals established by the regulations or when an emergency situation occurs (i.e., without taking into account the scheduled maintenance or repair). The introduction of the proposed express method is aimed at preventing and excluding the occurrence of such an emergency situation in the open sea and proposed as an auxiliary source of technical information, which is provided by the crew members of the combat ship to the personnel of the maintenance and repair department for further analysis and decision-making. At the same time, it should be noted that the express method is not able to replace the instrumental technical diagnostics of professional specialists of the maintenance and repair department, but only warns first of all the ship's crew, and then the specialists of the maintenance and repair department about the need for conducting the unscheduled maintenance of the mechanisms. In a sense, the express method can become a kind of "safety device" against unpredictable emergency situations in the open sea, which would work in time and warn of the danger of further operation and the approaching threat of failure of technical equipment.

Monitoring of the operating parameters of the engines controlled by the ECM occurs in real time with the ability to reflect their current values on digital displays of the control and monitoring panels on each of the two on-board autonomous groups: two multifunctional panels with color display for generating information within the main command post and two control panels with digital display for the boat's engines in the engine room (see Fig. 2).

a *b*

Fig. 2. On-board system for monitoring the operating parameters of the boat's powerplant: (*a*) multifunctional panel with color display; (*b*) control panel with digital display for the boat's engine

Both displays can reflect information in the format of sensor image and also in the digital or graphic format. In addition, the on-board integrated information system for controlling and monitoring the ship's equipment can be programmed by the maintenance and repair department for recording the operating parameters and accumulating the recorded information.

The most informative data related to determining the operability of the main powerplant turned out to be the data transmitted from the ECM to the boat's engine control panel in the engine room. This panel allows conducting not only remote control of the actuators for starting and stopping the engine, but also carefully monitoring the engine operation data together with the gearbox taking into account providing the operator with information about their current state, recording and notifying the deviations of parameters from standardized logbook values (in digital, color and sound formats), generating diagnostic messages and registering them. In addition, this control panel has the capability to preset engine operating time intervals to warn and notify about the need for conducting the maintenance work.

It should be added to the aforesaid that Caterpillar Co. diesel engines with electronic control systems are equipped with a self-diagnostic system. For example, when an "active" abnormal condition is detected in the system at a certain moment, a visual notification is transmitted to the personnel servicing the powerplant by lighting up the diagnostic indicator. In this case, the information or nature of the abnormal situation is not displayed on the screen, but is recorded in the permanent memory of the ECM in the form of diagnostic codes, which can only be read using specialized computer equipment in Caterpillar Co. maintenance and repair departments (Caterpillar Electronic Technician Software). Thus, based on the aforesaid, it follows that the capabilities of the combat boat's crew to quickly evaluate the technical condition of the engine and prevent failures are very limited and are reduced to visually monitoring the operating parameters of the mechanism. But this does not always help prevent any emergency situation, especially when it concerns high-speed combat boats while they are performing combat or special missions.

Within the scope of this research and the task of determining the numerical values of parameters that change their values during the operation of the powerplant, a series of test measurements of the current operating indices of the main engine of the CAT 18 ACERT type in maximum power mode were carried out with a measurement interval of 3 minutes (see Table 1).

Table 1

Results of measurements of the current operating indices of the main engine of the CAT 18 ACERT type in the maximum power mode

Description of index	Test 1	Test 2	Test 3	Test 4	Note
Power, kW	823.62	850.41	854.07	853.02	Engine Load
Rotation frequency, rpm	2350.58	2300.88	2251.01	2199.90	Engine Speed
Fuel consumption, g/min	3109.126	3120.72	3086.06	3074.85	Fuel Rate
Fuel inlet temperature, °C	29.82	30.36	29.70	29.23	Fuel Temp
Coolant inlet temperature, °C	75.80	75.43	75.04	74.88	Coolant Temp
Coolant outlet temperature, °C	80.12	80.04	79.69	79.62	Coolant Temp
Exhaust manifold gas temperature, °C	270.01	270.01	270.01	270.01	Manifold Temp
Oil pressure, kPa	459.36	455.54	453.42	452.26	Oil Pres
Charged air pressure, kPa	266.00	265.50	265.50	268.00	Charge air Pres

Preliminary analysis of the obtained results showed that the most informative parameters for the prompt evaluation of the technical condition of the components of the powerplant are the parameters whose values change through time. Such parameters include: coolant temperature (Coolant Temp), diesel oil pressure (Oil Pres), charged air pressure (Charge air Pres), and fuel consumption (Fuel Rate), which can be conditionally considered as determining parameters for the development of the express method.

To perform the set tasks, a series of full-scale experimental studies were conducted on two boats of project No. 58155 with identical CAT 18 ACERT (Caterpillar) diesel engines with different working life (the working life of the main diesel engines of boat No. 1 was 76.6% before the 1st scheduled maintenance (repair), and the working life of the main diesel engines of boat No. 2 was 54.1%, respectively). Measurements of the chosen operating parameters were carried out in a certain initial operating mode of the diesel engines with an interval between measurements of 1 minute by photographically recording numerical values characterizing the current technical condition of the units and assemblies of the above-mentioned diesel engine.

When analyzing the obtained values and evaluating their practical significance for further research, the most informative parameters were finally determined and singled out, the values of which change through time and which can be used as diagnostic criteria for the for the prompt evaluation of the technical condition of the components of the powerplant. Such determining parameters include: coolant temperature (Coolant Temp), diesel oil pressure (Oil Pres) and fuel consumption (Fuel Rate).

Based on the data obtained, graphical dependencies were constructed by the criterion of the rate of change in the obtained values of the determining parameters of the operation of diesel engines through time (one main starboard diesel engine on each boat), which are presented in Figure 3 (the colors of the jogged lines and their numerical values correspond to the number of tests performed).

The investigation of the operating modes of the boats' diesel engines has shown that, with identical constant loads and rotation speeds, the technical condition of the mechanisms is characterized by the regularities of change in their operating parameters, and especially the thermal index (since the rate of change in oil pressure directly depends on its temperature). At the same time, during the operation of diesel engines, three time phases of their thermal stress can be distinguished, which are matched with the uneven mode, regular mode, and stabilized mode of engine heating-up with a corresponding change in values of the most informative parameters determined above.

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

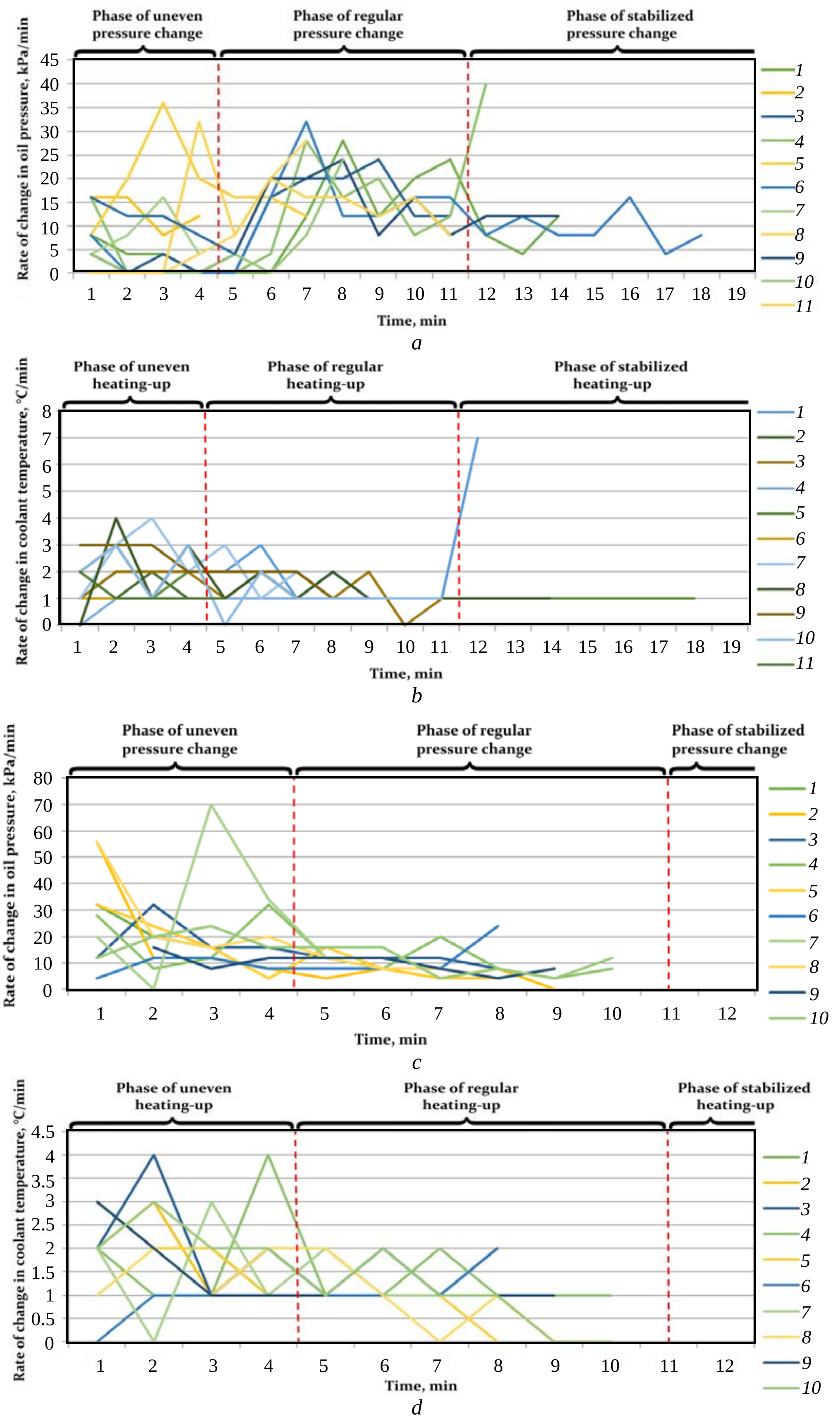

Fig. 3. Graphic dependencies by the criterion of the rate of change in the values of the determining parameters of the operation of diesel engines through time: (*a*), (*b*) characteristics of the starboard diesel engine of boat No. 1; (*c*), (*d*) characteristics of the starboard diesel engine of boat No. 2

Having analyzed the graphical dependencies of the determining parameters from the moment of starting the diesel engine in the heating-up mode (i.e., from the moment of starting the engine until some stabilization of its operating parameters has been achieved), it was established that the main changes in the values of the parameters occur before the beginning of the 11th minute of the engine operation period in idle mode, and this makes it possible to forecast the occurrence of a breakdown (emergency) with sufficient probability and quickness, and also to check the technical condition of the mechanism at the initial stage of its operation.

In addition, it was ascertained that after starting the engine, in the interval from the 1st to the 4th minute of its operation, an uneven change in the values of all operating parameters is observed, which is characterized by instability of the modes of thermal and mechanical load on the engine. The time interval between the 4th and 11th minutes of operation is characterized by regular jumps and changes in the values of operating parameters with characteristic peak zones, which corresponds to the transient mode in the process of growing the values of operating parameters and is the most informative phase during engine operation. The last phase, which occurs at the 11th minute, differs by continuity of increasing in the values of operating parameters and characterizes the process of stabilized operating process of the diesel engine.

5. Results of Physical Analysis

When comparing the graphical dependencies by the rate of change in the values of the oil pressure and coolant temperature parameters for the engines of boats No. 1 and No. 2 with different working life before the 1st scheduled maintenance (repair), the following can be stated (see Fig. 3*a*, 3*c*).

In the time interval from the 4th to the 11th minute, which corresponds to the phase of regularity of the change in the determining parameter, the rate of change in the oil pressure values within the main diesel engine on the starboard side of boat No. 1 (see Fig. 3*a*) with a working life of 76.6% before the scheduled maintenance (repair) decreases from 30 to 10 kPa/min. In the same time interval from the 4th to the 11th minute, the rate of change in the oil pressure values within the main diesel engine on the starboard side of boat No. 2 (see Fig. 3*c*) with a working life of 54.1% before scheduled maintenance (repair) fluctuates within the range of 15...5 kPa/min, which is 2 times less than that of the engine of boat No. 1.

It can be assumed that this difference in the change in the values of the determining parameter (oil pressure) within the main engine of a third-party boat with a working life close to 99.9% before scheduled maintenance (repair) will be even greater in the time interval from the 4th to the 11th minute, more than 30 kPa/min, and using interpolation (linear interpolation with respect to the values of the working life of the main engines $76.6\% : 54.1\% = 1.42$), it can be stated that this value will not be lower than 42 kPa/min. In addition, it can be seen from the image (see Fig. 3*a*, 3*c*) that such a dependence of values doesn’t has the linear nature, therefore it can be stated with a high degree of probability that this value will even exceed the value of 42 kPa/min (taken as the estimated one). To confirm the aforesaid, it is necessary to conduct additional similar full-scale measurements within the main diesel engine of a third-party boat with a working life close to 99.9% before scheduled maintenance (repair).

The obtained maximum value of the rate of change in oil pressure within the main engine in the time interval from the 4th to the 11th minute can be taken as standardized one for the express method of diagnosing technically sound main engines by crew members in the open sea, and accordingly all other values of the determining parameter (rate of change in oil pressure), which exceed the established standardized value, are quite appropriate to consider as critical ones for the main engines, which is associated with the acceleration of degradation processes in the intermediate period of time between the conducting of scheduled maintenances (repairs).

To confirm the conclusions made regarding the criticality or non-criticality of changes in the parameters within the ship’s main diesel engine during monitoring of its technical condition using the available measuring instruments on the on-board control panel, it is quite reasonable to study another determining parameter when conducting diagnostics, therefore an analysis of the graphical dependencies of the change in coolant temperature through time was made in the same time intervals as in the case of the oil pressure parameter (see Fig. 3*b*, 3*d*).

In the time interval from the 4_{th} to the 11th minute, which corresponds to the phase of regularity of the change in the determining parameter, the rate of change in the coolant temperature values within the main diesel engine on the starboard side of boat No. 1 (see Fig. 3*b*) with a working life of 76.6% before the scheduled maintenance (repair) decreases from 3 to 1 °C/min. In the same time interval

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

from the 4th to the 11th minute, the rate of change in the coolant temperature values within the main diesel engine on the starboard side of boat No. 2 (see Fig. 3*c*) with a working life of 54.1% before scheduled maintenance (repair) fluctuates within the range of 2...1° C/min, which is 1.5 times less than that of the engine of boat No. 1.

By analogy with the line of reasoning on the oil pressure parameter, it can also be assumed here that this difference in the change in the values of the second determining parameter (coolant temperature) within the main engine of a third-party boat with a working life close to 99.9% before scheduled maintenance (repair) will be even greater in the time interval from the 4th to the 11th minute, more than 3 °C/min, and taking into account the conducted interpolation with respect to the values of the working life of the main engines ($76.6\% : 54.1\% = 1.42$), it can be stated that this value will not be lower than 4 °C/min. To confirm the aforesaid, as in the case of the first determining parameter (oil pressure), it is necessary to conduct additional similar full-scale measurements within the main diesel engine of a third-party boat with a working life close to 99.9% before scheduled maintenance (repair).

Here we have come to a similar conclusion and formulated it as follows. The obtained maximum value of the rate of change in coolant temperature within the main engine in the time interval from the 4th to the 11th minute can be taken as standardized one for the express method of diagnosing technically sound main engines by crew members in the open sea, and accordingly all other values of the determining parameter (rate of change in coolant temperature), which exceed the established standardized value, are quite appropriate to consider as critical ones for the main engines, which is associated with the acceleration of degradation processes in the intermediate period of time between the conducting of scheduled maintenances (repairs).

6. Conclusions

The detection of critical values of the determining parameters by crew members in the time interval from the 4th to the 11th minute of operation of the main engines is a clear reason to contact specialists of the maintenance and repair department to conduct an unscheduled instrumental check of the operation of the main engines by them in order to ascertain a defective assembly and to formulate further actions to restore the working life of such an assembly at the expense of conducting unscheduled maintenance (repair) during the ship's stay at the berth, and thus to prevent and fully exclude the probability of the occurrence of an emergency situation because of a malfunction of this assembly in the open sea.

Since the quality properties (characteristics) of the oil (or coolant) may become excessively deteriorated in the course of engine operation, and then a need to perform unscheduled maintenance will be generated (which was not previously established by the schedule), during which the oil (or coolant) will be replaced in the main engines, taking into account a specific type of oil (or coolant) for a specific type of engine. Such a case may indicate both a discrepancy in the quality of the oil (or coolant) on the part of the supplier and on the part of the maintenance and repair department during preliminary scheduled maintenance, and which subsequently led to premature failure of the mechanical assembly and became the reason for the unscheduled repair of engine. Such a combination of circumstances is a reason for appointing an official investigation into the causes of unscheduled financial costs associated with the conducting of one or another unscheduled maintenance (repair).

However, the main practical achievement of the conducted research is that the application of the proposed diagnostic express method by the ship's crew for independently tracking the onset of critical changes in the operation of the main engines will allow early warning and thus preventing emergency situations associated with an engine breakdown in the open sea while the ship is performing her combat mission. In addition, this is directly related to the increased responsibility of the maintenance and repair department when its specialists perform the scheduled maintenance work in the future, which in turn will increase the ship's combat readiness to perform her missions on the open sea.

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Боряк Костянтин Федорович; Kostiantyn Boriak, ORCID: https://orcid.org/0000-0003-4226-0102
Ігнатенко Олександр Анатолійович; Oleksandr Ihnatenko, ORCID: https://orcid.org/0009-0009-6938-6208

Received November 04, 2024

Accepted December 12, 2024