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K. F. Boriak, DSc, **O. A. Ihnatenko**

Institute of Naval Forces under Odessa Maritime Academy (with Conferred Status of National University)

TESTING A NEW EXPRESS METHOD FOR PROMPT EVALUATION OF THE CURRENT TECHNICAL STATE OF SHIPBOARD DIESEL ENGINES PRODUCED BY CUMMINS INC

This article presents the results of testing a new express method for prompt evaluation of the current technical state of main shipboard diesel engine produced by Cummins Inc. using current information through standard on-board instruments. This new express method was successfully tested on shipboard diesel engines produced by Caterpillar Inc. during our previous research. Within a recent full-scale experiment to test our express method on Cummins ReCon QSB5.9 diesel engine in the time interval from the 4th to the 11th minute in the starting heating-up mode, positive results were obtained, which confirm the full acceptability of the method during the starting heating-up mode (at no load) in relation to diagnosing various types of diesel engines (produced by different manufacturers) based on two determining parameters: the rate of change of oil pressure in the lubricating and the rate of change of coolant temperature in the cooling system. These two parameters clearly determine the technical state of engine as serviceable or requiring unscheduled maintenance.

The researches being conducted by us are aimed at the improvement of the existing maintenance and repair system for shipboard diesel engines produced by various manufacturers. The results confirm the practical suitability and effectiveness of the proposed new express method, which ensures the timely detection of signs of degradation processes, resulting in increased operational reliability, durability, and survivability of shipboard powerplants. The universality of the new express method is confirmed by the fact that the rates of change of the determining parameters are key indicators, regardless of the diesel engine type, its dimensions, or the design features of the cooling and lubrication systems. This enables one to integrate the method into the routine procedures of tending on small ships and boats equipped with Cummins ReCon QSB5.9 and Caterpillar C18 ACERT diesel engines.

***Keywords**: express method; shipboard diesel engine; determining parameters; heating-up mode; current values; on-board instruments; technical state of engine.*

К. Ф. Боряк, д.т.н., **О. А. Ігнатенко**

ВИПРОБУВАННЯ НОВОГО ЕКСПРЕС-МЕТОДУ ОПЕРАТИВНОЇ ОЦІНКИ ПОТОЧНОГО ТЕХНІЧНОГО СТАНУ КОРАБЕЛЬНИХ ДИЗЕЛЬНИХ ДВИГУНІВ ВИРОБНИЦТВА CUMMINS INC

У цій статті представлені результати випробування нового експрес-методу оперативної оцінки поточного технічного стану головного дизельного корабельного двигуна виробництва компанії Cummins з використанням поточної інформації зі стандартних бортових приладів. Раніше новий експрес-метод успішно пройшов випробування на корабельних дизельних двигунах виробництва компанії Caterpillar. У рамках нещодавнього проведеного натурного експерименту з випробування на практиці нашого експрес-методу на дизельному двигуні типу Cummins ReCon QSB5.9 в часовому інтервалі з 4-ї до 11-ї хвилини в режимі пускового прогріву були отримані позитивні результати, які підтверджують повну прийнятність методу під час пускового прогріву (без навантаження) по відношенню до діагностування різних типів дизельних двигунів (випущених різними виробниками) на основі двох визначальних параметрів: швидкості зміни тиску масла в системі змащування та швидкості зміни температури холодоносія в системі охолодження. Ці два параметри однозначно визначають технічний стан двигуна як працездатний або такий, що вимагає проведення позапланового технічного обслуговування.

Дослідження, що проводяться нами, спрямовані на вдосконалення існуючої системи технічного обслуговування та ремонту корабельних дизельних двигунів різних виробників. Результати цих досліджень підтверджують практичну придатність та ефективність запропонованого нового експрес-методу, що забезпечує своєчасне виявлення ознак деградаційних процесів, наслідком чого є підвищення надійності роботи, довговічності та живучості корабельних енергетичних установок. Універсальність нового експрес-методу підтверджується тим, що швидкості зміни визначальних параметрів є ключовими показниками незалежно від типу дизельного двигуна, його габаритів чи конструктивних особливостей систем охолодження та змащування. Це дозволяє включити метод до складу типових процедур обслуговування на малих кораблях та катерах, оснащених дизельними двигунами Cummins ReCon QSB5.9 та Caterpillar C18 ACERT.

***Ключові слова**: експрес-метод; судновий дизельний двигун; визначальні параметри; режим прогріву; поточні значення; бортові прилади; технічний стан двигуна.*

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Statement of the problem in general

In difficult combat or intensive operational conditions, the reliability of the powerplants and auxiliary technical systems of a ship (boat) is a determining factor in ensuring her fighting capability and safety of navigation. Any failure in the operation of the main diesel engines, cooling systems, lubrication systems, fuel supply systems, or disruption of control, warning, and emergency signaling systems creates a high risk of loss of controllability over the operational-tactical situation and the capability to promptly respond to threats, and leads to a decrease in maneuverability, loss of propulsion, or a complete shutdown of the powerplant, which actually deprives the ship (boat) of the capability to perform her combat mission. Under such conditions, the ship's (boat's) crew loses the capability to maneuver quickly, to avoid damage (from fire, torpedoes, missiles, etc.), and also to interact with other combat units. International maritime practice, reflected in the requirements of the SOLAS Convention and the recommendations of the IMO (International Maritime Organization), defines the dependability and reliability of powerplants as key elements of navigation safety. According to these documents, failure of the main engine or critical auxiliary systems is classified as a high-risk event that can lead to catastrophic consequences—from loss of propulsion in the open sea to the occurrence of emergency situations taking into account the threat to the lives of crew members and the loss of the ship (boat) as a whole.

In everyday conditions during scheduled goings to sea, inability to promptly detect deviations in the operating parameters of the main engines and auxiliary systems (pressure, temperature, level, loads, etc.) or errors in technical operations can lead to breakdowns and, consequently, to increased operating costs. The danger lies not only in a local failure: if spare parts, critical components, or backup systems are unavailable or ready for immediate replacement, even a minor failure can quickly spread to other systems (a chain failure), requiring significant resources and time to restore functionality. The main international regulatory documents for maritime industry [1] and [2] indicate the importance of identifying critical systems (and therefore their components and elements) that directly affect the safety of navigation, managing the supply of spare parts and timely implementation of procedures for restoring the technical resource of such systems, since the consequences of their failure (due to unpredictable accidents) can cause harm to the environment and crew members who will be unable to continue performing the mission assigned to them.

Among other things, an important factor in ensuring the reliability of powerplants is the level of technical awareness during the training of crew members, as well as their ability to promptly identify, localize, and eliminate failures of the ship's (boat's) technical equipment. The operational efficiency of even the most modern shipboard powerplant depends on the tending squad's mastery of technical diagnostic methods, parameter monitoring tools, as well as emergency procedures and correct sequence of recovery work. International experience in the operation of military and civilian ships shows that failure to comply with maintenance regulations, irregular training of tending squads and officers, and also the lack of practiced actions (through ignorance) in the event of failure of components of the main powerplant lead to damage to auxiliary mechanisms and ship's service systems (through chain reaction, domino effect), and in some cases to the occurrence of fires, loss of controllability of the ship, etc. That is why, in modern maritime practice (both military and civilian), special attention is paid to training crew members in matters of engine damage control, including prompt response to powerplant malfunctions, providing backup power, and maintaining a minimum level of operability of ship's systems in the open sea. Regular training, simulation exercises, and the use of automated engine condition monitoring systems help minimize the risk of emergency situations and improve crew members' ability to perform missions even in complicated combat conditions or during long-term sea duty.

When examining emergency cases and analyzing the consequences of emergency situations across a wide range of environmental impacts, the international practice of maritime industry shows that technical failures of ships' powerplants can generate additional economic costs unforeseen by the register and also exacerbate environmental crises and political relations between countries. Historical examples of civilian shipping accidents demonstrate a clear causal relationship between navigational errors, shipboard system failures, and crew members' incorrect actions, leading to large-scale oil spills at sea, long-term recovery programs, and also concomitant high-profile cases against the backdrop of international politics [3].

Thus, from the point of view of the impact on the performance of a combat mission and on the safety of navigation, the failure of technical means may have the following consequences:

- Sudden tactical deterioration associated with reduced maneuverability, increased vulnerability, loss of navigational information or orientation, and limited coordination with other interacting combat units.
- Operational and tactical disruption of the mission with delays in decision-making, inability to maneuver, and, as a result, the inability to complete the mission within the designated time-frame.
- Complications in the supply of spare parts, the need for dismantling and repairs, and also financial costs for spare parts and repairs.
- Accompanying problems inside and outside the combat zone: environmental damage, legal and political disputes, loss of trust from allies or the civilian population.

International standards and accumulated experience point to specific areas for risk minimization: (1) strict adherence to rules and requirements for resource management for critical components; (2) systematic diagnostics and technical inspection of critical systems; (3) regular and enhanced technical training of the crew members in emergency scenarios; (4) the development of proactive procedures that will allow the crew members to continue to perform their combat mission in conditions of gradual (or graceful) degradation of the ship's main systems and auxiliary devices.

The introduction of new methods for current diagnostics of ship's machinery allows us to eliminate or significantly reduce the probability of technical failures, reduce the time required to deploy repair facilities and perform repairs, and prevent large-scale losses. This essentially increases the capability of a ship (boat) to maintain combat readiness and not compromise the safety of navigation, even under adverse conditions.

Thus, the improvement and introduction of modern methods for monitoring operational parameters and prompt evaluation of the technical state of ships' (boats') powerplants is of particular importance for the navy and civilian fleet both during martial law and under peaceful operating conditions. The issue of ensuring the reliability, safety, and efficiency of shipboard diesel engines is directly related to the introduction of modern approaches to monitoring their technical states, as well as predicting and preventing potential failures. In the navy, such measures contribute to increased combat readiness and operational stability of naval forces; and in case of the civilian fleet, these measures ensure the continuity of transportation, as well as increase economic efficiency and environmental safety of navigation. As Ukraine transitions to strict adherence to international shipping standards and the adoption of NATO standards for the technical operation of various types of ships, comprehensive improvement of the approaches and methods used is a pressing strategic objective that unites the interests of the state’s defense and transport sectors.

Analysis of the recent published achievements

Ensuring the serviceableness, reliability, and safe operation of seagoing ships is a key task for operational and technical services and requires the introduction of comprehensive diagnostic systems. One of the leading areas of monitoring the technical state of shipboard powerplants is non-destructive testing (NDT), which allows one to evaluate the state of elements, mechanisms, and materials without disassembling them.

In marine operating conditions, given limited time resources, remoteness from repair bases and laboratories, as well as difficult access to equipment, the selection of an easy-to-use and optimal (by resources) NDT method becomes critically important, as the method has a direct influence on the technical readiness of shipboard systems. According to the international standard ISO 9712:2021 and the rules of classification societies (DNV, ABS, Lloyd’s Register), the effectiveness of control is determined not only by the selected diagnostic method, but also by the qualifications of maintenance personnel, repeatability of results, quality of measurement of determining parameters and standardized inspection procedures [4], [5].

In the international operation practice of ships, ensuring the trouble-free operation of main diesel engines is based on an integrated approach that includes technical, organizational, and operational measures. In accordance with a number of documents issued by the International Maritime Organization (IMO), particular importance is attached to the introduction of control systems taking account of the maintenance of shipboard powerplants by their technical states (Condition-Based Maintenance, CBM), which allows one to conduct the continuous monitoring of the determining parameters of engine running: temperature, pressure, vibration, fuel and oil lubricant consumption. Such an approach does not contradict the general recommendations set forth within the ISM Code and therefore confirms the need to integrate this approach into the ship’s operational maintenance routine. It is aimed at ensuring the earliest possible detection of deviations in the determining parameters of the running of diesel engines and allows one to conduct maintenance based on current state rather than scheduled intervals, thereby increasing the reliability of the ship’s powerplant and extending its service life.

The IACS (International Association of Classification Societies) standard sets strict requirements for the design quality, certification, and operational monitoring of diesel engine parameters. Specifically, it establishes requirements for dual redundancy of lubrication and cooling systems, on-load reliability testing, and periodic inspections of the technical state of shipboard powerplants. The measures conditioned by such requirements are aimed at preventing failures of critically important components in the open sea, especially during autonomous long-distance navigation or when performing a combat mission without the possibility of technical support from shore.

The experience of NATO navies demonstrates the effectiveness of combining technical inspections with systematic training of crew members. NATO Naval Engineering Standardization Agreements (STANAGs) programs provide for the introduction of standardized procedures for technical diagnostics, emergency response, and exercises in fault isolation within ship’s powerplant. Specifically, scenarios for dealing with sudden capacity loss, cylinder overheating, or engine room fires are practiced, enabling crew members to act in concert and minimize the consequences of failures.

Lloyd’s Register in turn is placing particular emphasis on the introduction of digital monitoring technologies for technical state such as Digital Twin and Smart Ship, which enable one to create the virtual models of main engines and forecast probable failures based on analytics and the processing of large arrays of empirical data. This not only increases reliability but also reduces operating costs and the risk of human error.

Thus, the generalization of international experience shows that the main up-to-date concept of increasing the reliability of shipboard diesel engines is based on three main principles: (1) continuous monitoring of the technical state; (2) correct planning of maintenance; (3) systematic training of crew members and maintenance department personnel. The implementation of these principles, combined with the introduction of digital technologies, redundancy procedures, and strict adherence to international standards for technical operation, significantly increases the survivability of shipboard machinery, reduces the risk of accidents, and ensures the preservation of its operability under complicated conditions.

For shipboard powerplants with diesel engines, it is important to monitor deviations in the values of determining parameters such as temperature, pressure, and vibration. In so doing, this monitoring is preferable at the initial stage of heating-up mode of diesel engines, when the greatest risk of failure arises owing to the most unfavorable thermomechanical conditions of their operation. The use of non-destructive testing and diagnostic methods for powerplants during condition-based maintenance (CBM) ensures early detection of deviations from normalized values of determining parameters, optimization of their maintenance, as well as an increase in the service life of engines.

In modern global trends in the domain of non-destructive testing, a rapid shift toward digitalization, automation, and the integration of various diagnostic methods takes place. Technologies such as phased array ultrasonic testing (PAUT), time-of-flight diffraction (TOFD), eddy current testing, laser flaw detection, and thermography are gaining popularity for the quick detection of defects in ship's constructions and machinery. At the same time, methods for prompt evaluation of the technical state of shipboard diesel engines, which are based on real-time monitoring of operating parameters, are rapidly developing. These methods include monitoring the pressure and temperature of working fluids, analyzing fuel combustion parameters, monitoring the parameters of vibration and acoustics, as well as measuring the speed and load of engine. Current data from running engines are displayed on electronic information screens, and this enables one to timely detect deviations from normalized parameters and prevent the further development of defects.

Thus, up-to-date approaches to non-destructive testing methods form a comprehensive, multi-level system for evaluating the technical state of shipboard powerplants, in which conventional methods are supplemented by digital technologies and intelligent analysis tools using artificial intelligence. Integrating more accurate diagnostic methods with monitoring of current data on the performance of shipboard powerplants into everyday tending practice allows one to increase their operational reliability and service life. The combination of digital instruments and sensor-based system enables one to receive more reliable diagnostic data in real time, which is critically important during combat and special missions, when even a short-term failure within powerplant can impact on the ship's controllability and operational readiness. The widespread use of automated monitoring systems enables one to conduct the diagnostics of the current state of equipment without shutting down, ensuring the continuous collection of data and their subsequent processing using artificial intelligence algorithms. According to paper [6], modern approaches to digitalization of the maritime industry involve the implementation of sensor-based networks to collect operating parameters of shipboard equipment in real time, taking into account the use of automated monitoring systems and big data analysis algorithms to evaluate the technical state of machinery and predict probable failures. This paper highlights that such digital technologies significantly improve the efficiency and safety of shipboard powerplants.

One of the most important components of technical diagnostics is evaluating the current state of diesel engine cooling and lubrication systems. These systems directly characterize the engine's thermal and stress state, and therefore indicate its operability, reliability, and remaining service life.

Cooling system parameters (coolant temperature and pressure, heat transfer rate, and pressure drops in heat exchangers) reflect the efficiency of heat removal from the engine's main components. Deviations in these parameters often indicate wear on cylinder liners and pistons, corrosion in the passages, carbon deposits, or clogging within heat exchangers. According to paper [7], a practical approach to the diagnostics of marine diesel engines is based on the analysis of sensor data followed by statistical formation of empirical dependencies of parameters on the operating state of the engine and determination of permissible limits of their change—namely, exceeding these thresholds in real time is recorded as a symptom of abnormal operation, which allows one to timely identify the faults of individual components without great computational complexity and delays when detecting deviations.

The lubrication system is also an important source of diagnostic information. Its parameters—lubricant pressure and temperature, impurity levels, the presence of foreign metal particles, and viscosity—directly reflect the technical state of the main bearings, crankshaft journals, piston assemblies, and turbocharger. The study [8] emphasized that adaptive methods for analyzing lubrication parameters using machine learning can significantly improve the accuracy of early defect detection, which is especially important for shipboard powerplants operating under varying loading conditions.

Thus, it is the systematic (continuous) analysis of changes in the parameters of the coolant temperature in the cooling system and the oil pressure in the lubrication system that enables one to timely detect deviations in the operation of individual components of engine, which appear in the early stages of malfunction development and can be used as the most important diagnostic indicators. In other words, the combination of continuous monitoring of the cooling and lubrication systems creates a comprehensive picture of the engine's technical state, allowing us to evaluate not only its current operability but also predict the development of defects. According to paper [9], the parameters of these two systems provide the highest level of information content among all diagnostic indicators of shipboard powerplants with diesel engines. The integration of NDT data and continuous monitoring (temperature mapping, oil debris analysis, vibration, and acoustic emission) forms the basis of the modern concept of predictive maintenance—tending the equipment based on the current technical state—which allows one to minimize the risk of unforeseen failures and increase the reliability of shipboard powerplants in real-world conditions of the open sea.

Our previous studies [10], [11] are the links of a single chain in the consecutive and comprehensive development of the area of improving procedures within the framework of the maintenance and repair system of shipboard powerplants based on the use of modern methods of monitoring, analysis of current operating parameters, and forecasting the technical state of ship’s mechanisms in the course of their further operation.

In paper [10], the conceptual foundations for the creation of a new express method for forecasting the development of degradation processes in ship’s mechanisms using current information coming from standard on-board measuring devices were substantiated. Our proposed approach to the use of the express method for the prompt evaluation of the technical state of diesel engines by crew members creates the preconditions for the transition from the conventional reactive system of their maintenance to a predictive model of technical state control, which fits into today’s trends in improving the maintenance and repair systems for the warships of leading NATO countries.

Further development of this approach was reflected in paper [11], in which we substantiated the expedience of introducing our express method into maintenance practice for the diesel engines of combat boats. The essence of the method consists in constructing an empirical model based on an analysis of the rate of change of the determining parameters over a given time interval—namely, when starting the engine in heating-up mode. The conducted full-scale testing on Caterpillar diesel engines allowed us to identify the most informative parameters sensitive to the onset of degradation processes and establish standardized limit values, the exceeding of which signals a potential risk of failure or a sudden emergency shutdown of the engine in the near future. Our research focused on analyzing the diagnostic significance of individual operating parameters. All indicators displayed on the on-board electronic panel were divided into two groups based on their impact on diesel engine operability and the risk of breakdown initiation: critically important and accompanying ones. We have found that among the entire set of controlled parameters, only two have a clear and decisive influence on the stability and reliability of engine operation—namely, the temperature of the circulating cooling water and the pressure of the lubricating oil. It is these two parameters that should be considered as the critically important characteristics during operation, the current changes of which determine the thermal and mechanical state of the ship‘s powerplant. Any deviation of these parameters from the nominal values has a direct impact on thermal stability, lubrication reliability, fuel efficiency and the remaining technical service life of the unit.

Based on the aforesaid, coolant temperature and lubricating oil pressure should be used as basic diagnostic parameters when conducting a real-time prompt evaluation of the technical state of a diesel engine. Analyzing the rate of change of these parameters at fixed intervals during the starting of diesel engine in heating-up mode is fundamental for evaluating its technical state, since they clearly reflect the nature of internal degradation processes in the cooling, lubrication, combustion, and thermal loading systems. Deviations in the rate of change of the current values of these parameters from the normalized values indicate appeared malfunctions in the operation of individual components, which can be both latent and accumulative. In other words, the rate of change of coolant temperature and lubricating oil pressure over fixed time intervals act as an integral pair of indicators for evaluating the current technical state of a diesel engine, simultaneously characterizing the efficiency of the heat exchange and lubrication systems, the degree of internal wear of components, the stability of the generating mode, and the level of remaining engine life. For this reason, the inclusion of these parameters in the rapid diagnostic algorithm provides the most informative, timely, and objective evaluation of the operability of a shipboard diesel engine without the use of complex instrumentation.

The express method we developed serves as an auxiliary tool for a primary monitoring which enables one to organize more effective interaction between the ship’s crew and the maintenance and repair department. Such an approach is particularly important in situations where crew members do not have sufficient technical training to conduct in-depth diagnostics, and decisions regarding continued safe operation or the need for unscheduled maintenance must be made quickly and within a limited timeframe. At the same time, it should be emphasized once again that our method does not replace full-fledged instrumental diagnostics, but rather acts as a kind of “safety net” that allows one to early detect the negative indicators of excessive degradation and to transfer the monitoring results to maintenance and repair department specialists for further clarification of the technical state of systems and individual units, taking into account their use of in-depth and more accurate instrumental diagnostics.

Our previous experiments focused on diesel engines from only one manufacturer (Caterpillar Inc.), within which we obtained normalized critical values of the determining parameters of their operability. If the obtained results are generalized, they could theoretically be applied to diesel engines of other types and manufacturers; however, this assumption requires substantiation. For this reason, we tested our express method on Cummins diesel engines to verify our assumption about the universality of the obtained critical values and evaluate their applicability to a wide range of diesel engines from other manufacturers.

An analysis of international standards, as well as today's scientific and technical publications, shows that the problem of forecasting the development of degradation processes in shipboard powerplants with diesel engines remains insufficiently studied. This is particularly noticeable given the small number of published studies in which experimental results were obtained for diesel engines from specific manufacturers, making their applicability to engines of other types and manufacturers difficult. When conducting research, the greatest difficulties, as a rule, arise in transient operating modes (start-up, reaching nominal loads and, maneuvering), when even minor deviations in fuel combustion or heat exchange parameters can lead to accelerated development of degradation processes in key components and assemblies.

The insufficient development of methods for rapid diagnostics the technical state, including the use of standard on-board information systems, is hindering the transition from conventional scheduled maintenance to the practice of condition-based maintenance. In this situation, the issue of creating large-scale approaches that could confirm the possibility of extending the obtained critical parameters and diagnostic criteria to a wide variety of diesel engine types becomes particularly important. It is for this reason that up-to-date researches in this area are generally aimed at developing express methods that allow one to conduct the rapid and reliable evaluation of the technical state of shipboard diesel engines using standard on-board instruments, and also to adapt the obtained results to the widest range of shipboard powerplants.

The goals and tasks of the study

The main goal of this study is to confirm the correctness the results obtained (when studying the Caterpillar diesel engines) against the singled-out and calculated key criteria by us for introducing our express method for the prompt evaluation of technical state based on current data through the standard on-board instruments of information system into the tending practice of shipboard powerplants equipped with Cummins diesel engines. The accompanying goal of this study is to verify the applicability of the previously normalized values for critical parameters determined in our studies on Caterpillar diesel engines to powerplants produced by other manufacturers. This approach allows one to evaluate the universality of the constructed diagnostic model and its capability to provide reliable conclusions, regardless of the design and technological features of a specific diesel engine.

To achieve the stated goals, the following tasks were fulfilled within the framework of this study:

- Integration of our express method with existing control and monitoring systems for shipboard powerplants equipped with Cummins diesel engines. A series of experiments was conducted, covering the capabilities of the on-board information systems.
- Testing of the express method on Cummins diesel engines under real-life operating conditions on Ukrainian combat boats. A series of experiments was conducted, covering the start of engines and recording of relevant operating parameters in initial operating stages (during heating-up mode at idle).
- Comparative analysis of the rates of change of lubricating oil pressure and coolant temperature during the initial stages of diesel engine operation, i.e., the collation of the results obtained for Cummins ReCon QSB5.9 engines with the results obtained for Caterpillar CAT 18 ACERT engines, to confirm the correctness of the proposed critical values for these determining parameters.

The fulfillment of the set tasks created the basis for the dissemination of our express method in the technical diagnostics system for other types of marine diesel engines, taking into account their future testing and confirmation of the correctness of the established critical values for the determining parameters of the rates of change of pressure and temperature.

Materials and methods of the conducted study

In our previous article [11], we noted that warships of various classes are equipped with on-board electronic control and monitoring systems with varying levels of information content and diagnostic capabilities. Furthermore, we also noted that large-displacement ships have advanced integrated control and monitoring systems that provide a high level of automation for monitoring the operation of their mechanisms and propulsion systems. At the same time, the excessive complexity, high cost, and need for specialized maintenance of such systems limit their effective use on small-displacement ships, including combat boats.

In such circumstances, there is a need to develop technically simplified and reliable, and at the same time low-cost technical diagnostics systems capable of providing a sufficient level of tracking of the varying technical state of the ship's mechanisms with minimal operating costs.

In our previous studies [10], [11], we examined diagnostics of Caterpillar CAT 18 ACERT diesel engines installed on combat boats equipped with simplified electronic information systems. These systems belong to ADEM A3 version and provide integrated control, protection, and monitoring functions of technical state with diagnostic capabilities via the Cat Electronic Technician (ET) interface. In the course of conducting our research, we discovered that obtaining the majority of diagnostic data is only possible after the boat returns to her home port, i.e., there is a limitation in the scope of tracking the technical state of the powerplant while the boat is performing missions in the open sea.

For this reason, it became necessary to develop and introduce a new rapid method for quickly evaluating the technical state of diesel engines into the technical diagnostics system, and consequently, into the tending practice of engines. This method will provide the ship's (boat's) crew with a process tool for promptly identifying indicators and progression of degradation processes, thereby minimizing the risk of sudden failures and unpredictable breakdowns during the operation of the ship's powerplant while the ship (boat) is performing combat or special missions on the high sea.

When fulfilling the assigned tasks within the framework of our study, a combination of instrumentation and practical approaches was formed that ensured a completely acceptable level of reliability of the obtained results, as well as the possibility of using this combination together with the control and monitoring systems installed on the combat boats.

As discussed above, to confirm the universality and effectiveness of our express method, it is necessary to test it on diesel engines from other manufacturers. This will allow one to verify the correctness of the application of the singled-out and calculated key criteria by us for a wide range of powerplants. On the other hand, the need to test our method on engines from other manufacturers is conditioned by a large number of single-type powerplants with diesel engines installed on small ships and boats of the navies of many countries.

Despite differences in models and manufacturers, most of these diesel engines are equipped with standard on-board monitoring and control systems that allow one to read basic parameters, including coolant temperature and lubricating oil pressure.

Furthermore, the critical values and algorithmic criteria we determined for the express method should correlate with those determined for powertrains from other manufacturers, thereby confirming both its effectiveness and scalability. For this reason, testing our express method on diesel engines from various manufacturers is key condition to its large-scale introduction and universal applicability. Since coolant temperature and lubricating oil pressure parameters are recorded on almost all modern marine powerplants with diesel engines, confirming the feasibility of using these parameters for rapid diagnostics is critically important. In other words, conducting appropriate experimental measurements on diesel engines from other manufacturers will allow one to fully determine the applicability of our express method and ensure the formation of a unified approach to monitoring the technical state of shipboard powerplants. This, in turn, will pave the way for appropriate decisions regarding the safe operation of powerplants in the open sea and will increase the efficiency of maintenance and repair systems in the marine industry.

Based on the above, we tested the applicability and effectiveness of our rapid method for quickly assessing the technical condition of a Cummins diesel engine, thereby expanding the range of engine types fully compatible with our method. Main characteristics of the engine: Cummins ReCon QSB5.9, inline 6-cylinder, 4-stroke, 5.9-liter displacement, 1,740 hours of running time out of 2,000 hours before the first scheduled maintenance. To evaluate the technical state of the engine under real operating conditions, standard on-board monitoring systems were used, allowing one to read key operating parameters, including coolant temperature and lubricating oil pressure.

On engines of this type, operational diagnostics is carried out using standard sensors, which allow one to timely record changes in engine running during the modes of starting, operating, or transient (starting, heating-up, reaching operating mode, or loading). This circumstance allowed one to apply our express method using data on the rates of change of coolant temperature and lubricating oil pressure, which played the role of indicators of the initial stages of degradation in relation to components and systems. We also took into account the fact that standard sensors do not provide high resolution for minor deviations, and their graduation and reading frequency may be limited in capturing early, minor changes, requiring additional data processing.

To read the coolant temperature and lubricating oil pressure, Cummins ReCon QSB5.9 diesel engines are equipped with corresponding sensors.

The coolant temperature sender (part number: 4954905) is used as a temperature-sensitive element and is supplied with many types of diesel engines, including QSB, ISB, QSM, QSC/QSL, ISX/QSX. This sensor allows one to monitor the engine heating and cooling processes during starting, heating-up, and operating modes. Main characteristics of the sensor: 2-pin; operating range from –40°C to +130–150 °C; nominal resistance ~2.5 kOhm; accuracy (error): ±1.4°C at ~25 °C; response time < 20 s; connection:

standard size threaded; body material: brass.

The oil pressure sending unit (part number 4921517), which is supplied with QSB and ISB diesel engines, is used as a pressure-sensitive element. This sensor allows one to monitor the pressure increases and decreases within the lubricating system of engine in real time. Main characteristics of the sensor: 3-pin; analog; signal transmission: proportional to pressure in the range of 0–300 psi (≈ 0–20.7 bar) with a supply of 5 VDC; accuracy ±1.5 % FSO; temperature error ±3.5 % FSO; operating temperature range: 0–85 °C, response time < 2 ms; connection: standard size threaded; body material: brass. In the technical and operational documentation for QSB5.9 engines, produced by the well-known American company Cummins Inc. [12], it is indicated that the lubricating oil pressure in the main oil-duct at normal operating temperature should be maintained at a level of 28 PSI (≈ 193 kPa) (low loading) to 62 PSI (≈ 427 kPa) (high loading).

The use of these two sensors in the standard control and monitoring system of the marine power plant allows one to real-time monitor coolant temperature and oil pressure, which enables us to analyze the rates of change of these two parameters as indicators of the current technical state of the diesel engine and thereby promptly detect the initial signs of degradation of its components and systems.

Presentation of the main material

In our previous studies on diesel engines manufactured by Caterpillar Inc., we determined the critical values for the rate of change of two key operating parameters: oil pressure ($\Delta P/\Delta t \leq 35$ kPa/min); coolant temperature ($\Delta T/\Delta t \leq 4.9$ °C/min). The limit values we established allowed one to evaluate the technical state of engines before they reached their stabilized thermal mode of running. These limit values were obtained by analyzing the parameters of diesel engines with different degrees of wear (i.e., different numbers of running hours), providing a sufficient statistical basis for constructing a model for a new express method for diagnosing. Taking into account the aforesaid, the main element in the constructed model of our method is analyzing two determining parameters in proper time: the rate of change of coolant temperature and the rate of change of oil pressure. These parameters are particularly informative in the early stages of a diesel engine's running, as they clearly indicate thermohydraulic anomalies that may later develop into both local faults and serious malfunctions. Unlike conventional diagnostic methods that focus on analyzing steady-state modes, our express method allows one to evaluate the engine's state within the first 11 minutes after its starting.

The Cummins ReCon QSB5.9 on-board digital engine control and monitoring system was used for the experiment. The digital panel ensured high accuracy, measurement stability, and recording of parameter changes with a resolution of up to 1 minute. The absence of external load at the initial stage made it possible to focus exclusively on internal thermohydraulic processes. The tests were carried out on the main diesel engine on the starboard side of boat No. 3. Figures 1 and 2 show the experimentally obtained values of two determining diagnostic parameters (oil pressure and coolant temperature) according to the criterion of the rate of their change with time.

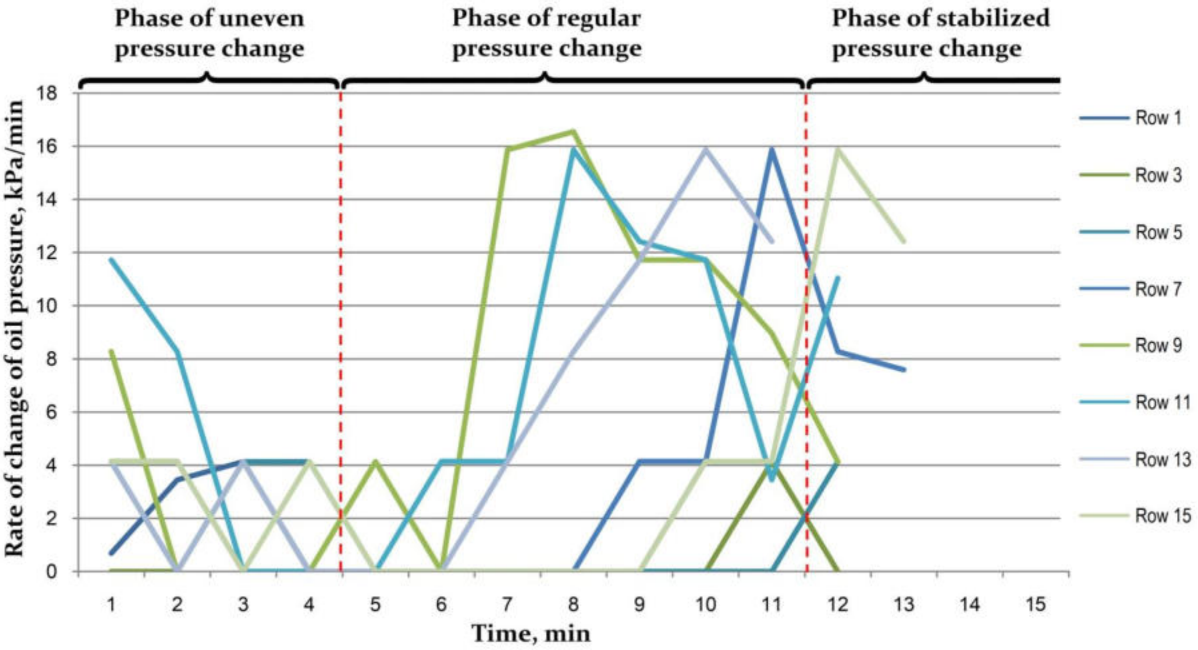

Figure 1. Boat No. 3: Rate of change in the values of oil pressure in the heating-up mode of engine (Cummins ReCon QSB5.9).

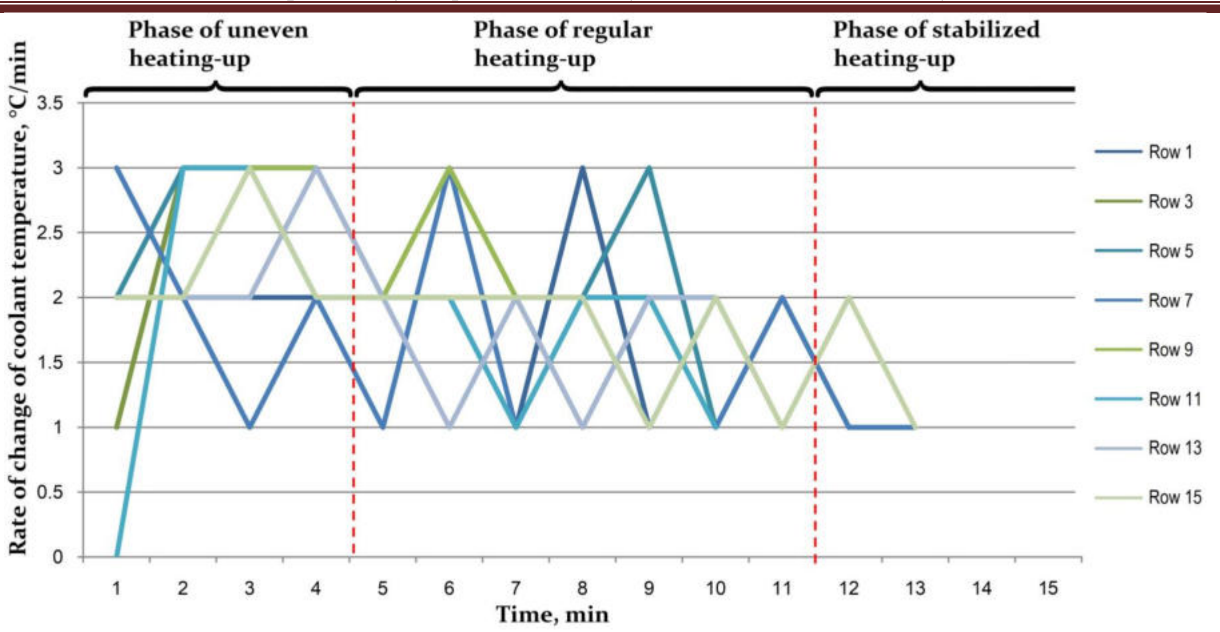

Figure 2. Boat No. 3: Rate of change in the values of coolant temperature in the heating-up mode of engine (Cummins ReCon QSB5.9).

The change in current temperature values during the Cummins ReCon QSB5.9 engine heating-up mode revealed three distinct phases. Between the 1st and the 4th min, a sharp change in the values of the key parameters was observed, characteristic of the uneven heating-up phase. The rate of change in oil pressure was recorded as nonuniform and jumping. The maximum rate of change was 12 kPa/min, which is three times lower than the normalized critical value of 35 kPa/min. Relatively small values of the rate of change of oil pressure (up to 12 kPa/min) indirectly indicated the high design quality of the Cummins ReCon QSB5.9 engine and its good technical state at the time of diagnosing. In addition, the very noticeable differences in the values of the determining parameters obtained by us when comparing the Cummins ReCon QSB5.9 engine and the Caterpillar C18 ACERT engines are explained by the difference in the design of the lubrication and cooling systems, in particular the working volume of the circulation circuit, the features of the operating characteristics of the pumps, differences in sensitivity to the viscosity of the oils used and the high sluggishness of the cooling jacket. Based on a comparative analysis of the determining parameters in the uneven heating-up phase, an unambiguous conclusion was made that the Cummins ReCon QSB5.9 diesel engine was in a better technical condition than the Caterpillar C18 ACERT engines during our previous research [11].

The maximum value of the rate of change of the coolant temperature with time during the uneven heating-up phase does not exceed 3 °C/min and is significantly lower than the permissible normalized limit value $\Delta T/\Delta t \leq 4.9$ °C/min, i.e., it corresponds to the standard thermal values in the engine heating-up mode. While diagnosing and comparing with the permissible standardized critical values ($\Delta P/\Delta t \leq 35$ kPa/min and $\Delta T/\Delta t \leq 4.9$ °C/min), all current values of two determining parameters were in the safe zone, indicating the absence of hydraulic shocks and any signs of abnormal behavior, such as sticking of relief valves, deterioration of filter permeability, or unstable pump operation. Generally speaking, when diagnosing diesel engines, analyzing the values of the determining parameters in the time interval from the 1st to the 4th min is not a fruitful step. This is explained by the fact that thermodynamic processes during the very first phase are disordered and intermittent, and the parameter values are highly dependent on the environment (temperature, humidity, atmospheric pressure) in which the engine is started.

For this reason, we reckon that the very first phase should be ignored during the prompt evaluation of the technical state of diesel engines of any type (if the starting conditions are standard, as required by the operating instructions).

Furthermore, during this phase, exceeding the normalized critical values of the determining parameters ($\Delta P/\Delta t \leq 35$ kPa/min and $\Delta T/\Delta t \leq 4.9$ °C/min) is permitted. A clear example is the double excess (70 > 35 kPa/min) of the established norm of the first determining parameter (rate of change of oil pressure, $\Delta P/\Delta t$) in this phase for engine #2 manufactured by Caterpillar Inc., as shown in our previous paper [11]. Such excess is an indicator that the oil in the engine has almost exhausted its useful properties and requires replacement, and this was confirmed by the relevant data—the expiration of the number of running hours of the engine and its scheduled maintenance in the near future (according to the records in the accompanying documentation for this engine). On the other hand, this excess (based on the rate of pressure change criterion) does not mean the need for an immediate engine shut-down and its decommissioning, since during the phase of regular heating-up (2nd phase), the current values of the first determining parameter showed a significant decrease (20 < 35 kPa/min). At the same time, the value of the second determining parameter (the rate of change of coolant temperature with time, $\Delta T/\Delta t$) did not exceed the normalized critical value (4.0 < 4.9 °C/min), and therefore there was no threat to further operation of the engine (see Figs. 3 and 4).

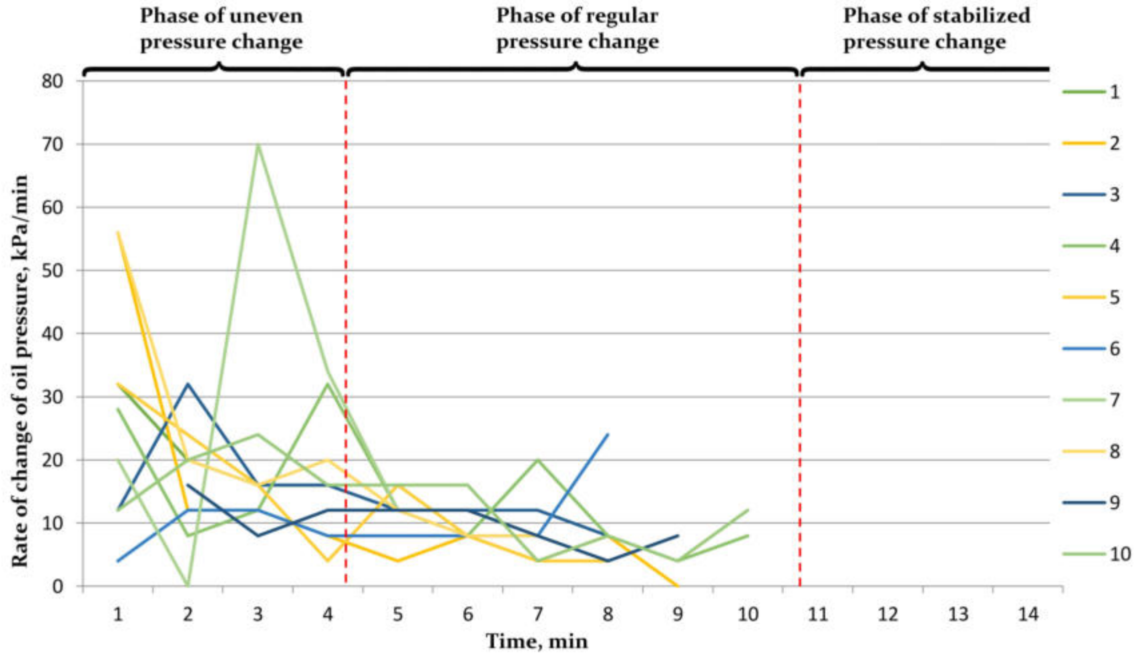

Figure 3. Boat No. 2: Rate of change in the values of oil pressure in the heating-up mode of engine (Caterpillar C18 ACERT).

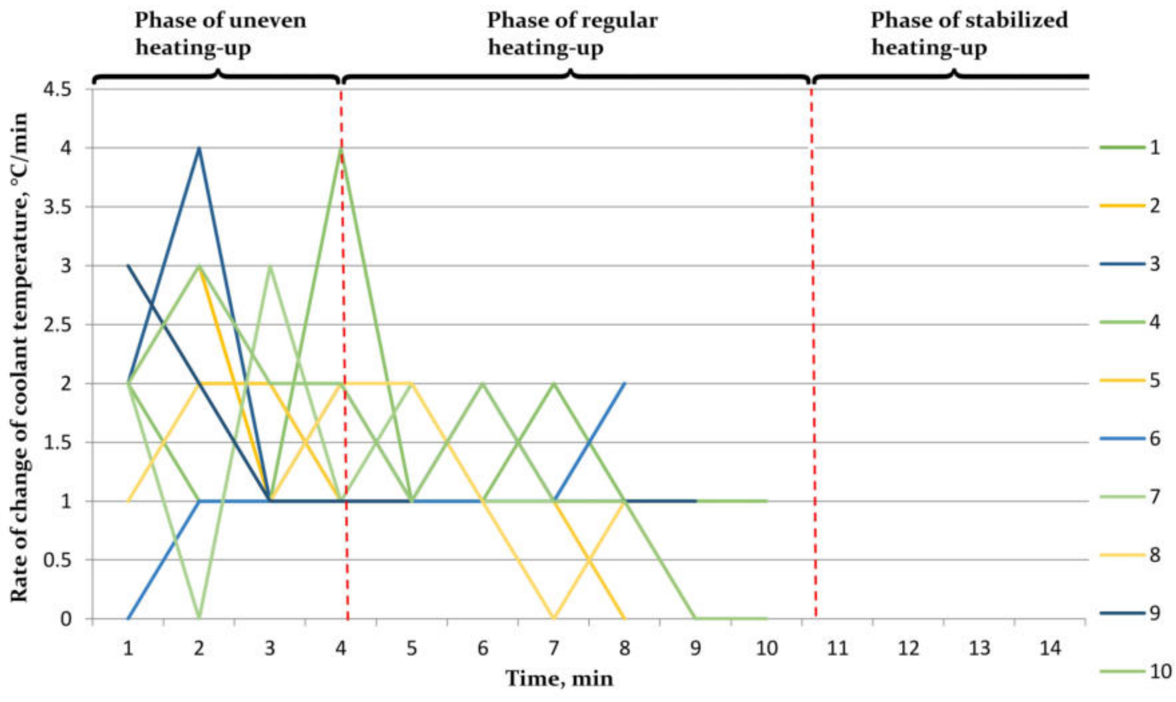

Figure 4. Boat No. 2: Rate of change in the values of coolant temperature in the heating-up mode of engine (Caterpillar C18 ACERT).

While applying our express method for promptly diagnosing the current technical state of a diesel engine of any type, we recommend analyzing the phase of regular heating-up in the interval from the 4th to the 11th min (2nd phase), in which the rates of change of the values of two determining parameters (oil pressure in the lubrication system and coolant temperature in the cooling system) are the most informative (see Figs. 1–4).

When conducting our recent tests, it was discovered that in the Cummins engine lubrication system, during the phase of regular heating-up (under average load), jumps in the rate of pressure change up to 17 kPa/min occurred (which does not exceed the permissible standard value of 35 kPa/min). Such surges may indicate unbalanced operation of the pressure regulator, a local drop in oil viscosity upon reaching the operating temperature in the system owing to the non-uniformity of the rapid distribution of the already limited partial volume of oil within the total volume of oil in the lubrication system (by reason of the high sluggishness of the thermal processes of heating the oil), as well as insufficient permeability of oil with low temperature and increased viscosity through the filter membrane (by reason of partial clogging of the membrane or the low quality of the material of the membrane itself) when the pump operates in alternating modes.

In contrast to the pressure parameter, the value of the second determining parameter (the rate of change of coolant temperature) remained quite stable during this phase: most values were maintained in the range of 1–2 °C/min and only a few times reached 3 °C/min, which is less than the standard criterion of 4.9 °C/min, i.e., the engine cooling system demonstrated its full serviceability.

During the next phase of heating-up (3rd phase, time interval after the 11th minute), the engine entered a quasi-steady-state mode. Here, the rate of oil pressure change for most rows gradually decreased to 2–8 kPa/min, which is quite typical for the operation of a stabilized lubrication system, although separate surges up to 12 kPa/min occurred (which did not exceed the normalized criterion of 35 kPa/min). Such nonfluctuating behavior of the lubrication system indicated that the engine had completely entered a steady-state operating mode, and the adaptation processes in the system had been completed. The temperature behavior of the cooling system during the 3rd phase of heating-up also demonstrated stabilization of the current values of the rate of change of coolant temperature: 1–2 °C/min with several increases up to 2.5 °C/min (which did not exceed the normalized criterion of 4.9 °C/min). Fluctuations in discrete readings on the onboard temperature measuring instruments were minimal and approached their operating stabilized values, indicating the effective operation of both the thermostat and the circulating cooling system as a whole. For rapid diagnostics, this time interval (after the 11th minute) is also important in the event of detection of protracted anomalies, such as prolonged pressure peaks, slow temperature stabilization or cyclic fluctuations, which may indicate a malfunction of the pressure reducing valve, a failure in the thermostatic group, or the presence of air locks in the cooling circuit. However, in our experiments with both Caterpillar C18 ACERT and Cummins ReCon QSB5.9 diesel engines, there were no such deviations, and the behavior of the lubrication and cooling systems corresponded to the nominal steady-state load conditions after the engines had fully heated up.

The results of our research on the Cummins ReCon QSB5.9 diesel engine clearly showed that the obtained values of the rate of change of oil pressure were within safe limits and did not exceed the marginal threshold of 35 kPa/min, which had been determined during our research on the Caterpillar C18 ACERT diesel engines. This indicated the absence of any pre-emergency conditions associated with hydraulic overloads or signs of dangerous behavior of the lubrication system in the Cummins ReCon QSB5.9 engine. We paid the greatest attention to the time interval from the 4th to the 11th min (2nd phase), where distinct jumps of the rate of change of pressure (up to 12–17 kPa/min) occurred. Although these values remained within acceptable limits, their recurrence and abruptness indicated instability in the lubrication system during the transient heating-up mode, which could be caused by the operation of the regulating valve, a change in oil viscosity with increasing temperature, or the pump switching to delivery mode.

The cooling system also demonstrated stable and predictable behavior during all three phases of engine heating-up at the corresponding time intervals. The temperature change rate did not exceed 3 °C/min (which is below the critical value of 4.9 °C/min), thereby confirming the full operability of the thermostatic valve, normal coolant circulation, and the absence of thermal overload.

A comparative analysis of the dynamics of the rates of change in cooling temperature and lubrication pressure indicates that such changes do not affect oil pressure fluctuations, i.e., the identified instability segments are local in nature and affect only the lubrication system, not the engine cooling system. Furthermore, our studies have not revealed any signs of long-term anomalies or supercritical deviations in the running of the engines.

A comparison of the research results for the Caterpillar C18 ACERT and Cummins ReCon

QSB5.9 engines confirmed the universality of the information content of the derived parameters, in particular the rates of change of pressure and temperature in the initial phases of heating up the diesel engines.

It is these parameters that are the most sensitive to deviations in lubrication and cooling systems, which are associated with both the wear of components and troubles of thermal conditions. The fact that engines from different manufacturers exhibit similar characteristic ranges of the parameters of their serviceable state indicates a common physical nature of the processes in the lubrication and cooling systems, regardless of their design features.

Thus, the limit values of the rates of change of pressure and temperature for Caterpillar C18 ACERT engines that we have singled out and calculated, taking into account the checking of their correctness for the Cummins ReCon QSB5.9 engine, indicate the full acceptability of using these values during the starting heating-up (at no load) in relation to diagnosing different types of diesel engines (using our express method). Ultimately, through the timely detection of signs of hidden and high-probability failures, the effectiveness of both control of the technical state of diesel engines on many small ships and boats, and the existing maintenance and repair system as a whole (in maritime industry), will significantly grow.

SWOT analysis of the obtained results

In order to comprehensively evaluate the potential of our express method, we conducted a so-called SWOT analysis, which highlighted its strengths and weaknesses, as well as the opportunities and threats associated with its widespread introduction into the tending practice of diesel engines.

According to our previous paper [11], the express method for diagnosing diesel engines during their initial heating-up in the interval from the 4th to the 11th min (phase of regular heating-up, at no load) is based on the prompt checking of two determining parameters: the rate of change of oil pressure in the lubrication system ($\Delta P/\Delta t$) and the rate of change of the difference in the temperature of the circulating water in the cooling system ($\Delta T/\Delta t$). The analysis and calculation of the critical values of these parameters were also shown there: $\Delta P/\Delta t \leq 35$ kPa/min and $\Delta T/\Delta t \leq 4.9$ °C/min, which were taken as the limiting quantitative thresholds when evaluating the technical state of engines. Testing our method on Caterpillar C18 ACERT and Cummins ReCon QSB5.9 diesel engines confirmed its high sensitivity to changes in the technical state of engines, as well as the diagnostic value of the method as a whole.

(1) Strengths

One of the key advantages of the express method is its simplicity and accessibility, making it suitable for use by rank-and-file crew members without the involvement of separately trained specialists. The method is based on comparing derivative values of key operating parameters with time and allows one to promptly record the dynamics of their changes, rather than simply reading absolute values. This factor is critical, as the rate of change of parameters is the most sensitive to deviations in the engine's technical state. From the mathematical standpoint, the ratios $P/\Delta t$ and $T/\Delta t$ can be interpreted as discrete approximations of the first derivative of the functions $P(t)$ and $T(t)$. It is the derivative (not the function) that makes it possible to detect local anomalies, including sudden changes that precede the development of degradation processes and their transformation into subsequent engine malfunctions.

A second strength is that the method exploits the universal physical characteristics of the diesel cycle. The viscosity properties of the oil and the heat removal of the cooling system are common to all types of diesel engines—from low-power ones for boats and cars to stationary ones for industrial plants. Therefore, criteria such as $dP/dt \leq P_{cr}$ and $dT/dt \leq T_{cr}$ can be easily scaled, and only the critical limit values will need to be adapted to the specific engine design, pump performance, and cooling jacket volume.

The constructed model of the method, based on monitoring two key parameters, also ensures highly reliable results. Specifically, by means of the current values of oil pressure, the lubrication system reacts to viscosity changes quite quickly, while the temperature of circulating water in the cooling system is characterized by a significant sluggishness. This creates a pair of parameters that physically complement each other: the first parameter ($\Delta P/\Delta t$) provides early warning of anomalies in the lubrication system, while the second one ($\Delta T/\Delta t$) identifies incipient failures in the cooling system or in the overall thermal equilibrium of the engine.

Furthermore, practical application of the method has demonstrated its capability not only to evaluate the current state of engine but also to verify the quality level of scheduled maintenance. The example described in our previous paper [11] concerning two engines (with 2,236 hours of running without maintenance and 3,112 hours of running with maintenance) confirmed that the engine which had undergone scheduled maintenance had significantly smaller deviations of parameters and, consequently, better technical state. This fact underscores a high level of information content of the method (when diagnosing) and its capability to serve as an indicator of the quality of performed maintenance.

(2) Weaknesses

Our express method also has its weaknesses in the form of some limitations that should be highlighted and comprehended in detail.

The first limitation is the singled-out time interval, i.e., the method must be applied exclusively during the initial heating-up phase, from the 4th to the 11th minute. This means the method is not applicable for evaluating the technical state of engine during long-term load cycles, partial power modes, or operation under non-standard conditions. Outside the starting mode, the behavior of the parameters $P/\Delta t$ and $T/\Delta t$ may be nonlinear and determined by other physical factors, such as load fluctuations, temperature imbalance of engine case, or hydraulic effects within engine systems.

The second limitation is the dependence of measurement results on the ambient environment (temperature, pressure, humidity). Although diesel engines are designed to operate over a wide range of ambient temperatures, their heating-up under cold conditions (e.g., in winter) as well as under hot conditions (e.g., in summer), has a significant impact on the $\Delta P/\Delta t$ and $\Delta T/\Delta t$ values. In addition, at low temperatures the viscosity of the oil increases, therefore the $\Delta P/\Delta t$ values may be overestimated and for this reason they may have no connection with the degradation process or the initiation of malfunction signs.

The third limitation is the discreteness of the measurements. Since parameter measurements are taken every minute ($\Delta t = 1$ min), the method uses a discrete derivative: $\Delta X/\Delta t = [X(t_i) - X(t_{i-1})]/\Delta t$. If, in reality, a parameter changes rapidly or exhibits high-frequency fluctuations, such fluctuations may be "invisible" with a one-minute step. To improve measurement accuracy, it is necessary to put into practice an automated data collection system with a sampling frequency of at least 1 Hz.

(3) Opportunities

Our proposed express method offers broad opportunities for scalability and integration into up-to-date digital systems of technical diagnostics within the framework of improving the maintenance and repair system. One promising area is the automation of data collection and processing using network applications. Integration of the method with on-board instruments (sensors) will enable a fully automated calculation algorithm to be implemented in real time by tracking the current $P/\Delta t$ and $T/\Delta t$ values and comparing them with normalized criteria, as well as generating corresponding notifications (prescriptions) for the captain of a small ship (boat).

The second promising area is adapting the method to diesel engines of any type: marine, automotive, railroad, tractor, and stationary industrial (attached to large-size electric generator). Since all the enumerated engine types have a similar schematic diagram of lubrication and liquid cooling systems, our method can be scaled by taking into account the correlation between the normalized limit values of the determining parameters $P/\Delta t$ and $T/\Delta t$, the design features of a specific diesel engine type and the characteristics of its thermal sluggishness.

The third promising direction is the combination of our method with machine learning technologies. Aggregating large amounts of data from dozens of similar engines will allow one to create a prediction model of technical state, in which the values of the determining parameters $P/\Delta t$ and $T/\Delta t$ will play the role of key input parameters. Ultimately, this will not only provide a quick evaluation of the engine's current state but also allow one to forecast its operation in the long-term outlook by means of analyzing data on remaining engine lifespan (under slow, standard, or accelerated operating conditions). Based on this forecast, the scheduled dates of conducting maintenance and repair work for engine can be corrected.

(4) Threats

Despite the promising potential for introduction, several threats exist that can limit the effectiveness of the express method in the case of its large-scale use. The first threat is the risk of misinterpreting the readings of on-board instruments and the calculated values of the determining parameters by reason of the lack of the data-handling procedure automation (measurement results) and the insufficient technical qualifications of the crew members. Although the method is simple, any violation of the measurement procedure, incorrect determination of initial conditions, or incorrect data recording can lead to an erroneous conclusion regarding the technical state of engine.

The second threat is the lack of standards for different diesel engine classes. For widespread introduction of the express method, it is necessary to correlate the normalized critical values of the determining parameters $P/\Delta t$ and $T/\Delta t$ for different engine types. Otherwise, one or other decision of the captain or tending squad concerning the technical state of the engine may be based on incomplete or incorrectly adapted data.

The third risk is the possibility of missing indiscernible and deeply hidden defects. Specifically, solitary microcracks in the engine block (EB), localized clogging, or undistinguished flaws in gaskets may not be reflected in the $P/\Delta t$ and $T/\Delta t$ parameters within a short starting interval. This means that the express method cannot replace diagnostics by means of specialized instrumentation and must be used as an additional tool for the current tracking of the engine's behavior to detect emerging and clearly evident signs of malfunctions or as a warning facility about the need for urgent diagnostics with the help of specialized instrumentation in case of overestimated values of the parameters $P/\Delta t$ and $T/\Delta t$.

Taking into account the aforesaid, the conducted SWOT analysis shows that our express method has quite a lot of potential for large-scale application for the technical needs of the marine industry, as well as other sectors of the economy where diesel engines are used. Our method is scientifically substantiated, physically correct, and supported by empirical data on the operation of specific types of engines.

The planned improvement of the method in the future will focus on digitalization, automation, adaptation to different engine classes, and integration with the predictive modules of machine learning. In the aggregate, such practical steps should transform our method into a full-fledged element of an intelligent technical diagnostics system within the framework of the updated maintenance and repair system for diesel engines.

Conclusions

Given the scope of researches we have conducted to test the universality and applicability of our express method through full-scale experiments, the method was tested on a shipboard diesel engine of the Cummins ReCon QSB5.9 type during the starting heating-up mode (at no load) in the interval from the 4^{th} to the 11^{th} minute. The testing was carried out on the basis of the current values of two determining parameters—namely, the rate of change of oil pressure ($\Delta P/\Delta t$) in the lubrication system and the rate of change of coolant temperature ($\Delta T/\Delta t$) in the cooling system. The obtained results confirmed the full and unhindered possibility of applying the method, taking into account the normalized limit values: $\Delta P/\Delta t \leq 35$ kPa/min and $\Delta T/\Delta t \leq 4.9$ °C/min, by means of which the current technical state of the engines, i.e., their serviceableness, is determined.

During our researches, we determined that when diagnosing engines, it is most effective to use derivatives (their rates of change with time) rather than discrete absolute values of the determining parameters. Such an approach eliminates instrumental errors and the influence of the accuracy of the instruments on the measurement results. Besides, it is deemed that derivatives are the most sensitive indicators of local anomalies and the initiation of hidden defects in running mechanisms. Similar to well-known methods of vibration diagnostics for diesel engines, where vibration velocity and vibration acceleration (which are derivatives of vibration displacement with time) are used as determining parameters, our method also uses derivatives (rates of change of pressure and temperature with time) of discrete absolute values of oil pressure and coolant temperature.

A fundamentally important and key advantage of our express method is the capability to early detect discrepancies between the current values of parameters and the maximum normalized criteria (for pressure and temperature) in the starting mode of diesel engine. This makes it possible to early detect hidden defects, which can only be detected by means of conventional methods as a result of their long-term development with time and only during the scheduled maintenance intervals of diesel engine.

The universality of our method is confirmed by the fact that the rates of change of the determining parameters are key indicators regardless of the diesel engine type, its dimensions, or the design features of the cooling and lubrication systems. This allows the method to be integrated into the routine procedures of tending on small ships and boats equipped with Cummins ReCon QSB5.9 and Caterpillar C18 ACERT diesel engines.

On the whole, our method enables the following tasks to be fulfilled:

- Early detection of defects in diesel engine lubrication and cooling systems before the engine enters the operating mode.
- Rapid evaluation of the serviceability of thermostats, pumps, and valves.
- Fast and sufficiently accurate diagnostics of diesel engines without the use of complex specialized instrumentation.
- Formation of an information base for automated and intelligent systems for predicting the technical state of running diesel engines.

Among other things, our method can be easily adapted to up-to-date statistical and mathematical tools, thereby increasing the accuracy of diagnostic inferences. When reading the current values through on-board instruments, the reproduced signals can be combined with Z-scores to identify anomalies, DBSCAN clustering algorithms to group atypical patterns, and regression models to assess trends and predict parameter values. Besides, we strongly recommend applying our method on small ships and boats equipped with Cummins ReCon QSB5.9 and Caterpillar C18 ACERT diesel engines, taking into account its simple and unimpeded integration into condition-based maintenance procedures within the framework of the up-to-the-minute control and monitoring systems of shipboard powerplants.

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О. В. Червотока[1], В. П. Квасніков[2], д.т.н.

[1]*Державний науково-дослідний інститут випробувань і сертифікації озброєння та військової техніки, м. Черкаси*
[2]*ДНП Державний університет «Київський авіаційний інститут», м. Київ*

ІНТЕЛЕКТУАЛЬНА ІНФОРМАЦІЙНО-ВИМІРЮВАЛЬНА СИСТЕМА НА ОСНОВІ АДАПТИВНО РЕКОНФІГУРОВАНОЇ СЕНСОРНОЇ МЕРЕЖІ ДЛЯ ЛАБОРАТОРНИХ ВИПРОБУВАНЬ

Стаття присвячена забезпеченню метрологічної довіри до інтелектуальних інформаційно-вимірювальних систем з можливістю адаптивної реконфігурації у задачах лабораторних випробувань. У роботі удосконалено модель когнітивної реконфігурації сенсорних мереж при врахуванні усіх чотирьох етапів замкнутого циклу інтелектуальних вимірювань OODA. Наведено гібридну структурно-логічну графічну модель інформаційно-вимірювальної системи. Підвищення точності та простежуваності результатів досягнуто шляхом поєднання принципів дворівневого інтелектуального зважування при вимірюваннях та когнітивного управління процесами. За результатами імітаційного експерименту підвищено показники точності на 38 % та простежуваності на 36 % у порівнянні з середніми показниками трьох розглянутих аналогічних моделей реконфігурації.

Ключові слова: *інформаційно-вимірювальна система, сенсорна мережа, інтелектуальні вимірювання, лабораторні випробування, замкнутий цикл OODA, когнітивна реконфігурація.*