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Estimation methodology of the ship diesel engine cylinder-piston group technical condition on the basis of graph theory and mathematical analysis

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Abstract. Carrying out diagnostics of the ship power plant and estimation of the technical condition still remain not fully resolved issues. This is due, first of all, to a large number of active external factors, as well as to the complex process of interaction of the constituent plant elements. The cylinder-piston group of the ship diesel engine is especially sensitive to the effects of the environment. The operating conditions of this mechanism are under the influence of high temperatures and loads. The operational condition of the mating elements of the cylinder-piston group also largely depends on the physical and chemical characteristics of the working media – participants in the energy generation process. Forecasting the occurrence of both increased wear and the timing of natural aging of materials has been a task of engineering science since the advent of technology. The modern methods used in most scenarios imply the need to stop the engine, disassemble it and defect it (to determine the actual condition of the equipment and establish the amount of wear on the parts). This practice is extremely inconvenient for the prompt assessment of the technical condition under sailing conditions. Non-disassembly diagnostics is an alternative. The usage of four approaches to non-disassembly diagnostics of the marine diesel engine consists of sampling and oil analysis; vibration diagnostic control; thermographic research; and the usage of logic-oriented approaches. The method for non-disassembly diagnostics based on a logic-oriented approach to assessing the technical condition of the cylinder-piston group of a marine power plant is described, which will be equipped with the necessary mathematical and software-analytical devices. The method should allow indirectly determining the current state of the cylinder-piston group of a marine engine and predicting the development of potentially possible defects and failures.

Keywords: marine engine, logic-based approach, non-disassembly diagnostics, directed graph, set theory, system entropy

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Научная статья

Методика оценки технического состояния цилиндропоршневой группы судового дизеля на основе теории графов и математического анализа

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Аннотация. Проведение диагностики судовой энергетической установки и оценка ее технического состояния до настоящего времени остаются не в полной мере решенными вопросами, что в первую очередь связано с большим количеством действующих внешних факторов, а также со сложным процессом взаимодействия составных элементов установки. Особенно чувствительной к действию окружающей среды является цилиндропоршневая группа судового дизеля. Условия эксплуатации данного механизма проходят при воздействии высоких температур и нагрузок. Эксплуатационное состояние сопряженных элементов цилиндропоршневой группы также во многом зависит от физических и химических характеристик рабочих сред – участников процесса выработки энергии. Прогнозирование возникновения как повышенного износа, так и сроков естественного старения материалов является задачей инженерной науки со времени появления техники. Используемые современные методики в большинстве случаев подразумевают необходимость остановки двигателя, его разборки и дефектации (для определения фактического состояния оборудования и установления величины износа деталей). Такая практика крайне неудобна для оперативной оценки технического состояния в условиях плавания. Альтернативой является безразборная диагностика. Использование четырех подходов по безразборной диагностике судового дизеля заключается в отборе проб и проведении анализов масла; проведении вибродиагностического контроля; осуществлении термографического исследования; использовании логико-ориентированных подходов. Рассматривается методика безразборного диагностирования на основе логико-ориентированного подхода по оценке технического состояния цилиндропоршневой группы судовой энергетической установки, которая будет снабжена необходимым математическим и программно-аналитическим аппаратами. Методика должна позволять косвенно определять текущее состояние цилиндропоршневой группы судового двигателя и прогнозировать развитие потенциально возможных дефектов и отказов.

Ключевые слова: судовой двигатель, логико-ориентированный подход, безразборная диагностика, ориентированный граф, теория множеств, энтропия системы

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Introduction

For any operating mechanical system, certain patterns of change in its state can be established. This is due to the general physical and chemical laws to which the system is subject. Accordingly, in the presence of a large quantity of data on the system characteristics, on the factors that affect the functioning of the system, it is possible to forecast changes in its technical state. It should certainly be emphasised that such forecasting will have a probabilistic character, but due to the nature laws, it is quite accurate.

Based on the second law of thermodynamics in an isolated system, entropy either remains unchanged or increases (in non-equilibrium processes), achieving a maximum at the setting of thermodynamic equilibrium (the law of increase entropy). The examined ship engine is basically a system isolated from the external environment, in which the components of the future operating body (fuel and air) and lubricating and cooling components are supplied, which is necessary for the fulfilment of a non-equilibrium process – operation. During this non-equilibrium process entropy gradually increases in the system.

Entropy increase (determined by energy dissipation or deviations in influencing external factors) is interrelated directly with the structural integrity of the operating system. The ship engine is a high-specialised mechanism and the entropy increase in it demonstrates the wear processes and accumulation of defects.

Thus, using the tools of the logic-centred approach involving the graph theory and set theory, it is available to develop a method allowing to estimate (with an acceptable error) the current technical condition of the engine cylinder-piston group (CPG). It should be noted that it is convenient to use graphs in the methodological part, because they make it possible to reflect logically-oriented interconnections between factors, processes and consequences of deviations in the CPG operation (graphs correspond well with the logic-oriented approach) On the other hand, the application of the set theory is conditioned by the polyaspectivity of the considered issue, and a great variety of states of the system elements. To simplify, we can say that the size of the set will be directly correlated with the entropy value. The more entropy a system has, the larger will be the set of its states [1].

The technical condition assessment should be evaluated by comparing the actual measurement of parameters with their basic values (specific for the given plant type) and with values that are typical for different system failure scenarios. The comparison should be based on a single property of the system. In this case, it is entropy. Such as the entropy at the beginning of operation (after running-in), the entropy at the moment of measurement, and the entropy characterizing the system condition in different failure scenarios. We shall proceed directly to the used tools and form an algorithmic methodology for assessing the technical condition of the CPG of the ship engine on the basis of graph theory and mathematical analysis.

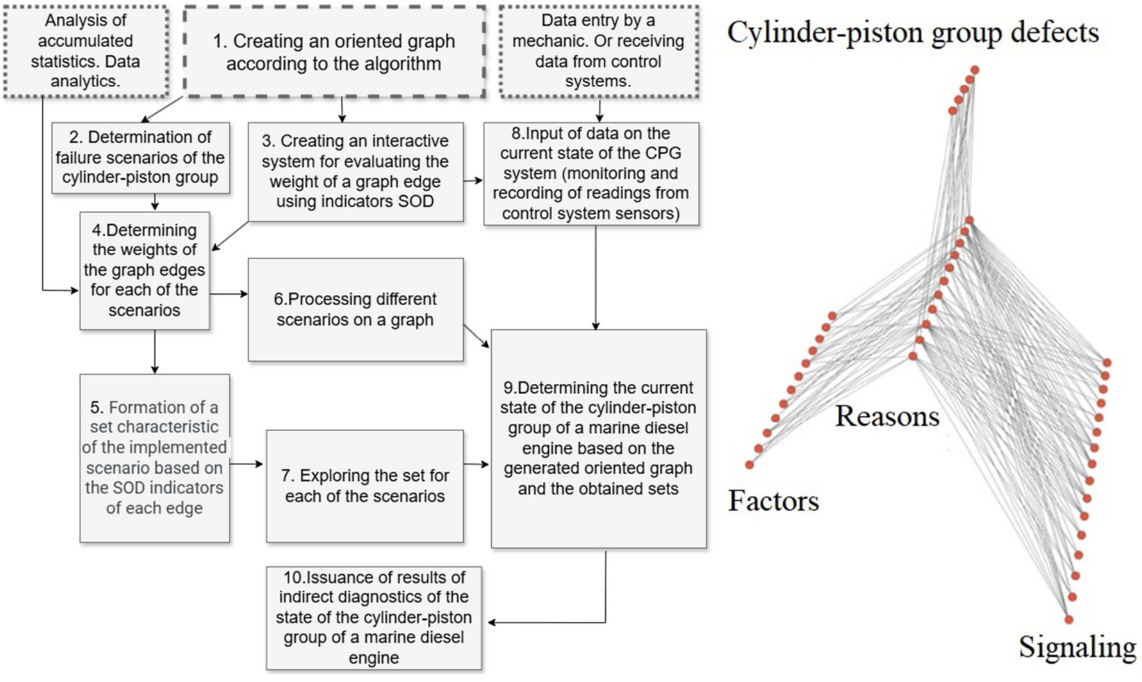
Algorithm development for assessment of the technical condition of the cylinder-piston group and formation of an oriented graph

The logic-oriented approach indicates the interrelation between the factors influencing the system, the processes occurring in the system and the reasons of deviations in these processes and, as a consequence, the defects formed, as well as the signals of various controlling sensors. These connections certainly do exist, and their character, often, not simple linear dependencies can not be described. This does not prevent the drawing of the oriented graph, in which the indicated indicators are interconnected. The graph will be oriented, because there is a clear sequence: a deviation in the external factor leads to a deviation in the process, a deviation in the process leads to the defect formation and to the system alarming the unresolved state [2].

In this way, a graph edge system is formed, which describes the sequence of actions that lead to the formation of various defects in the CPG. In whole, each such an edge can be assigned a certain weight, which will describe the influence degree of the edge on the implementation of this or that scenario.

The question arises, accordingly, how to set a weight for each of the edges in this or that scenario. To do this, it is reasonable to use one of the risk assessment methods (USS R 58771-2019), specifically the Failure Mode and Effects Analysis (FMEA) method. This method allows to analyze any process (and, in fact, the oriented edge represents the process) by three components: frequency of occurrence (*O*), strength of impact (*S*) and difficulty of detection (*D*). Each of the components is ranked from 0 to 10. The more frequent the conditions that facilitate the implementation of the edge potential occur, the higher the value.

In result, the following evaluation algorithm of the technical condition of the CPG of the ship engine on the basis of the oriented graph is formed (Fig. 1, *a*). Consecutively performing the procedures according to this algorithm, it is allowed to obtain on the basis of the logic-oriented approach the result of the technical condition assessment of the CPG.



a *b*

Fig. 1. Algorithm for assessing the technical condition of the CPG of a ship diesel engine based on a directed graph (*a*) and directed graph for assessing the technical condition of the CPG of the MAK 6M32C ship diesel engine (*b*)

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Certainly, a number of important conditions must be achieved in order to fully implement the algorithm. Firstly, to have the oriented graph itself, to form the edge evaluation system, to evaluate the weights of edges in the basic and different failure scenarios, to investigate the state sets of the CPG system, to determine the specific characteristics of the scenarios realized on the graph (to form their arrays) to provide the operational analysis of technical processes via express questioning of the ship mechanic [3].

We shall form an oriented graph (Fig. 1, *b*) evaluating the interrelation of the defect occurrence on CPG of the ship engine with the factors, causes and response of signaling systems. All groups of vertices presented in the graph shall be arranged in a single list (Table 1).

Table 1

A list of factors, causes, defects and reactions considered within the orientated graph of signaling systems (to Fig. 1, *b*)

Factors	Causes	Signaling	Defects
Defective assembly of parts	Mounting clearance error	Oil pressure at the root bearing	Scuffing; corrosion wear; burning and graphitization on surfaces; fatigue cracks; surface glossing
Parts failure	Running-in program failure	Differential pressure at oil filter	
Oil pressure failure	Lubrication system malfunction	Oil temperature at engine inlet	
Incorrectly selected lubricant	Ingress of water, polluting particles	Oil mist concentration in a crankcase	
Fuel grade non-compliance	Solid particle deposit	HT cooling water pressure at an engine inlet	
Cooling system malfunctions	Load fluctuations	Cooling water pressure LT at the cooler inlet	
Failure to comply with the technical conditions while manufacturing parts	Overheating	Cooling water temperature HT at the engine outlet (H)	
Insufficient lubrication	Unheated engine load	Oil pressure at the engine inlet	
Low quality of oil filtration	Disturbance of internal combustion engine thermal mode	Differential fuel pressure at the dual filter	
Fuel supply disturbance	Overloading of the entire combustion engine or an isolated cylinder	Fuel temperature at the engine inlet	
Low quality of air filtration	Fuel injection angle change	Fuel viscosity at the engine inlet	
Lubricant wear		Starting air pressure at the engine inlet	
		Charge air temperature at the engine inlet	
		Exhaust gas temperature after the cylinder	

Consequently, causal interrelation between factors, causes, emerging defects and responses of alarm sensors has been established. In addition, the available edges of interrelations will exist regardless of the implemented "scenarios", but they will have higher or lower weights (respectively, different for *S*, *O*, *D*), which will form a different pattern of "sets" that are characteristic of different system states in the failure states. The generated vertices are in fact basic opened lists and can be completed, supplemented with links and levels depending on the required depth and accuracy demanded by the method and the kind or brand of the investigated ship power plant [4].

We shall proceed to consideration of potential states of the cylinder-piston group system of the MAK 6M32S ship diesel engine. By comparing the results of modelling the array of system states in the base scenario, it allows to determine its current technical condition in the actual scenario and in different failure scenarios.

The scenario modelling of the states of the cylinder-piston group of the ship engine

Many different failure scenarios of ship engines and, in particular, failures related to the CPG are distinguished. We shall consider some of them within the limits of the formed method. Thus, for each of the failure scenarios we will rearrange the weights of the edges of the previously formed graph (Fig. 1, *b*) by means of the *S*, *O*, *D* indicators focusing on the statistical data [5]. Consequently, we obtain a unique (for each of the scenarios) distribution of weights on edges, and a unique combination of *S*, *O*, *D* parameters. The specificity of each scenario can be traced by the change in the average weight of an edge in the graph system, and by changing of the highest weight (Table 2). Finally, it can be argued that a different cause-and-effect pattern will be formed for each failure, and it can be described as a tree of interconnections with changed branch weights, or as a set in which the distribution density of branch states will be divided in a way specific to the scenario in question. The number of failure scenarios is not limited to those given in the table; in total, there are about three dozen of them. Only those scenarios in which statistical data were available for MAK 6M32S type engines are given in the study.

Table 2

Test failure scenarios of the CPG of the ship diesel engine and general parameters of graph edges weight

No.	Scenario description	Average edge weight	Highest edge weight
Base	Engine after running tests and running-in (new)	7.29	27.00
1	Corrosion and cavitation damage on the cooling side of the sleeve surface.	111.72	577.28
2	Scuffing of the cylinder sleeve in the area where the upper piston ring stops at the top dead point	217.15	672.84
3	Burnouts and deposits on the piston head	182.89	650.59
4	Excessive corrosion of the outer surface of the cylinder liner	158.61	696.87
5	Breakage of piston and piston rings	265.41	689.04
6	Scoring due to insufficient clearance on piston skirt	235.37	640.80
7	Scratches, nicks, dents, and marks on the machined surfaces of the lid	118.52	517.14
8	Crumpling, or other damage to the head seating shoulder	105.30	620.51
9	Gas leaks from under the cylinder head through seals	139.75	650.59
10	Corrosion, burnout or other damage on nozzle support seat	134.45	621.35

When considering these deviations, both in the weights of the edges and in the formed sets of edge states (by S, O, D) for each of the scenarios, the question arises as to what physical component underlies the formation of such a varied pattern. Undoubtedly, the key power forming the pattern that is typical for each of the scenarios is entropy [6].

Entropy in the current scenario is meant as the degree of irreversibility, non-perfection of the real thermodynamic process. The entropy is a measure of energy dissipation, and is also a measure of energy evaluation in the aspect of its suitability (or efficiency) to be used for conversion of heat into operation [7]. Due to a number of physical and chemical limitations that are imposed both by the physical laws of nature and the design of the ship power plant, not the whole energy released in the process is converted into useful operation. A significant part of it is spread in the system through heat transfer, vibrations, etc. This fact itself is the basis of "ageing" of the operating mechanism and leads to its gradual degradation through metal fatigue, tightness of joints, geometry violation. It should be noted that the entropy increases unevenly in the ship power plant system, its "equal" growth is occasionally sharply increased due to external factors (for example, low-quality fuel, insufficiency or low quality of engine oil, violation of load distribution). The increase can be reduced or even slowed down by maintenance and repair (at the same time it will be impossible to return to the "initial" positions, again due to the existing physical and chemical dependencies). Obviously, in these arguments we avoid the dilemma of Theseus' ship, because we consider actually available and operated objects within the current principles of maintenance and repair associated with the economic component [8].

Therefore, we can say that for each type of failures of CPG the ship diesel engine, its own set of states of cause-effect indicators is formed. The same set can be formed for the "base state", i.e. for the situation when the ship power plant has passed the run-in stage and in it the entropy value is "lowest".

This may result in the formation of a data library for a set of state indicators that are characteristic of failures of the CPG of the ship power plant. This library will also contain the basic state with the lowest entropy in the system. It is necessary to methodically link the formed library with the actual system state at the moment of assessment of the technical conditions of the CPG based on the logic-oriented approach. This can be done by means of creating a specialised questionnaire for engineers and mechanical engineers. Answering a certain list of questions, the engineer assigns the corresponding S, O, D values to the edges of the graph on the basis of his/her own observations and data from maintenance and technical condition logs. As the result, a state set of cause-and-effect indicators is formed.

By comparing the obtained state set of the cause-effect indicators with the scenario sets and with the base set in the library, we can assess the technical conditions of the CPG system. We can determine which of the potential scenarios the obtained state set tends to, in which direction degradation processes develop, and accordingly predict, potential defects and failures with a certain accuracy.

We shall proceed to the study of the system state of the CPG at different scenarios and further to the development of a full operational software, under which the created methodology will work.

The system state in different scenarios and its entropy. Usage of the set theory to assess the technical condition of the cylinder-piston group

We shall consider each scenario S_i as a set of points in a subspace of the three-dimensional Euclidean space bounded by a cube with vertices at the origin and at the point (10, 10, 10). We calculate the midpoint and the spread of points in each S_i. The midpoint $\mu_i = \frac{\sum_{x \in S_i} x}{|S_i|}$ will determine the conditional centre of the set S_i. The point spread C_i can be defined as the norm of the covariance matrix Var_{S_i} of the points of the set S_i. For the purposes of the current study, the norm $L_{2,1}$ was chosen as the norm, which is defined as the sum of the Euclidean norms of the columns of the matrix [9]. We give the values of the midpoint, and point spread for each scenario (Table 3).

Table 3

Average value and spread of points for each scenario of the CPG conditions group of the MAK 6M32S diesel engine

Scenario	Average value	Spread
Base	(2.23 1.67 1.85)	1.2
1	(3.86 3.39 3.39)	16.72
2	(5.13 4.73 4.48)	23.4
3	(4.69 4.3 4.11)	22.34
4	(4.37 3.93 4.03)	20.4
5	(6.19 6.11 5.82)	7.92
6	(5.19 4.67 4.51)	21.25
7	(4.08 3.68 3.75)	15.32
8	(3.92 3.4 3.22)	15.55
9	(4.52 4.17 4.03)	15.43
10	(4.73 3.97 4.05)	13.98

Comparing the scenarios to each other will require a slightly different approach. We will construct a metric space on the scenario set $\Omega = \{S \subset R^3 | \, 0 \le x, y, z \le 10, \forall (x, y, z) \in S\}$.

A metric space is characterised by a distance function. This is the distance in the scenario space that can be used as a metric, evaluating the similarity of different scenarios. As defined, the distance function d must satisfy the following conditions:

1. The distance from an object to itself is always zero $d(x, x) \equiv 0$.

2. The distance between different objects is strictly positive $d(x, y) > 0, x \neq y$.

3. The triangle inequality is fulfilled $d(x, z) \le$ $\le d(x, y) + d(y, z)$.

To compare the scenarios, we will choose Hausdorff and Mahalanobis distance functions, i.e., we will compare the scenarios in terms of two metric spaces built on the same set of scenarios.

The Hausdorff distance between two sets is defined as the maximum of the minimum distances between the points of these sets [10].

We assume that $S_i, S_j \in \Omega$ and $d(x, y)$ is the Euclidean distance. Then the Hausdorff distance HD between the scenarios S_i and S_j is calculated by the formula:

$$HD(S_i, S_j) = \max\left(\sup_{x \in S_i} d(x, S_j), \sup_{y \in S_j} d(S_i, y) \right).$$

The Hausdorff distance is a natural generalisation of the Euclidean distance to the case of a point set and it satisfies every single condition in the definition of the distance function.

While the Hausdorff distance includes scenarios exclusively as geometric objects and consequently includes only the geometric properties of the compared sets, the second distance function considered in this paper, the Mahalanobis distance, also includes the statistical properties of scenarios.

The Mahalanobis distance MHD measures the distance between points $x, y \in R^n$, which are viewed as implementations of some random variables. Thus, the distance is calculated considering the correlation between these points. If no correlation exists, the Mahalanobis distance coincides with the Euclidean distance [11].

In the current case, the distance needs to be evaluated between sets of vectors rather than between specific vectors. A generalisation of the Mahalanobis distance function to calculate the distance between the sets, while preserving its original properties, was proposed in the research paper [12]. The Mahalanobis distance between sets that contain realizations of two allocations has the following formula:

$$MHD(S_i, S_j) = \sqrt{(\mu_i - \mu_j)^T \, Cov^{-1} (\mu_i - \mu_j)}.$$

Here the value Cov is calculated by the formula

$Cov = \dfrac{|S_i| R_i + |S_j| R_j}{|S_i| + |S_j|}$, where R_i and R_j are correlation matrices of elements of sets S_i and S_j respectively.

We shall present the change values of the Hausdorff and Mahalanobis distances from the basic scenario to all other examined failure scenarios of the CPG of the MAK 6M32S ship diesel engine (Table 4).

To visualize the entropy of the system state, we need to describe a convex hull around the points of each scenario in three-dimensional space. The Quickhull algorithm was chosen to find the convex hulls of the scenarios. The implementation of the algorithm and the construction of the visualization was done using the Python programming language. All examined scenarios of the state set of the CPG system of the MAK 6M32S diesel engine were formed graphically Thus the state set of the system is meant as a set of points in the three-dimensional space, each of which provides an idea of the state of the graph edge. The sets of points which are characteristic for this or that type of failure are called scenarios.

Table 4

Value changes of the Hausdorff and Mahalanobis distances from the base scenario to all other examined scenarios of failure of the CPG of the MAK 6M32S ship diesel engine

Scenario	Hausdorff distance	Mahalanobis distance
1	9.26	0.96
2	10.00	1.45
3	9.82	1.29
4	10.16	1.18
5	10.11	3.56
6	9.79	1.52
7	8.78	1.18
8	9.59	0.99
9	9.82	1.42
10	9.58	1.51

We interpret the results obtained in Tables 2-4, as well as their visualization in the form of sets of states of the CPG system of the MAK 6M32S ship diesel engine. It is obvious that the basic scenario in which the cylinder-piston group is after the process of running-in is conditioned by minimally expressed entropy. However, at this stage there are practically no prerequisites for severe failures, the probability of their occurrence is extremely low, and the system is in the most controlled state. Consequently, the base scenario has the smallest weights of graph edges, average value, spread and it forms a compact set of states – all its points are contained in the cube 20 × 20 × 20. The entropy is minimal in the system.

Implementation of any other scenarios related to the defects and failures in the CPG (in particular, the reviewed model scenarios), leads to a sharp increase in entropy in the system. This is expressed in a sharp increase in the weights of the edges of the graph associated with an increase in the strength of cause-effect indicators and the severity of the realized event, an increase in the probability of its occurrence in the scenario and a decrease in the possibility of detecting a deviation. The entropy increase is uneven and varies from scenario to scenario involving different edges of the graph and forming a specific set in the state space for each scenario (Fig. 2, 3). Thus, by the type of the set (specificity of entropy increases in the system) we can judge which scenario is implemented.

The more different the scenario is from the base state, the easier it is to identify it among all others – using a logic-oriented approach and indirect diagnostics. Among the examined variants, scenario *5* (piston and piston ring failure) is the most distinctive, it stands out sharply both in epy Hausdorff distance and epy Mahalanobis distance. In general, this is a justified finding. The entropy of the system is maximised in this state. Scenario *7* (scratches, nicks, dents, and marks on the machined surfaces of the lid) is also specific. It has the smallest deviations from the base case. As a whole, for each of the failure scenarios of the cylinder-piston group we obtain a unique set of entropy states of the system. This allows to determine the cause of the CPG failure by the indirect diagnostics method without disassembly.

At the practical level, to determine the cause of the CPG failure by such method it is required to compare the actual state of the system with the obtained sets. To do this, a ship engineer-mechanic needs to answer a number of special questions (the authors have formed an appropriate questionnaire) about the state of the ship engine and the main characteristics of its operation during the last time. The set of answers obtained from the engineer allows assigning unique values to the edges of the developed graph, on the basis of which a specific set of states of the CPG system is formed for the examined case. By comparing the characteristics of this set with the "base scenario", as well as with each of the model ones, it is possible to state how close the investigated failure (or the ordinary studied state of the CPG) is to this or that failure scenario. The software is under development, which allows to apply this methodology promptly and form a finding about the current condition of the CPG of the ship diesel engine on the basis of the logic-oriented approach and observation of the system.

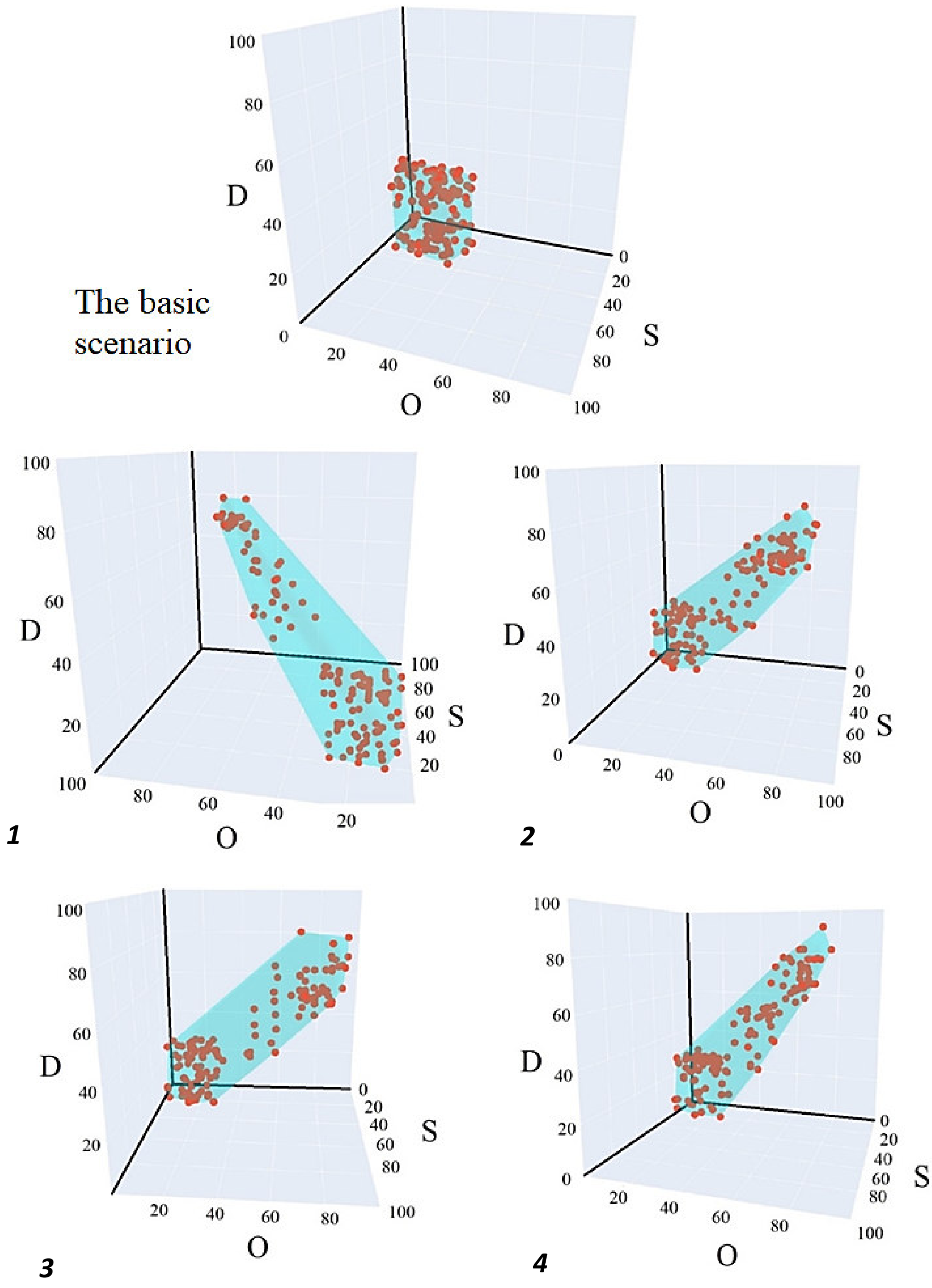

Fig. 2. State of the CPG system of the MAK 6M32C engine: *S* – impact force; *O* – frequency of occurrence; *D* – difficulty of detection; the basic scenario – engine after sea trials and running-in (basic scenario); *1* – corrosion-cavitation destruction of the bushing surface on the cooling side (scenario 1); *2* – abrasion of the cylinder liner in the zone where the upper piston ring stops at the top dead point (scenario 2); *3* – burnouts and deposits on the piston head (scenario 3); *4* – excessive corrosion of the outer surface of the cylinder liner (scenario 4)

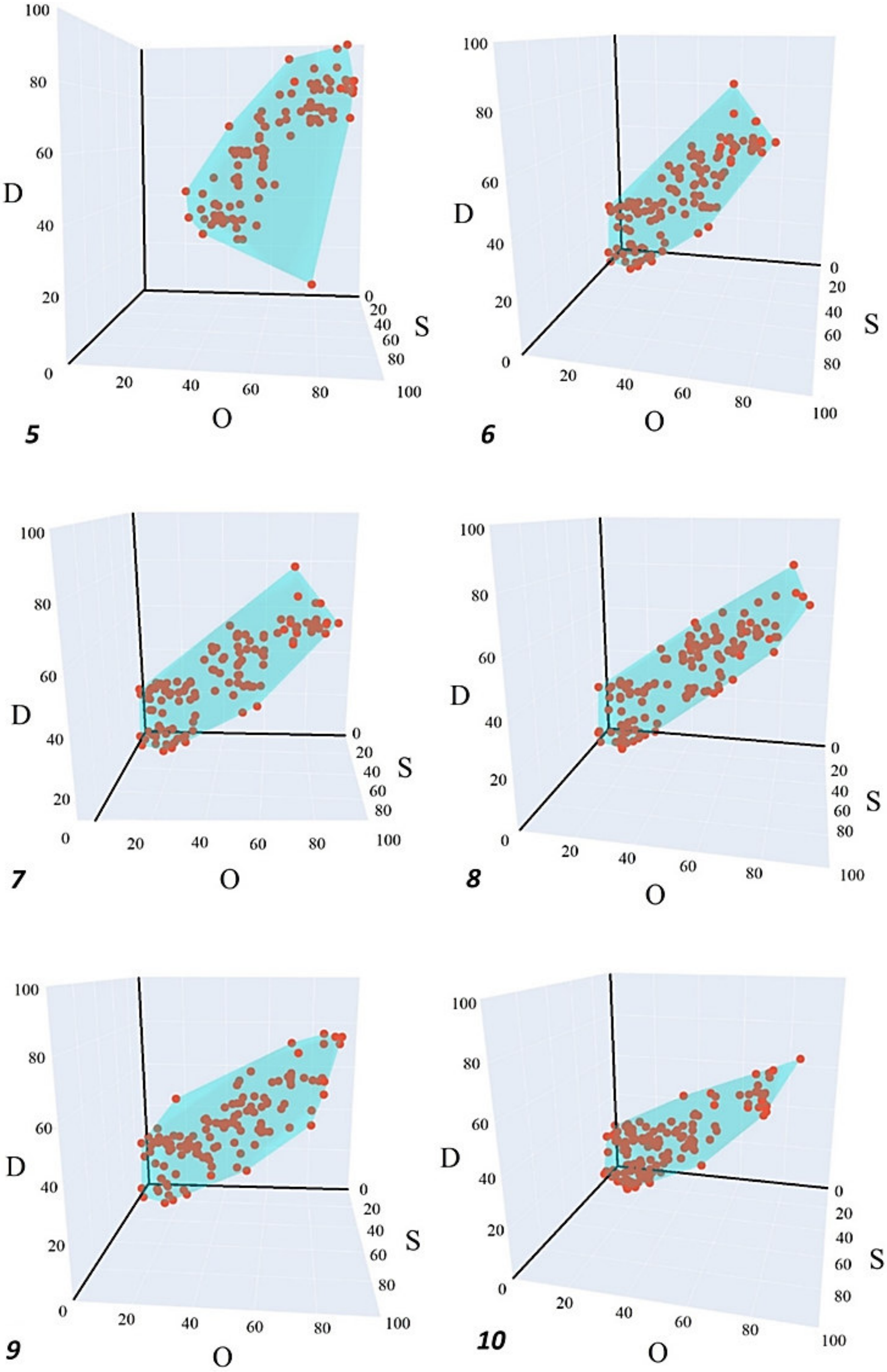

Fig. 3. State of the CPG system of the MAK 6M32C engine: *S*, *O*, *D* (Fig. 2);
5 – breakage of the piston and piston rings (scenario 5);
6 – scuffing due to insufficient clearance on the piston skirt (scenario 6);
7 – sinks, nicks, dents and risks on the treated surfaces of the cover (scenario 7);
8 – collapse or other damage to the cover mounting collar (scenario 8);
9 – gas leaks from under the cylinder cover through the seals (scenario 9);
10 – corrosion, burnout and other damage on the injector support seat (scenario 10)

Conclusion

Obviously, it is necessary to note that the reviewed model failure scenarios of the CPG system of the ship diesel engine do not cover all its possible failures. Thus, there are about 40 classical failure scenarios for the CPG. However, it does not cancel the proposed methodology and does not refute its tools. It only indicates the necessity of forming a larger amount of data that would allow a comprehensive assessment of the system condition under other scenarios as well. This issue is currently under development.

The issue of studying the entropy increase in mechanical systems and development of a methodical tool allowing to reveal characteristic predictive signs of implementation of one or another failure scenario is one of the key and actively developing directions of engineering mechanics and tribology. For ship power plants it acquires special importance, in light of relative complete and deep development of classical diagnostic procedures.

Consolidating the results obtained in the study, it can be argued that for the first-time developed method allows by combining a logically oriented diagnostic approach, processing the results of observations of the ship power plant, using statistical data and mathematical analysis methods, to determine the cause of failure of the CPG of the engine.

The development of such a method and providing it with the necessary software tools will significantly increase the efficiency of the mechanical service on ships, increase the detection of defects in the CPG of the ship engines at early stages, and make it possible to more accurately determine the causes of failures.

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