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Determining the probability of failure of marine diesel engine parts

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Abstract. Maritime transportation is the essence of the international economy. Today, about ninety percent of world trade is carried out by sea through 50,000 merchant ships. Most of these vessels are powered by mainline diesel engines due to their reliability and fuel efficiency. Reliability of system elements in general depends on random failures, significant wear during operation, additional wear during start-up. Accidental damage to diesel engine components is a major hazard during operation, as some parts (such as cylinder liners and pistons) are usually replaced during repairs. On the other hand, preventive service does not eliminate random malfunctions. Therefore, in the general problem of assessing the reliability of a diesel engine, there is a mathematical problem of assessing the reliability and durability, taking into account only the random failures of its elements, which are of the greatest practical importance. The purpose of the work is a mathematical study of the reliability of parts of the cylinder-piston group of the main engines of dry cargo ships. Using a systematic approach and a probabilistic statistical method, it was established that the most common and difficult case is the simultaneous action on a system element (for example, a cylinder sleeve) of factors that cause wear during the period of operation (including during the start-up period) and accidental failures. It was determined that the quality of the cylinder-piston system in ships of the “Ostriv Rosiyskiy” type is higher than in the ships of the “Simferopol” and “Murom” types. Empirical formulas for estimating the probability of emergency failure of main engine system elements during the period of operation between factory repairs were obtained, where the main danger during the period of operation was carried by accidental failures. Based on the results of the study, it is possible to establish a schedule for the periodicity of maintenance of the ship's main engine and the cost of losses due to ship downtime due to failures, and can also be used in the reliability study of other types of ship's main engines. The results make it possible to determine the reliability of the parts of the cylinder-piston group of the main engines of dry cargo ships. and, in particular, to establish the maintenance schedule of the ship's main engine and the cost of damages due to ship downtime due to failures, and can also be used in the study of the reliability of other types of main engines of other series of ships

Keywords: wear; operating time; cylinder sleeve; piston; cylinder cover

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INTRODUCTION

The problem of quality and reliability for sea transport is of particular importance, as it is related to the safety of navigation. In order to predict the quality and reliability of the ship's main diesel engines, it is necessary to study the operating conditions of the main power plants, determine and forecast the probability of an emergency failure in any period of time, as well as the probability that there will be no emergency failures for the entire period or an emergency failure will occur in the first transition. Trampert *et al.* (2008) emphasize the importance of accurately defining the boundary conditions and the sensitivity of the service life of cast iron cylinder heads to the defined engine operating boundary conditions.

On the basis of operational data and results, which are verified with the help of a computer program to determine the relevance of the obtained results, it is established that the reliability of system elements in general depends on the effect of component aging on system reliability (Mihanović *et al.*, 2021).

Munir & Shah (2015) discuss available analysis methods, also a step-by-step approach to systematic qualitative analysis of engine reliability.

J. Kowalski *et al.* (2017) propose an automatic system based on machine learning for intelligent fault diagnosis of marine diesel engines.

Wear of main engine parts during maneuvers for transport refrigerated vessels of the "Surf" series, the average number of starts and reverses during one stop (7 days) is 20. For quantitative assessment, it is assumed that one start from a cold state corresponds to the amount of wear for 5 hours of running time. The amount of wear during one hot start or reverse – one time of running time. In the total number of starts, 25% belong to the cold state. All reversals are considered hot, since less than 4% belong to the cold state. Then the average wear during one parking lot corresponds to the wear during 34.5 hours of normal work. The additional time proportional to maneuvering wear (for parking time) will be: with 31 parking spaces per year, this time is 1070 hours/year. With an average annual running time of 2,300 hours, the additional time is 46.5%.

The identification of car failures as a way to increase its reliability is considered in the work (Pagán Rubio *et al*., 2018; Vera-Garcíaetal., 2019). In the conditions of the operating company, in order to increase the operational reliability of the car, it is important to classify failures by the source of occurrence. Today, most modern enterprises implement a quality management system in order to increase the efficiency of their activities. From the point of view of the quality management system, taking into account its continuous improvement, it is necessary to identify problem areas of operational reliability and direct appropriate efforts to increase it.

The issue of information systems for monitoring the technical condition of cars, a general approach to the formation of models for evaluating the technical condition of a car in operating conditions, and the study of an agent approach to control the technical condition of vehicles are discussed in works Anantharaman *et al.* (2019), Fang & Cui (2020), Zhang *et al.* (2022).

Predicting the fatigue life of the main engine cylinder head and taking into account accurate and acceptable models is discussed by Jing *et al.* (2022).

Detection and elimination of marine diesel engine failures based on real-time diagnostic signals, i.e., symptoms and their relationship to failures in an extended form with symptom onset time tracking and based on human expert heuristic knowledge, is discussed by Sánchez-Herguedas *et al.* (2021), and for more accurate identification of wear defects, a multi-model fusion system based on the rule of evidentiary reasoning is proposed (Xu *et al.*, 2020).

The article by Lazakis *et al.* (2018) proposes a systematic approach to the identification of critical systems/components of ship equipment and the analysis of their physical parameters. Critical systems/components of the ship's main engine are used as inputs to a dynamic time series neural network to monitor and predict future values of physical parameters associated with critical ship systems.

The development of a 4-stroke high-speed marine diesel engine used on military and civilian vessels as a main engine is described in work Pagán Rubio *et al.* (2018). The failure simulator is based on a one-dimensional thermodynamic model developed, adjusted and validated with experimental data from a real engine on a test bench. The novelty of this work is the applied methodology that combines asset expertise, methodology and failure modeling to obtain an accurate and reliable database for failure prediction, which is a key element of diesel engine failure.

The authors Sánchez-Herguedas *et al.* (2022) presented a new method for calculating the optimal time interval before preventive maintenance and developed a mathematical expression represented by a system of differential equations.

In their study, Zhang *et al.*, (2022) analyze relevant data collected from various sources to determine the most plausible failure model representing a particular component. The collected data and the developed model will be very useful for assessing the reliability of ship engines and planning maintenance activities on board the ship. This can lead to a reduction in marine engine failures, which will ultimately contribute to a reduction in accidents in the shipping industry.

The purpose of the study is to study the operating conditions of the main power plants, to determine and forecast the probability of an emergency failure in any period of time, as well as the probability that there will be no emergency failures for the entire period or an emergency failure will occur in the first transition.

MATERIALS AND METHODS

A systematic approach and a probabilistic statistical method were used to obtain empirical formulas that allow determining the probability that there will be no emergency failures during the entire period or that an emergency failure will occur on the first transition and to predict the probability of emergency failures of parts of the cylinder-piston group of the main engines.

It is presented that the ship's main diesel engine is a sequence of chains of N elements (parts or assembly units), the reliability of which depends on the overall failure-free operation of the engine.

First, the law of the distribution of random failures of elements is determined, which is expressed by the reliability function – the probability of trouble-free operation P(t) for the time from 0 to the moment t, as well as the time of operation, wear and failure of each element, separately for the following cases: 1 – failure with replacement, where it is possible to determine the time after which all the initially delivered parts will fail, i.e. the term of their work; 2 – failure with replacement and recovery, where the parts that failed are replaced with new ones, so there will be mixed parts in the work. This will allow you to calculate the number of failures of parts of this type for a given period of time.

Knowing the laws of distribution (the number of accident-free transitions during the normative period), we find the mathematical expectation - the average number of error-free transitions. The time interval T can be considered random, since its choice did not require the condition that T is the standard service life, and it can be replaced by any time interval from the start of operation to the moment t. Then it is necessary to calculate for engine cylinder liners. Having obtained the result, it can be argued that at the current rate of failure of the bushings, none of them will reach the wear limit.

Significant wear occurs when starting and revving the engine. This additional wear is quantified based on the number of starts and reverses.

To maintain reliability at a sufficiently high level at time points t1, t2,..., ti, the number of preventive inspections and repairs is determined. They must be performed during parking time so that the running time is not affected.

The failure data together with the failure time is used, comparing the preventive interval obtained after applying the methodology with the interval obtained when only the failure data without hours of attendance are known. As a result, there is a need to compare the exponent calculation for cylinder sleeves with the average data to determine the adequacy and validity of our dependencies.

Having determined the time loss due to failures of each part for the entire inter-repair period or the number of failures of parts, it is possible to estimate the full cost of operational time for failures at sea (in hours), which is one of the main factors that affect the cost of transportation and maintenance of main diesel engines in trouble-free operation work.

RESULTS

A diesel turbopiston engine is considered as a sequential chain of N elements (parts or assembly units), the reliability of which depends on the overall reliability of the engine. Reliability of system elements mainly depends on random failures, basic wear and tear during operation, additional wear and tear during start-ups.

Accidental failures of diesel engine system elements are the primary danger during operation, because some parts (for example, cylinder liners and pistons) are replaced, as a rule, during repairs. On the other hand, accidental failures are not eliminated by the preventive service. That is why, in the general problem of diesel engine reliability assessment, the mathematical problem of reliability and durability assessment taking into account only random failures of its elements has the greatest practical importance.

The law of the distribution of random failures of elements is expressed by the reliability function - the probability of failure-free operation $P(t)$ for the time from 0 to the moment t:

$$P(t)=\exp(-\alpha t), \tag{1}$$

where t – time in thousands of hours; α – coefficient of the exponential law of parking time distribution.

The rate of wear of the cylinder liners during operation will be assumed to be constant and independent of accidents, which is natural for the period of normal operation. The amount of wear ξ during one transition is a random variable ($\xi=v\cdot\tau$) with an exponential distribution law:

$$f(x)=\lambda exp(-\lambda x). \tag{2}$$

Here $\lambda = \frac{\beta}{v}$, $x \geqslant 0$; β – the coefficient of the exponential law of the transition time distribution.

For the following decisions, it is necessary to have the value of α, which refers to the details we need under different conditions. Note that the failure exponent should be determined for the relative proportion of parts that fail. If there is an information about z_s of ships, and the ship's engine has z_c of parts of this type, then their total number is equal to the product of $z_s z_c$. The number of failures in any interval of the statistical series is determined by the ratio $m_i/(z_s z_c)$.

The final expression will be written in the following form:

$$exp(-\alpha t) = 1 - \frac{m_i}{z_s z_c}. \tag{3}$$

Hence, for the given value of t, there is an opportunity to find the value of α for the following cases:

1. Rejection with replacement of α_z. It is possible to determine the time after which all the initially supplied parts will fail, i.e. the term of their operation.

2. Failure with replacement and restoration of α_v. The parts that failed are replaced with new ones, so there will be mixed parts in the work. This will make

it possible to calculate the number of failures of parts of this type for a given period of time (mixed failures).

The value of α for the main engines of some types of vessels is given in Table 1.

Table 1. *The value of α for the main engines of some types of ships*

Ships series	Value $\alpha\cdot10^{-2}$, 1/thousands of hours		
	cylinder liners	pistons	cylinder covers
"Simferopol"	2.08/3.38	2.08/2.40	–
"Murom"	2.80/3.38	2.70/3.04	3.13/3.46
"Lysychansk"	1.75/2.38	–	–
TR "Ostriv Rosiyskiy"	0.47/0.74	0.75/1.21	0.87/0.87

Note: *The numerator is the value of α_z, the denominator is α_v*
Source: *author's development*

Currently, shipping companies and administrations have introduced a four-year period of operation of ships between factory repairs, so the reliability calculation for this period is of undoubted interest. The working time corresponding to this period will be determined, as it is called, normative.

Knowing the laws of distribution of the value of η_m (the number of accident-free transitions during the regulatory period):

$$P(\eta_m = k) = \frac{a^k(1-a)}{(k-1)!}[k, (\alpha+\beta_n)T_n] + \\ +a\frac{(\beta_n T_n)^k}{k!}exp[-(\alpha+\beta_n)T_n]; \qquad (4)$$

$$P(\eta_m = 0) = \frac{\alpha}{\alpha+\beta_n}exp[-(\alpha+\beta_n)T_n]. \qquad (5)$$

There is an opportunity to find the mathematical expectation – the average number of error-free transitions:

$$M\eta_m = \frac{\beta}{\alpha}[1 - exp(-\alpha T)]. \qquad (6)$$

Formulas (4) and (5) give the final solution to the problem. The first formula gives the probability that there will be no failures during the entire period, and the second – that the failure will occur on the first transition.

Expression (6) can be represented in the form:

$$M\eta_m = Q(T)\cdot M\eta. \qquad (7)$$

That is, the average number of failure-free transitions for the normative period T is equal to the multiplication of the probability of a random failure during this period by the average theoretical number of failure-free transitions.

In formulas (6) and (7), the time interval T is considered random, since its selection did not require the condition that T is the standard service life, and it can be replaced by any time interval from the start of operation to the moment t.

For cylinder liners of vessel engines, the calculation according to formula (8) gives the result (values of coefficients α, β, b and λ are given in Table 2).

Table 2. *Values of coefficients $\alpha, \beta, b, \lambda$*

Ships series	α_z, 1/(thousands of hours)	β, 1/(thousands of hours)	*b*, mm	λ, 1/mm
"Simferopol"	0,0208	5,75	6,5	261
"Murom"	0,0280	7,00	6,5	279
"Lysychansk"	0,0175	3,40	7,0	170
TR "Ostriv Rosiyskiy"	0,0047	7,40	4,5	7350

Source: *author's development*

That is, at the current rate of bushing failure, none of them will reach the wear limit. This statement is also true for pistons.

As you know, significant wear and tear occurs when starting and revving the engine. This additional wear is quantified based on the number of starts and reverses. For example, for transport refrigerated vessels (TR) of the "Kamchatka Mountains" type, the additional time proportional to wear on maneuvers (during docking) is 870 hours or 38% of working time. This value is 800 hours or 20% of the average annual working hours on dry cargoes of the "Morom" series.

The probability of failure-free operation of the element before its replacement at the specified level "b" of the wear limit is:

$$P(b) = \left(\frac{\beta}{\alpha+\beta}\right) exp\left(-\frac{\alpha\lambda\beta}{\alpha+\beta}\right). \qquad (8)$$

Indeed, the average time to reach the wear limit, expressed in the number of transitions, can be defined as:

$$M(b)=\lambda\cdot b. \tag{9}$$

The calendar time of reaching the wear limit (in hours and thousands of hours) is found from the expression:

$$T_k = \frac{M(b)}{k}, \tag{10}$$

where k is the average annual number of conversions.

Finally, there will be a period of random failure of the cylinder liners due to accidental breakages:

$$T_{vc} = \frac{4.6}{\alpha_z}. \tag{11}$$

The values of the numbers included in formulas (9)-(11) are given in the Table 3.

The time to reach the limit of wear is such that the bushings are discarded much earlier than necessary, and their wear period will exceed another period between factory repairs (four years).

Table 3. *Values of quantities M(b), T_k, T_{vc}*

Ships series	$M(b)$, transitions	T_k		T_{vc}, thousands of hours
		years	thousands of hours	
“Simferopol”	1700/1410	69.0/57.0	290/240	221
“Murom”	1830/1500	65.5/53.5	262/214	164
“Lysychansk”	1190/995	59.0/49.3	352/294	263

Source: *author's development*

Thus, the main safety during operation, in particular directly during transitions, is created by accidental (emergency) failures that cause stops (delays) at sea to eliminate them. This leads to an unproductive waste of time, increasing the transition time. In addition, sometimes it is necessary to finish the transition or even travel at a reduced speed after eliminating a malfunction at sea.

Various parts and assemblies can fail in main engines at sea. An example of indicators for transportation of refrigerators and dry cargo is given in Table 4.

Table 4. *Indicators for transport refrigerated and dry cargo vessels*

Parts and assembly units of main engines	Refusals in the sea	
	Quantaty	Percentage of the total
TR “Ostriv Rosiyskiy”:		
High pressure fuel pumps	396	53.0
Injectors	227	30.0
TR “Sea of Okhotsk”:		
Injectors	102	16.0
Cylinder cover	89	14.0
High pressure fuel pumps	84	13.5
“Murom”:		
Injectors	56	26.0
Bearings	51	24.0

Source: *author's development*

The average indicators of the number of failures, warnings and disclosure of the main parts and assembly units of the main engines of the ships of the “Murom” series at sea are shown in the Table 5.

Table 5. *Average indicators of the number of failures, prevention of parts of the main engines of the "Murom" series ships at sea*

Detail of the assembly unit Injectors	Values			
	Δn_{ms}	Δn_{tr}	T_{ms}	T_{tr}
Bearings	0.3800	0.1680	2.63	5.95
Piston-sleeve	0.3460	0.2380	2.89	4.20
Fuel pumps	0.2720	0.7760	3.67	1.29
Cylinder covers	0.1360	0.1145	7.35	8.74
Outlet valves	0.1220	0.2415	8.20	4.15
Gas turbochargers	0.0952	0.1350	10.50	7.40
Telescopic pistons	0.0340	0.2210	29.40	4.53
Detail of the assembly unit	0.0340	0.1520	29.40	6.58

Source: *author's development*

They are obtained by calculations according to the formulas:

$$\Delta n_{ms} = \frac{n_m}{z_s \cdot T_{avg}}; \; \Delta n_{tr} = \frac{n_{tr}}{z_s \cdot T_{avg} \cdot z_c};$$

$$T_{ms} = \frac{1}{\Delta n_{ms}}; \; T_{tr} = \frac{1}{\Delta n_{tr}}. \qquad (12)$$

Here, Δn_{ms} is the number of failures at sea for one vessel per 1,000 hours of operation; n_m – the number of failures at sea; z_s – number of vessels; T_{avg} – vessel operating time, thousand hours; Δn_{tr} – number of disclosures and warnings per element per 1,000 hours of work; n_{tr} – number of cases of discovery, transfer and prevention on the dock; z_c – the number of parts of this type of engine; T_{ms} – the average operating time of the vessel between element failures, thousand hours; T_{tr} – the average operating time of the element between opening and warning, thousand hours.

The probability of failure-free operation of the part during the standard time is determined by the formula:

$$P(T_n)=exp(-\alpha_v T_n), \qquad (13)$$

where α_v is the rate of failures with replacement and restoration, 1/(thousand hours), see Table 1; T_n – standard time, thousands of hours. The values of parts of the cylinder-piston group of ships of the "Simferopol", "Murom" and "Ostriv Rosiyskiy" series are given in the Table 6.

Table 6. *Values of $P(T_n)$ for parts of the cylinder-piston group of ships of the "Simferopol", "Murom" and "Ostriv Rosiyskiy" series*

Details	Time intervals, thousands of hours	$P(T_n)$		
		"Simferopol"	"Murom"	"Ostriv Rosiyskiy"
Cylinder bushings	0-8 0-16 0-32	0.763 0.583 0.340	0.763 0.583 0.340	0.943 0.888 0.790
Pistons	0-8 0-16 0-32	0.825 0.682 0.464	0.784 0.616 0.379	0.908 0.823 0.678
Cylinder covers	0-8 0-16 0-32	– – –	0.758 0.574 0.330	0.880 0.774 0.599

Source: *author's development*

The average number of accident-free transitions during the standard period is determined by formula (6). The average number of transitions for the established period between factory repairs is based on statistical information about the operating experience. It is equal to 112 and 32, respectively, during the four-year period of operation of the ships of the "Murom" and "Ostriv Rosiyskiy" series. The above dependencies allow you to calculate the number of failures.

The number of element failures that may occur during the established repair period can be determined by the formula:

$$z = \frac{M_{per}}{M\eta_t} = \frac{M_{per}}{\frac{\beta}{\alpha}[1 - exp(-\alpha_v T_{n)}] + 1}\,. \qquad (14)$$

The values of the average number of accident-free transitions and the number of failures of engine parts of the above-mentioned vessels are given in the Table 7.

Table 7. *The value of the average number of accident-free transitions and the number of failures of engine parts of dry cargo and transport refrigerated ships*

Time intervals, thousands of hours	$M(T_n)$			z, pcs		
	"Simferopol"	"Murom"	"Ostriv Rosiyskiy"	"Simferopol"	"Murom"	"Ostriv Rosiyskiy"
Cylinder bushings						
0–8	40.2	49.0	57.2	2.40/2.0	2.30/2.0	0.55/1.0
0–16	71.0	86.5	113.0	1.40/1.0	1.30/1.0	0.28/0
0–32	112.0	137.0	212.0	0.88/1.0	0.82/1.0	0.82/1.0
Pistons						
0–8	42.0	49.7	56.0	2.36/2.0	2.25/2.0	0.56/1.0
0–16	76.0	88.5	108.0	1.30/1.0	1.27/1.0	0.28/0
0–32	128.0	143.0	196.0	0.78/1.0	0.78/1.0	0.16/0
Cylinder covers						
0–8	–	48.0	56.0	–	2.33/2.0	1.57/1.0
0–16	–	86.0	104.0	–	1.30/1.0	0.31/0
0–32	–	136.0	181.0	–	0.83/1.0	0.17/0

Note: *in the denominator is the number of refusals accepted for calculation*
Source: *author's development*

Comparing the calculation based on the exponent for cylinder sleeves with the average data in the Table 5. The running time of the "Murom" series vessel over four years of operation is T_n=16 thousand hours. Then the probability of failures will be Q(16)=1-exp(-0.28·16)=0.36. So, out of six engine bushings (on one vessel), bushings will fail and need to be replaced. This will cause two vessel delays at sea. The average time between exits is thousand hours. According to the Table 5, it is possible to calculate that bushing and piston failures are distributed equally, the average working time between failures will be equal to 2·3.67=7.34 thousand hours, that is, a little more than the calculated one. This ratio is also valid for pistons.

For cylinder covers, the ratio between the calculation results and the data in the Table 5 will be different. Indeed, for T_n=16 thousand hours there will be: Q(16)=1-exp(-0.0313·16)=0.39.

Therefore, 0.39·6=2.34 covers need to be replaced. The average time of operation of the cover between failures will be 16·2.34=6.85 thousand hours, which is less than the data in the Table 5. This is explained by the fact that covers that have received water flow can be replaced at the parking lot, and this does not lead to delays at sea. At the same time, it should be noted that the calculation results and the data in the Table 5 are close to each other.

Estimated data for the "Ostriv Rosiyskiy" TR (at the value of running time for 4 years of operation T_n =10 thousand hours) are given in Table 8.

Table 8. *Calculation data for TR type "Ostriv Rosiyskiy"*

Indexes	Cylinder-piston group of ships		
	Cylinder bushings	Piston cylinder covers	Piston cylinder covers
Failure probability Q(10)	$1\text{-}e^{-0.0087\cdot 10}=0.09$	$1\text{-}e^{-0.0075\cdot 10}=0.073$	$1\text{-}e^{-0.00787\cdot 10}=0.05$
Number of failures	0,09·24=2.16	0.073·24=1.75	0.05·24=1.2
Average time between failures, thousands of hours	10/2.16=4.64	0/1.75=6.45	10/1.2=8.30

Source: *author's development*

The main negative result of failures at sea is the loss of operational time. For example, the average time of forced stops, obtained by averaging information on vessels of the "Murom" series, ranges from 0.5 to 4 hours. The loss of time due to failures of each part for the entire inter-repair period is (in hours) $\tau_{ei}=z_i\cdot\tau_i$. Here z_i is the number of part failures.

The total cost of operational time for failure at sea (in hours):

$$\tau_{\Sigma tl}=\sum_{i=1}^{n} z_{\mathrm{i}}\cdot\tau_{i}. \tag{15}$$

Damage (thousand hryvnias) arising from forced downtime at sea due to failures:

$$R=C\cdot\tau_{\Sigma tl}. \tag{16}$$

Here C – the cost of maintaining one vessel during the day, thousand hryvnias.

As an example, let's calculate the damage only for parts of the cylinder-piston group (piston, bushing, cover) of vessels of the "Murom" series over a period of 4 years. Taking into account that two of the named parts fail in a year, and the time spent on each output for bushings and pistons is 4 hours, for covers – 2.3 hours, we get for a four-year period: $R=2.98\,\frac{4}{24}$ (2·4+2·4+2·2.3)=10.23 thousand UAH.

DISCUSSION

The researchers Xu *et al.* (2020) proposed a multi-model fusion system for more accurate identification of wear defects. Authors agree that it is necessary to consider marine diesel engines, which consist of many tribological systems, such as cylinder liner-piston ring system, main bearing system, and that almost 50% of engine failures are caused by abnormal wear of friction pairs, the authors also consider a chain sequence of N elements (parts or assembly units), the reliability of which depends on the overall health of the engine.

The authors Sánchez-Herguedas *et al.* (2022) proposed a method for detecting and eliminating ship diesel engine failures, based on real-time diagnostic signals and on the basis of human expert heuristic knowledge, which may not provide fully accurate information about the true state of the parts and underestimate the period of trouble-free operation. However, the authors of the study derived dependencies that allow determining the probability of fault-free operation of elements based on statistical data.

In the research paper (Vera-García *et al.*, 2019), authors use a methodology that combines expert knowledge of the object and modeling of technical inspection to obtain an accurate and reliable database for predicting diesel engine failures based on a failure simulator. Lazakis *et al.* (2018) proposed a systematic approach to the identification of critical systems, components of the ship's main engine are used as input data to a neural network of dynamic time series for monitoring and forecasting future values of physical parameters related to critical ship systems. Zhang *et al.* (2022) propose a method for reconstructing dynamic fault trees to find weak links at the component level. Basurko *et al.* (2022) presented engine performance monitoring and fault detection to create a three-layer forward neural network of engine operation. Kowalski *et al.* (2017) presented an experiment consisting of measurements made during the operation of a laboratory engine with simulated faults to create a classification of fault patterns. The authors Rao *et al.* (2022) propose online condition monitoring and self-healing for in-service diesel CLPRs from a tribosystem perspective in a real-time maintenance context. However, the authors of the study use a probabilistic statistical method, which is a faster way to determine the prediction of diesel engine failures. The study of the operational reliability of the main engines of marine transport vessels was carried out taking into account the operating conditions and load level. The applied restoration theory apparatus is most convenient in the conditions of engine operation with alternating transitions and ship stops.

Trampert *et al.*, (2008) in their article predict the fatigue life of the cylinder head of the main engine. The authors similarly investigated the ultimate wear of the sleeve. In addition, the authors considered the joint effect of semi-random and random failures: main wear during running time; additional wear during maneuvering time associated with parking lots; accidental (emergency) failures.

The authors Anantharaman *et al.* (2019) are suggested to draw up an optimal maintenance plan taking into account the advice of engine manufacturers and/or chief engineers and ship captains. The authors obtained empirical formulas that allow determining the probability of work for the entire period or at the first transition. This method of calculation: the number of failures, stops at sea with or without replacement, emergency failures of parts of the cylinder-piston group. For this purpose, the value of the failure exponent indicator is determined for several cases: failure with replacement, which allows you to trace the gradual failure of the initial group of parts. It is possible to determine how long it will take for all initially delivered parts to fail, i.e. trace their service life; failure with replacement and recovery. Rejected parts are replaced with new ones, so there will be a mixed composition of parts in the work. This allows you to determine the number of failures of parts of a given type in a given period of time (mixed failures), failures with replacement and stoppage at sea; failure without replacement, but with a stop at sea.

CONCLUSIONS

The diesel turbopiston engine was considered as a sequential chain of N elements (parts or assembly units). The overall reliability of the engine depends on its reliability. On the basis of operational experience, it was established that the reliability of the system elements, for the most part, depends on random failures, basic wear and tear during operation, and additional wear and tear during start-ups.

The elements that make up the marine engine system, which are considered, work in conditions defined by various distribution laws, which are established during the statistical processing of information obtained from operational documents.

The given dependencies allow you to determine the probability of failure-free operation of the element before its replacement and the probability of failure-free operation of the part during the standard time.

It has been proven that the case of simultaneous action on an element (for example, on a cylinder sleeve) of factors that cause wear during the period of operation (including during the start-up period) and accidental failures is common and difficult. Other elements of the system under consideration correspond to the same complex of conditions or its partial case.

The calculation showed that the probability of failure-free operation of parts of the cylinder-piston group for the standard time of 8 and 32 thousand hours in the vessel of the "Ostriv Rosiyskiy" type is 0.943 and 0.790, respectively, and in the dry cargo vessels of the "Simferopol" and "Murom" series – 0.763 and 0.340 , which indicates higher quality details in the first type of vessels.

It has been studied that when the elements of the system reach the limit of wear during the set period of operation, between factory repairs is practically excluded, so the main danger during the period of operation is accidental failures. The period of accidental failure of cylinder liners is determined.

Empirical formulas were obtained for the first time, which make it possible to determine the probability that there will be no emergency failures during the entire period; that a failover will occur on the first transition.

Taking into account the different reliability of elements of the marine engine system, which affect the behavior of the control system as a whole, the results make it possible to establish the periodicity of their maintenance and the cost of downtime losses due to failures.

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CONFLICT OF INTEREST

The authors declare that the study was conducted in the absence of any commercial or financial relationships that could be interpreted as a potential conflict of interest.

REFERENCES

[1] Anantharaman, M., Islam, R., Khan, F., Garaniya, V., & Lewarn, B. (2019). Data analysis to evaluate reliability of a main engine. *TransNav*, 13(2), 403–407. doi: 10.12716/1001.13.02.18.

[2] Antonić, R., Vukić, Z., & Kuljača, O. (2003). Marine diesel engine faults diagnosis based on observed symptoms and expert knowledge. *IFAC Proceedings Volumes*, 36(21), 133-138. doi: 10.1016/s1474-6670(17)37796-0.

[3] Aziz, A., Ahmed, S., Khan, F., Stack, C., & Lind, A. (2019). Operational risk assessment model for marine vessels. *Reliability Engineering & System Safety*, 185, 348-361. doi: 10.1016/j.ress.2019.01.002.

[4] Basurko, O.C., & Uriondo, Z. (2015). Condition-based maintenance for medium speed diesel engines used in vessels in operation. *Applied Thermal Engineering*, 80, 404-412. doi: 10.1016/j.applthermaleng.2015.01.075.

[5] Fang, C., & Cui, L. (2020). Reliability analysis for balanced engine systems with m sectors by considering start-up probability. *Reliability Engineering & System Safety*, 197, 106829. doi: 10.1016/j.ress.2020.106829.

[6] Jing, G., Li, S., Chen, G., Wei, J., Sun, S., & Zhang, J. (2022). Research on creep test of compacted graphite cast iron and parameter identification of constitutive model under wide range of temperature and stress. *Applied Sciences*, 12(10), 5032. doi: 10.3390/app12105032.

[7] Kowalski, J., Krawczyk, B., & Woźniak, M. (2017). Fault diagnosis of marine 4-stroke diesel engines using a one-vs-one extreme learning ensemble. *Engineering Applications of Artificial Intelligence*, 57, 134-141. doi: 10.1016/j.engappai.2016.10.015.

[8] Lazakis, I., Raptodimos, Y., & Varelas, T. (2018). Predicting ship machinery system condition through analytical reliability tools and artificial neural networks. *Ocean Engineering*, 152, 404-415. doi: 10.1016/j.oceaneng.2017.11.017.

[9] Mihanović, L., Karna, H., & Matika, D. (2021). Research, processing and analysis of exploitation reliability results of high-speed radial diesel engine. *Engineering Review*, 41(2), 136-150. doi: 10.30765/er.1580.

[10] Munir, A., & Shah, H. (2015). FPSO propulsion machinery reliability analysis - a systematic approach. *SNAME 20th Offshore Symposium*. Retrieved from https://onepetro.org/SNAMETOS/proceedings-abstract/TOS15/1-TOS15/D013S010R001/3729.

[11] Pagán Rubio, J.A., Vera-García, F., Hernandez Grau, J., Muñoz Cámara, J., & Albaladejo Hernandez, D. (2018). Marine diesel engine failure simulator based on thermodynamic model. *Applied Thermal Engineering*, 144, 982-995. doi: 10.1016/j.applthermaleng.2018.08.096.

[12] Rao, X., Sheng, C., Guo, Z., & Yuan, C. (2022). A review of online condition monitoring and maintenance strategy for cylinder liner-piston rings of diesel engines. *Mechanical Systems and Signal Processing*, 165, 108385. doi: 10.1016/j.ymssp.2021.108385.

[13] Sánchez-Herguedas, A., Mena-Nieto, A., & Rodrigo-Muñoz, F. (2021). A new analytical method to optimise the preventive maintenance interval by using a semi-Markov process and z-transform with an application to marine diesel engines. *Reliability Engineering & System Safety*, 207, 107394. doi: 10.1016/j.ress.2020.107394.

[14] Sánchez-Herguedas, A., Mena-Nieto, Á., & Rodrigo-Muñoz, F. (2022). A method for obtaining the preventive maintenance interval in the absence of failure time data. *Maintenance and Reliability*, 24(3), 564-573. doi: 10.17531/ein.2022.3.17.

[15] Trampert, S., Gocmez, T., & Pischinger, S. (2008). Thermomechanical fatigue life prediction of cylinder heads in combustion engines. *Journal of Engineering for Gas Turbines and Power*, 130(1), 012806. doi: 10.1115/1.2771251.

[16] Ünver, B., Altın, İ., & Gürgen, S. (2021). Risk ranking of maintenance activities in a two-stroke marine diesel engine via fuzzy AHP method. *Applied Ocean Research*, 111, 102648. doi: 10.1016/j.apor.2021.102648.

[17] Vera-García, F., Pagán Rubio, J.A., Hernández Grau, J., & Albaladejo Hernández, D. (2019). Improvements of a failure database for marine diesel engines using the RCM and simulations. *Energies*, 13(1), 104. doi: 10.3390/en13010104.

[18] Xu, X., Zhao, Z., Xu, X., Yang, J., Chang, L., Yan, X., & Wang, G. (2020). Machine learning-based wear fault diagnosis for marine diesel engine by fusing multiple data-driven models. *Knowledge-Based Systems*, 190, 105324. doi: 10.1016/j.knosys.2019.105324.

[19] Zhang, M., Liu, S., Hou, X., Dong, H., Cui, C., & Li, Y. (2022). Reliability modeling and analysis of a diesel engine design phase based on 4F integration technology. *Applied Sciences,* 12(13), 6513. doi: 10.3390/app12136513.

Визначення імовірності відмов деталей суднових дизельних двигунів

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Анотація. Морські перевезення є суттю міжнародної економіки. Сьогодні близько дев'яноста відсотків світової торгівлі здійснюється морським транспортом через 50000 торгових суден. Більшість цих суден приводиться в рух головними дизельними двигунами завдяки їх надійності та паливній ефективності. Надійність елементів системи в загальному випадку залежить від випадкових відмов, значного зносу в процесі експлуатації, додаткового зносу при пуску. Випадкова поломка компонентів дизельного двигуна є великою небезпекою під час експлуатації, оскільки деякі деталі (наприклад, втулки циліндрів і поршні) зазвичай замінюються під час ремонту. З іншого боку, профілактична служба не усуває випадкові несправності. Тому в загальній проблемі оцінки надійності дизеля – математична задача оцінки надійності і довговічності з урахуванням тільки випадкових відмов її елементів, що мають найбільше практичне значення. Метою роботи є математичне дослідження надійності деталей циліндро-поршневої групи головних двигунів суховантажних суден. Використовуючи системний підхід та ймовірносно-статистичний метод, було встановлено, що найбільш загальним і важким є випадок одночасної дії на елемент системи (наприклад на гільзу циліндра) факторів, що викликають зноси в період експлуатації (в тому числі в період пусків) і випадкові відмови. Визначено, що якість цилiндро-поршневої системи у суден типу «Острів російський» вища, ніж у суден типу «Сімферополь» і «Муром». Отримано емпіричні формули оцінки ймовірності аварійної відмови елементів системи головних двигунів за період експлуатації між заводськими ремонтами, де основну небезпеку в період роботи несли випадкові відмови. За результатами дослідження можна встановити графік періодичності проведення технічного обслуговування головного суднового двигуна та вартість збитків простоїв судна внаслідок відмов, а також можуть бути використані при дослідженні надійності інших типів суднових головних двигунів. Результати дають можливість визначити надійність роботи деталей циліндро-поршневої групи головних двигунів суховантажних суден. і, зокрема, встановити графік проведення технічного обслуговування головного суднового двигуна та вартість збитків внаслідок простоїв судна через відмови, а також можуть бути використані при дослідженні надійності інших типів головних двигунів інших серій суден

Ключові слова: знос; експлуатаційний час; втулка циліндра; поршень; кришка циліндра