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OPTIMIZATION METHOD FOR THE STRATEGY OF REGULATED MAINTENANCE OF MILITARY EQUIPMENT

***Annotation.** Complex technical objects in modern society are extremely important. Such objects belong to the class of recoverable objects of long-term multiple used. They tend to be expensive and require significant maintenance costs. To ensure the required level of reliability during their operation, maintenance is usually carried out, the essence of which is the timely preventive replacement of elements that are in a pre-failure state, which is very important for military equipment.*

A characteristic feature of complex technical objects for special purposes (military equipment) is the presence in their composition of a large number (tens, hundreds of thousands) of different types components that have different levels of reliability, different patterns of their wear and aging processes. This feature requires a more subtle approach to the organization and planning of maintenance during operation (military equipment).

The problem is that when developing such objects of military equipment, all issues related to maintainability and maintenance should be addressed already at the early stages of designing an object. If you do not provide in advance the necessary hardware and software for the built-in monitoring of the technical condition (TC) of the object, do not develop and "embed" the maintenance technology into the object, then it will not be possible to realize in the future a possible gain in the reliability of the object due to the maintenance. Since all these issues must be resolved at the stage of creating an object (when the object does not yet exist), mathematical models of the maintenance process are needed, with the help of which it would be possible to calculate the possible gain in the level of reliability the object due to maintenance, to estimate the cost costs required for this. Then, based on such calculations, make a decision on the need for maintenance for this type of objects and, if such a decision is made, develop the structure of the maintenance system, choose the most appropriate maintenance strategy, and determine its optimal parameters.

In this paper, we develop a methodology for optimizing the parameters of the strategy for regulated maintenance of military equipment.

The paper also confirms the general idea that the data obtained fully confirm assumption that the "adaptive maintenance" strategy is more preferable in the case of unreliable (inaccurate) information about the reliability indicators of the object's elements.

***Keywords:** maintenance, object of military equipment, regulated maintenance of military equipment, costs for the cost military equipment*

Introduction. Complex technical objects are understood as objects consisting of a large number of different types elements (tens, hundreds of thousands), each of which can be a rather complex technical device. Elements can be electronic, mechanical, electromechanical, hydraulic, etc. The heterogeneity of elements leads to the fact that different elements are characterized by fundamentally different physical processes (and, consequently, rates) of degradation, leading to their failure.

The objects under consideration belong to the class of repairable objects for long-term repeated use, and during their operation, maintenance is usually carried out to maintain the required level of reliability. Maintenance (MS) is understood as "a set of operations or an operation to maintain the operability or operability of an object when it is used for its intended purpose, simple, stored and transported" [1,2]. Also, when used as intended, only MS will be considered.

During operation, an object at any time can be in one of the following states: serviceable, operable, inoperable.

The object can be used for its intended purpose only in good or good condition. Restoration of a working or working condition is carried out at the expense of current repairs. The MS is usually carried out only when the object is in working order. If by the time of the start of maintenance (or in the process of maintenance) there was a complete failure, then the object is first restored, and then maintenance is carried out.

The essence of MS is to prevent some part of failures by replacing individual elements, cleaning, lubricating, adjusting, etc. (which is why MS is often called prevention). In modern technical facilities, in the vast majority of cases, maintenance is reduced to the replacement of elements (liquids, oils, etc.) that are in a pre-order state.

Analysis of the recent research. Currently, there is a decrease in the number of scientific publications devoted to the operation of complex technical objects. One of the reasons for this, in our opinion, is a sharp increase in the level of integration and reliability of components. Thanks to this, developers of complex equipment have been able to solve the problems of ensuring the required level of reliability without significant maintenance costs (or no maintenance at all). However, for the same reason (high integration and reliability of components), it became possible to implement more and more complex equipment with new functions, which was impossible with the old element base. This again objectively leads to reliability problems and, therefore, the question of need for maintenance and the choice of optimal strategy for its implementation again becomes relevant.

Unfortunately, the currently known mathematical models and methods for calculating the optimal parameters of maintenance processes are not very suitable for application to real technical objects. The main disadvantage of these models is that they either do not take into account the complex structure of the object, or it is possible to take into account only some of the simplest structures [3, 4]. In [5, 6], a comparative analysis of the problems that arise when solving maintenance problems "by resource" and "by state" is carried out. An overview of the latest work in the field of maintenance and repair of complex systems at that time. In [7], a theoretical generalization of known mathematical models of MS processes was made. However, these models do not allow one to construct a methodology suitable for practical use on their basis.

Main part. The problem of optimizing the parameters of regulated maintenance strategy, taking into account the determination of parameters, can be formally represented as follows:

$$T_0(\langle E^*_{\text{то}\,j}, T^*_{\text{то}\,j}\rangle; j=\overline{1, N^*_{\text{то}}}) \ge T_0^{\text{тр}}; \qquad 1)$$

$$c_{\text{уд}}(\langle E^*_{\text{то}\,j}, T^*_{\text{то}\,j}\rangle; j=\overline{1, N^*_{\text{то}}}) \to \min, \qquad 2)$$

where $N^*_{\text{то}}$ - is the optimal number of MS types;

$E^*_{\text{то}\,j}$ and $T^*_{\text{то}\,j}$ - optimal volume (a set of serviced elements) and the frequency of maintenance of *j*-th type.

The initial information for solving the problem is:

$E_{\text{то}}$ - set of potentially serviced elements of the given object;

$T_0^{\text{тр}}$ - specified required value of the mean time between failures, which must be ensured by carrying out maintenance.

Problem solving technology

To solve the problem, as before, it is necessary to create a database (DB) and, using the ISMPN program, enter into it all the necessary data about the object for which the problem is being solved. Determine for the object a set of potentially serviceable elements $E_{\text{то}}$.

To include elements in a set $E_{\text{то}}$, you need to open the database (run ISMPN program in the Database mode), select the required element in the structural structure tree, and then enter the “in” attribute for this element in PW column of the table.

To enter the parameters of types maintenance, it is necessary in Database mode to open the tab Parameters of service stations and maintenance systems (Fig. 1).

In the table of parameters types maintenance, enter the following data:

- name of the type maintenance;
- frequency of maintenance $T_{\text{то}\, j}$ (indicative value, since its optimal value has not yet been determined);
- duration of diagnosis during maintenance $T_{\text{д}\, j}$;
- cost of diagnosing during maintenance $C_{\text{д}\, j}$.

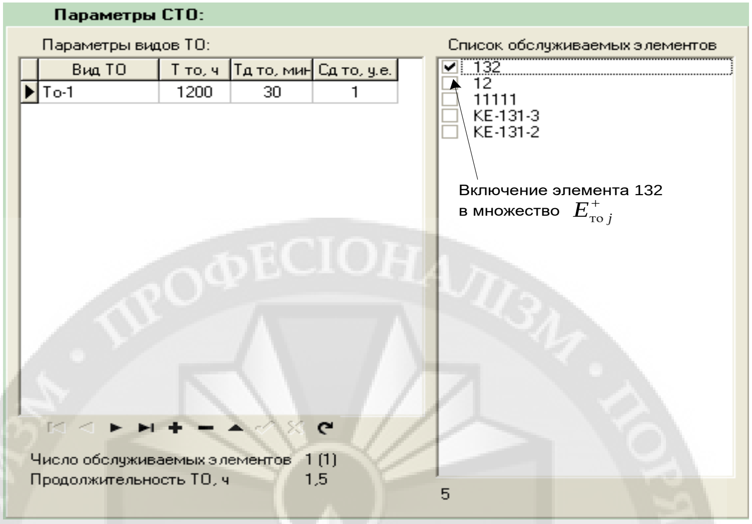

Figure 1 - Entering the parameters of maintenance $T^{+}_{\text{то}1}$ types MS-1

Then, in the list of serviced elements for the selected type $T^{(k)}_{\text{то}\, j}$ of MS, set (by mouse click) the switch to the on state for all elements that are included in the subset $T^{*}_{\text{то}\, j}$ (Fig. 1).

At the first step, one type of MS is introduced and one element is selected, which is included in the set .

The search for a conditionally optimal value $c^{(k)}_{\text{уд}}$, $T^{(k)}_{0}$ and $K^{(k)}_{\text{ти}}$ of the frequency of maintenance is performed in the mode Research MS | Regulated Maintenance. After opening this mode $T^{(k)}_{\text{то}} \geq T^{\text{тр}}_{0}$, you must do the following:

- set the parameters for varying the frequency of maintenance (initial and final values, interval);
- choose the type of maintenance, frequency of which will vary;
- click the Start button.

On fig. 2 shows PC screen after the calculation is completed.

To the right of the graphs, the value of the optimal frequency obtained in the current step is displayed, as well as the values $T^{(k)}_{\text{то}\, j}$ of the indicators , $c^{(k)}_{\text{уд}}$, $T^{(k)}_{0}$ and $K^{(k)}_{\text{ти}}$, obtained with the frequency of maintenance $T^{(k)}_{\text{то}\, j}$.

This completes the execution of the current (*k*-th) step, in which a conditionally optimal solution is obtained:

$$\mathbf{STO}^{(k)}_{R} = \left\{ \left\langle E^{*}_{\text{то}1}, T^{*}_{\text{то}1} \right\rangle, \ldots, \left\langle E^{*}_{\text{то}\, j\text{-}1}, T^{*}_{\text{то}\, j\text{-}1} \right\rangle, \left\langle E^{(k)}_{\text{то}\, j}, T^{(k)}_{\text{то}\, j} \right\rangle \right\}.$$

If the received value $T_0^{(k)}$ does not satisfy the requiremen $T_0^{(k)} \geq T_0^{\text{тр}}$t, the next step is performed. In the set $E_{\text{то}\,j}^{(k)}$, you need to add the next element $E_{\text{то}}$ from . To do this, switch to the Database mode and select the next element in the list of serviced elements for the current maintenance type (by turning on the switch, as shown in Fig. 1).

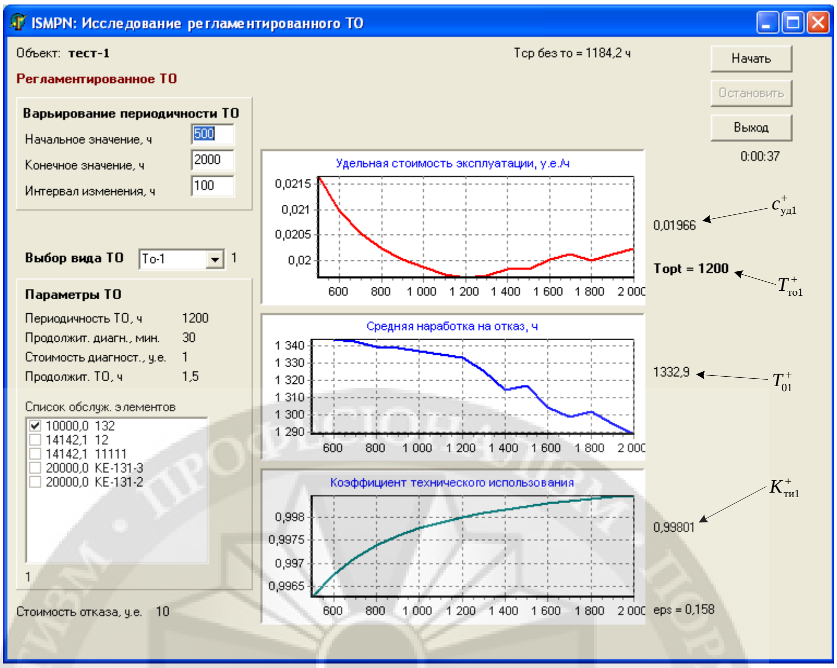

Figure 2 - Completion of the search for optimal frequency of maintenance $T_{\text{то}1}^{+}$ for the type of MS-1

When moving to the next type of MS, the frequency value $T_{\text{то}\,j}^{(k)}$ obtained in the last step must be entered into the table as the found optimal value $T_{\text{то}\,j}^{*}$.

After that, switch back to the Maintenance Research | Scheduled maintenance and re-calculate to determine the optimal frequency and the corresponding values $T_{\text{то}\,j}^{(k)}$ of the indicators , $c_{\text{уд}}^{(k)}$, $T_0^{(k)}$ and $K_{\text{ти}}^{(k)}$.

Repeat the calculations until the condition is met. Take the decision obtained in the last step as a solution $T_{\text{то}}^{(k)} \geq T_0^{\text{тр}}$ to the problem.

Below is a specific example of solving the problem.

An example of the application of the technique.

For example, we use the Test-1 test object, the data on which was given above. Next, we will make calculations in accordance with the technology described above.

At the 1st step, we set the set $E_{\text{то}1}^{(1)}$={132}. As a result of calculations at the 1st step, we obtain a conditionally optimal value of the periodicity of MS $T_{\text{то}1}^{(1)}$=1300 hours. In this case, the following values of indicators are obtained (Fig. 3):

$$c_{\text{уд}}^{(1)} = 0{,}01964 \text{ c.u./h}; \quad T_0^{(1)} = 1335 \text{ h.}; \quad \text{and } K_{\text{ти}}^{(1)} = 0{,}99801.$$

At the 2nd step, we include the next element in the set $E_{\text{то}1}^{(1)}$, after which we get the set $E_{\text{то}1}^{(2)}$ ={132, 12} (Fig. 4).

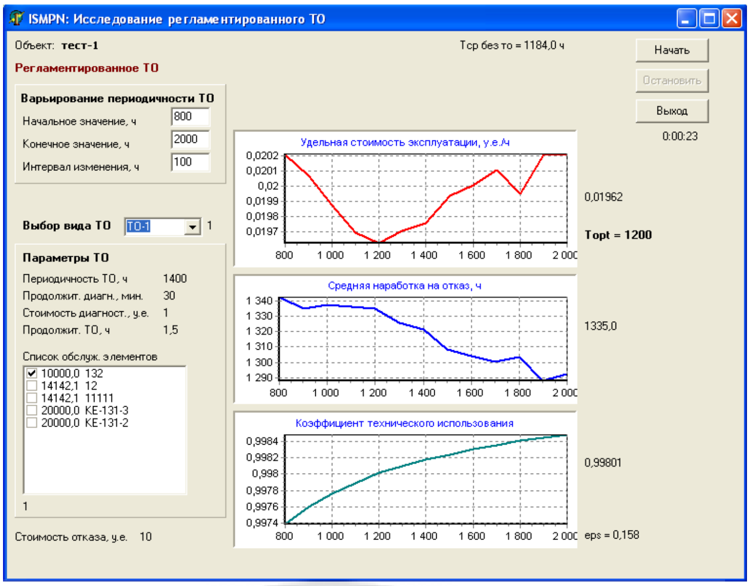

Figure 3 - Completion of calculations at 1-st step of the search (object Test-1)

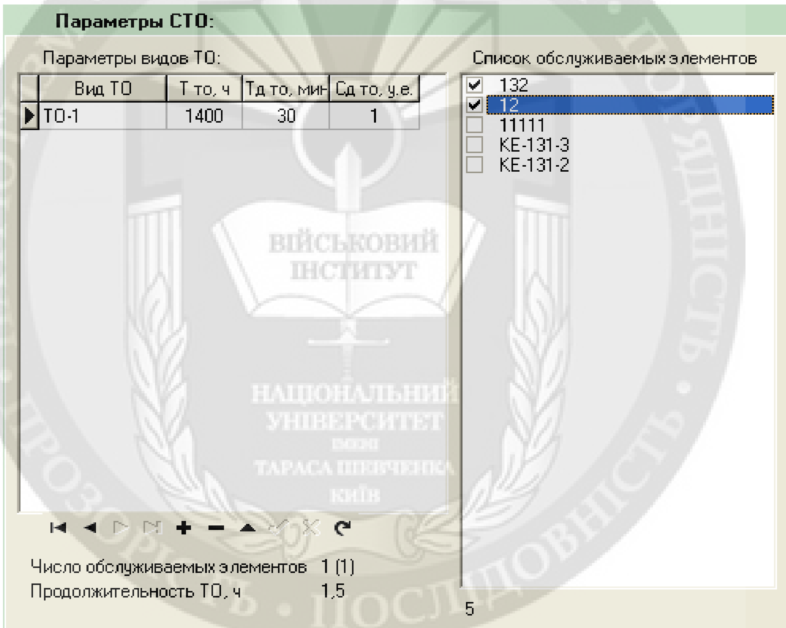

Figure 4 - Inclusion in the set of second element (object Test-1)

Further, in a similar way, we will make calculations for one type of MS with inclusion in all elements $E_{\text{то}}$ from $E_{\text{то}1}^{(k)}$. The calculation results are summarized in Table 1.

Table 1

Calculation results of conditionally optimal parameters of regulated maintenance (object Test-1)

Step number k	Maintenance type number j	Conditionally optimal parameters $\left\langle E_{\text{то}\,j}^{(k)}, T_{\text{то}\,j}^{(k)} \right\rangle$		Values of indicators obtained with conditionally optimal parameters $\mathbf{STO}_R^{(k)}$			
		$E_{\text{то}\,j}^{(k)}$	$T_{\text{то}\,j}^{(k)}$, h	$T_0^{(k)}$, h	$c_{\text{уд}}^{(k)}$, c.u./h	$K_{\text{ти}}^{(k)}$	ε
1	1	{132}	1300	1335	0,01962	0,99801	0,158
2	1	{132,12}	1300	1465	0,01827	0,99741	0,170
3	1	{132,12, 11111}	1400	1609	0,01695	0,99689	0,184
4	1	{132,12, 11111, 131-1}	1400	1756	0,01657	0,99623	0,190
5	1	{132,12, 11111, 131-1,131-2}	1400	1932	0,01619	0,99557	0,196

The presented results provide comprehensive information on the possibilities of improving the reliability of the object Test-1 due to regulated maintenance.

So, if, for example, the required value of the mean time between failures is set equal to $T_0^{\text{тр}}$ =1500 h, then the optimal solution is 1 type of maintenance with the parameters:

$$\mathbf{STO}_R^* = \{\langle\{132,12,11111\},1400\text{h}\rangle\}.$$

This results in the following values:

$c_{\text{уд}}^*$ = 0,01695 c.u./h; T_0^* = 1609 h.; and $K_{\text{ти}}^*$ = 0,99689.

Based on the results obtained, the following conclusions can be drawn:

1. The MS strategy is considered the best if the graph of the function T_0^+ is higher (for the function $c_{\text{уд}}^+$ - lower) in relation to the corresponding graph for the compared strategy. The maintenance strategy that is best in terms of T_0^+, as a rule, is also the best in terms of , $c_{\text{уд}}^+$ and vice versa.

2. The effectiveness of various maintenance $\mathbf{STO}^*$ strategies significantly depends on the reliability T_0 and $c_{\text{уд}}$ cost structure of the object $T_{\text{ср}\,i}$. If the distribution of the cost of repairable (including serviceable) elements is closely correlated with the distribution of their reliability indicators, the difference in the effectiveness of various maintenance strategies is reduced. This is clearly seen in the example of Test-2 object, for which the least reliable elements are also the most expensive.

We will also calculate the indicators for test objects in the case when the average time to failure of all recoverable elements is 2 times less compared to the indicators for which the parameters of the optimal maintenance strategy were calculated.

Obviously, the indicators obtained in this case T_0' and $c_{\text{уд}}'$ should be worse than the indicators T_0 and $c_{\text{уд}}$ obtained with the initial values of $T_{\text{ср}\,i}$. Tables 2 and 3 show the values of the coefficients of relative losses in the level of reliability δ_{T_0} and in the specific cost of operation $\delta_{C_{уд}}$, which were determined by the formulas:

$$\delta_{T_0} = \frac{T_0 - T_0'}{T_0} \cdot 100; \quad \delta_{C_{уд}} = \frac{c_{уд}' - c_{уд}}{c_{уд}} \cdot 100,$$

where T_0 ($c_{уд}$) - is the mean time between failures (specific cost of operation) obtained under optimal parameters $\mathbf{STO}^*$, provided that the indicators $T_{\text{ср}\,i}$ correspond to the values specified for test objects in test cases;

T_0' ($c_{уд}'$) - same indicators obtained with optimal parameters $\mathbf{STO}^*$, but under the condition that the indicators $T_{\text{ср}\,i}$ in the initial data are reduced by 2 times.

Table 2

Relative loss ratio of reliability level δ_{T_0} (in %)

Maintenance strategy	Technical object			
	Test-1	Test-2	Test-3	Test-4
MS by condition	52	53	67	79
Adaptive MS	49	49	63	56
MS on resource	55	59	69	82

Table 3

Relative loss ratio of unit cost operations $\delta_{C_{уд}}$ (in %)

Maintenance strategy	Technical object			
	Test-1	Test-2	Test-3	Test-4
MS by condition	110	144	187	192
Adaptive MS	98	100	167	117
MS on resource	121	712	185	166

In Fig. 5 and 6 these same coefficients are shown in the form of graphs.

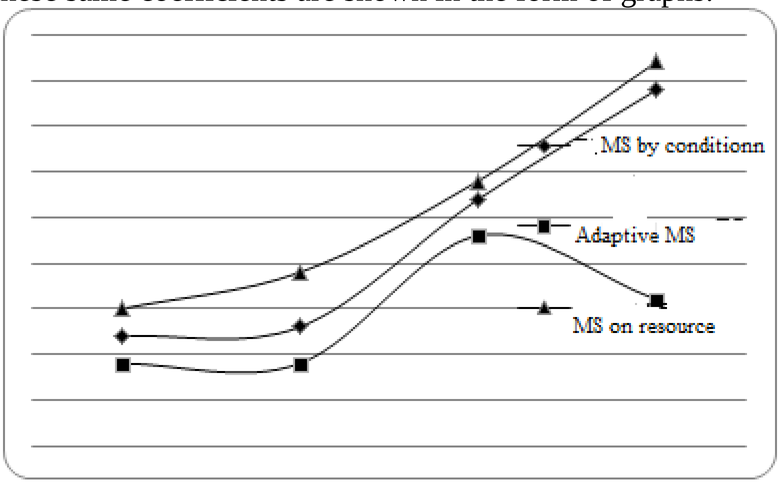

Figure 5 – Relative loss coefficient of the reliability level δ_{T_0}, %

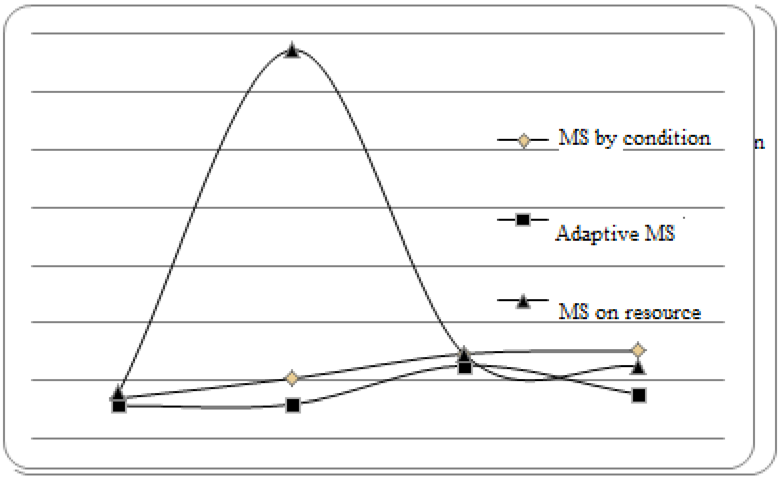

Figure 6 - The coefficient of relative losses of the unit cost operation $\delta_{C_{уд}}$, %

The data obtained fully confirm the assumption that the “adaptive maintenance” strategy is more preferable in the case of unreliable (inaccurate) information about the reliability indicators of the object elements.

The value of the loss factor $\delta_{C_{уд}}$ = 712% obtained for the Test-4 object is not an accidental outlier or error. Such large losses in the unit cost with “MS by resource” are explained by the high cost of the least reliable elements of the Test-4 object. This result is an additional confirmation of the critical sensitivity of the optimal parameters resource maintenance strategy in the case of unreliability initial data on the reliability of object.

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МЕТОДИКА ОПТИМІЗАЦІЇ ПАРАМЕТРІВ СТРАТЕГІЇ РЕГЛАМЕНТОВАНОГО ТЕХНІЧНОГО ОБСЛУГОВУВАННЯ ВІЙСЬКОВОЇ ТЕХНІКИ

***Анотація.** Складні технічні об'єкти у суспільстві мають виключно важливе значення. Такі об'єкти належать до класу відновлюваних об'єктів тривалого багаторазового застосування. Вони, як правило, є дорогими та потребують значних витрат на їх експлуатацію. Для забезпечення необхідного рівня безвідмовності в процесі їх експлуатації зазвичай проводиться технічне обслуговування (ТО), суть якого полягає у своєчасній запобіжній заміні елементів, що знаходяться в стані перед відмовою, що дуже важливо для об'єктів військової техніки.*

Характерною особливістю складних технічних об'єктів спеціального призначення (військової техніки) є наявність у їхньому складі великої кількості (десятки, сотні тисяч) різнотипних комплектуючих елементів, що мають різний рівень надійності, різні закономірності процесів їхнього зносу та старіння. Ця особливість потребує більш тонкого підходу до організації та планування ТО у процесі експлуатації (військової техніки).

Проблема полягає в тому, що при розробці таких об'єктів військової техніки всі питання, пов'язані з ремонтопридатністю та технічним обслуговуванням, повинні вирішуватися вже на ранніх етапах проектування об'єкта. Якщо не передбачити заздалегідь необхідні апаратні та програмні засоби вбудованого контролю технічного стану (ТЗ) об'єкта, не розробити і не вбудувати в об'єкт технологію проведення ТО, то реалізувати в майбутньому можливий виграш у безвідмовності об'єкта за рахунок проведення ТО не вдасться. Оскільки всі ці питання повинні вирішуватися на етапі створення об'єкта (коли об'єкта ще немає), необхідні математичні моделі процесу ТО, за допомогою яких можна було б прорахувати можливий виграш у рівні безвідмовності об'єкта за рахунок проведення ТО, оцінити необхідні вартісні витрати. Потім на підставі таких розрахунків прийняти рішення про необхідність проведення ТО для цього типу об'єктів і, якщо таке рішення прийнято, розробити структуру системи ТО, вибрати найбільш прийнятну стратегію ТО, визначити її оптимальні параметри.

У роботі проводиться дослідження впливу коефіцієнта варіації на величину оптимального рівня технічного обслуговування.

Також у роботі підтверджується загальне міркування у тому, що менше величина коефіцієнта варіації випадкової напрацювання до відмови обслуговуваних елементів, то більшим має бути оптимальне значення рівня ТО.

***Ключові слова:** технічне обслуговування, об'єкт військової техніки, регламентоване обслуговування військової техніки, витрати на вартість військової техніки*