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METHODS OF ADJUSTING THE PERIOD OF TECHNICAL MAINTENANCE OF COMPLEX TECHNICAL SYSTEMS DURING LONG-TERM OPERATION

The article examines methods for adjusting the maintenance frequency of complex technical systems with extended service life. These adjustment methods take into account the decline in the reliability of complex systems and, consequently, the increase in the duration of their forced downtimes due to maintenance procedures and the need to address failures and malfunctions. Mathematical models of downtime in complex technical systems due to maintenance are proposed, taking into account the failure flow density, the rate of failure and malfunction elimination, and the economic indicators of operation. Expressions have been derived for calculating the maintenance frequency and the optimal maintenance-related downtime of complex technical systems, the implementation of which will ensure their continued fitness for intended use.

Keywords: *collapsible technical systems; technical maintenance; specification; antiquity; reliability; optimization; frequency and triviality of technical maintenance.*

Statement of the Problem. Maintaining the operational condition and functional fitness of complex technical systems (hereinafter – CTS) is ensured through appropriate maintenance and repair systems. These are predominantly systems implementing scheduled preventive maintenance and repair strategies (hereinafter – PMS), or condition-based maintenance and repair models [1]. In most CTS with extended operational lifespans, PMS are typically applied, which involve fixed types, intervals, and durations of maintenance activities based on the system's operating time [2]. Forced downtimes of CTS due to scheduled maintenance, as well as the elimination of failures and malfunctions in their mechanisms, components, and assemblies (hereinafter – subsystems), reduce the overall time the systems are available for intended use and decrease operational profitability.

During prolonged operation, the subsystems of CTS are continuously subjected to operational factors that alter their technical condition. The stochastic nature of these factors' impact on subsystems results in varying actual conditions among identical systems, even under the same operational time or service duration. Consequently, operating hours or calendar lifespan cannot unambiguously characterize the technical state of a system [3]. To maintain a specified level of reliability and to reduce the forced downtime of CTS due to maintenance and repair activities, it is necessary to adjust the frequency and duration of maintenance operations in a manner that ensures (or sustains) the required level of reliability and prevents failures.

Analysis of Recent Research and Publications. An analysis of scientific literature reveals that, in addressing the problem of determining (or adjusting) the optimal maintenance frequency for complex technical systems, the principal approaches include condition-based maintenance, resource-based maintenance, and adaptive maintenance methodologies [4; 5; 6; 7]. Most of these studies focus on one of the critical and yet unresolved issues, ensuring the operational reliability of CTS of both conventional and high-criticality categories [8; 9], as well as systems characterized by high reliability and extended maintenance intervals [10; 11]. In the context of modern complex technical equipment, the problem is typically formulated and addressed within the framework of condition-based maintenance and repair strategies [7, 10].

In this context, the resolution of the aforementioned tasks is based on the following approaches: the periodicity of maintenance of complex technical systems is determined by developing a list of maintenance operations for their subsystems; the maintenance operations for these subsystems are grouped into specific types of technical maintenance; criteria for the optimality of the technical operation process and coefficients of technical utilization are employed; and an economic approach is applied, which includes the assessment of the economic consequences of forced downtime.

At the same time, the operation of complex technical systems (CTS) is typically considered under the assumption of an exponential distribution of the failure flow with a constant failure rate [12]. To a lesser extent, problems related to the adjustment of maintenance periodicity are addressed and formulated, particularly with regard to the increasing failure rate due to system aging.

The purpose of this article is to develop methods for adjusting the frequency of maintenance operations in a way that preserves (or sustains) the efficiency and quality of functioning of complex technical systems, taking into account their aging processes.

Presentation of the Main Material. Prolonged operation of any complex technical system is accompanied by an increase in the failure rate and the growing need for preventive measures to compensate for the degradation of subsystem conditions, as well as by an increase in the system's forced downtime due to the necessity of addressing failures and malfunctions.

To address the stated problem, several possible mathematical models of CTS downtime will be considered. Based on these models, methods for determining adjusted (refined) maintenance frequencies or quantities will be proposed, taking into account the decline in the reliability of their subsystems and of the system as a whole.

Maintenance Model No. 1. The total forced downtime of a complex technical system (CTS) due to maintenance can be defined as a function of the number of performed maintenance operations:

$$T_{\Pi}=n\cdot\overline{T}_{TO}+\frac{k\cdot T_B}{n}, \qquad (1)$$

T_{Π} – denotes the total (cumulative) downtime of the CTS over a given period of time;

n – the number of maintenance operations performed over a given period of time;

$\overline{T}_{TO}$ – the mean or planned downtime of a complex technical system resulting from maintenance activities within a specified time interval;

k – a constant coefficient associated with the specifics of maintaining a complex technical system, which accounts for downtime due to fault elimination;

T_B – the recovery time of a complex technical system due to failures of its subsystems over a given period.

Let us introduce the following constraints: the function $T_{\text{п}} = f(n)$ is continuous and bounded within the domain $t_{\text{пс}} < t < t_{\text{жц}}$, where t – denotes the operating time of the system during its service life, $t_{\text{пс}}$ – is the onset of aging, $t_{\text{жц}}$ – is the duration of the life cycle of the complex technical system.

To determine the optimum (minimum) of the function $T_{\text{п}} = f(n)$ we shall find its extremum. To this end, we differentiate function (1) to n, obtaining:

$$\frac{dT_{\Pi}}{dn}=\overline{T}_{TO}-\frac{k\cdot T_B}{n^2}. \qquad (2)$$

According to the existence and uniqueness theorem for the Cauchy problem, differential equation (2) has a unique solution for determining the optimal number of periodic maintenance operations for aging complex technical systems [13].

$$\overline{T}_{TO}-\frac{k\cdot T_B}{n^2}=0. \qquad (3)$$

Solving equation (3) with respect to the number of maintenance operations, we obtain:

$$n^2=\frac{k\cdot T_B}{\overline{T}_{TO}}.$$

Hence, the optimal number of maintenance operations for the CTS is as follows:

$$n^{opt}=\left(\frac{k\cdot T_B}{\overline{T}_{TO}}\right)^{1/2}. \qquad (4)$$

where n^{opt} – the optimal number of maintenance operations for a complex technical system to maintain its fitness for intended use over a given period.

By substituting expression (4) into expression (1), we obtain:

$$T_{\Pi}^{opt} = \left(\frac{k\cdot T_B}{\overline{T}_{TO}}\right)^{1/2}\overline{T}_{TO} + \frac{k\cdot T_B}{\left(\frac{k\cdot T_B}{\overline{T}_{TO}}\right)^{1/2}}.$$

After transformation, we obtain a formula for calculating the total optimal downtime of the CTS required to maintain its availability for intended use over a given period:

$$T_{\Pi}^{opt} = 2\left(k\cdot \overline{T}_{TO}\cdot T_B\right)^{1/2} \qquad (5)$$

where T_{Π}^{opt} – the total optimal downtime of the CTS required to maintain its availability for intended use over a given period.

We now consider the impact of CTS reliability on the total maintenance-related downtime and on the optimization of maintenance frequency. To this end, we construct an optimization model of system reliability and average downtime to ensure its fitness for intended use.

The following assumptions and constraints are adopted for the optimization model:

– subsystems of the CTS that fail are replaced with functional ones;

– CTS maintenance is performed every Δt hours, counted from the initial time following the last overhaul.

For the maintenance schedule, the time intervals for maintenance operations are expressed as:

$$t = t_i + \Delta t, \text{ при } i = 0, 1, 2, \ldots;\ 0 \le \Delta t < t_i\ , \qquad (6)$$

where t – current operating time of the CTS subsystems (in hours); t_i – time of the i-th maintenance operation; i – maintenance operation number, 0 – denotes the initial maintenance after the onset of aging effects; Δt – time interval between CTS maintenance operations, expressed in operating hours.

For i=1 and Δt=0 the system's availability for intended use is maintained through maintenance performed at the optimal interval Δt^{opt}.

The reliability of the CTS can be expressed by the following equation:

$$R_t(t = \Delta t^{opt}) = R\,(T^{opt}), \qquad (7)$$

where Δt^{opt} – optimal interval between CTS maintenance operations; T^{opt} – optimal maintenance frequency; $R\,(T^{opt})$ – eliability of the CTS at the optimal maintenance frequency.

As the maintenance interval increases, the reliability of the complex technical system decreases i for $t = 2\Delta t^{opt}$ and Δt=0 we have:

$$R_t(t = 2\Delta t^{opt}) = [R\,(T^{opt})]^2. \qquad (8)$$

In this case, the CTS is used in the first hours of Δt^{opt} without failures and malfunctions. Then, during the remaining hours Δt^{opt} c the system is used for its intended purpose after the failures and malfunctions during t_i are eliminated.

For operating time $0 < t_i < \Delta t^{opt}$ the system functions reliably in its intended role. Therefore, the reliability of the CTS is ensured by performing maintenance at the optimal interval Δt^{opt}:

$$R_t(t = 2\Delta t^{opt} + t_i) = [R\,(T^{opt})]^2 R(t_i). \qquad (9)$$

In the general form, equation (8) takes the following form:

$$R_t(t = t_i + \Delta t^{opt}) = [R\,(T^{opt})]^i R(T^{opt}), \text{ for } i = 0, 1, 2, \ldots;\ 0 \le t_i < \Delta t^{opt}. \qquad (10)$$

Average maintenance interval means the frequency of troubleshooting time and periodic maintenance to maintain the availability for purpose of the CTS:

$$\overline{T}_{TO} = \int_0^{\infty} R_t(\Delta t^{opt})dt. \qquad (11)$$

Evaluating equation (11), we write the composite period of the range $t_{пт} < t < t_{жц}$, as follows:

$$\overline{T}_{TO} = \sum_{i=0}^{\infty}\int_{t_i}^{t(i+1)} R_t(t)dt \qquad (12)$$

In equation (12), composed of equation (11), the time intervals are divided into lengths Δt.

For the time $t = t_i + \Delta t$ replacing into equation (12) reliability in equation (10), we obtain:

$$\overline{T}_{TO} = \sum_{i=0}^{\infty}\int_{t_i}^{\Delta t^{opt}} [R(T^{opt})]^i R\,(T^{opt})dt. \qquad (13)$$

In equation (12) for the time $t = t_i + \Delta t$, $dt = dt_i$ the limits will be 0 and Δt^{opt}.

Thus, restructuring equation (13), we obtain:

$$\overline{T}_{TO} = \sum_{i=0}^{\infty}[R(T^{opt})]^{i}R\,(T^{opt})dt \qquad (14)$$

Since:

$$\sum_{i=0}^{\infty}[R(T^{opt})]^{i} = \frac{1}{1-R\,(T^{opt})} \qquad (15)$$

equation (13) takes the following form:

$$\overline{T}_{TO}^{opt} = \frac{\int_0^t R\,(T^{opt})d\Delta t^{opt}}{1-R\,(T^{opt})} \qquad (16)$$

where $\overline{T}_{TO}^{opt}$ – is the optimal planned downtime for maintaining the suitability of the CTS at the optimal maintenance interval for a certain period of time; Δt^{opt} – is the optimal period of time between CTS maintenance; $R\,(T^{opt})$ – is the reliability of the CTS at the optimal maintenance interval.

Thus, the need to enhance the reliability of a complex technical system determines its downtime required to maintain availability for intended use.

By utilizing data on CTS reliability and the known distribution of the mean time to failure, it is possible to determine the average maintenance frequency for aging systems to ensure their continued operational availability.

Maintenance Model No. 2. This model can be used to determine the optimal maintenance frequency for a CTS and to minimize its forced downtime due to maintenance activities.

In this optimization model, the total downtime is a function of the system's operating time or the frequency of maintenance operations. Mathematically, this optimization model is defined by the following function:

$$T_{\Pi}(t) = \overline{T}_{TO}(t) + T_{B}(t) = \frac{t}{\Theta} + \frac{\lambda(t)}{\mu}, \qquad (17)$$

where $T_{\Pi}(t)$ – the total downtime of the CTS per unit of time; $\overline{T}_{TO}(t)$ – the downtime of the CTS due to maintenance per unit of time; $T_{B}(t)$ – the downtime of the CTS due to failure and malfunction elimination per unit of time; t – operating time of the CTS; $\lambda(t)$ – failure and malfunction intensity of the CTS; μ – rate of failure and malfunction elimination; $1/\Theta$ – coefficient of average maintenance duration (defined as the ratio of the average maintenance duration to its periodicity, i.e., $1/\Theta = \overline{T}_{TO}/\Delta t$, where Δt – is the period between system maintenances.

By differentiating function (17) with respect to t, we obtain:

$$\frac{dT_{\Pi}(t)}{dt} = \frac{1}{\Theta} + \frac{d\lambda(t)}{d(t_i)}\cdot\frac{1}{\mu}. \qquad (18)$$

The necessary condition for the extremum of function (18) yields the following results:

$$\frac{d\lambda(t)}{dt} = -\frac{\mu}{\Theta}. \qquad (19)$$

The maintenance periodicity will be optimal when the left-hand and right-hand sides of equation (19) are equal. In this case, the downtime of the CTS will be minimized.

Let us assume that the failure flow density of the CTS is defined by the following formula [12]:

$$\lambda(t) = f\cdot e^{t}, \qquad (20)$$

where f – the failure intensity function of the CTS up to $t = 0$.

Replacing the failure rate in formula (19) with the failure rate from formula (20), we obtain:

$$f\cdot e^{t} = -\frac{\mu}{\Theta}. \qquad (21)$$

Thus, equality (21) provides a formula for calculating the optimal maintenance periodicity of the CTS:

$$\Delta t^{opt} = \ln\left[\frac{f\cdot\Theta}{\mu}\right]. \qquad (22)$$

Substituting into equation (22) in place of the failure intensity function f into equation $\lambda(t)/e^{-t}$, we obtain:

$$\Delta t^{opt} = \ln\left[\frac{\lambda(t)\cdot\Theta}{\mu\cdot e^{-t}}\right], \qquad (23)$$

where Δt^{opt} – optimal maintenance periodicity; $\lambda(t)$ – failure and malfunction intensity of the CTS; μ – rate of failure and malfunction recovery, $1/\Theta$ – coefficient of average maintenance duration.

Maintenance Model No. 3. If the CTS is maintained too frequently, there is a risk that the cost of maintenance may exceed the losses incurred due to downtime from infrequent servicing. This is due to factors such as the loss of productive utilization, increased expenses for operational materials, and labour costs. This maintenance model is derived from the condition of ensuring maximum profit during the operation of the CTS [2].

In the model, the following rules and constraints will be applied: the operability of the system is restored at each maintenance interval; the failure intensity of the CTS subsystems and the maintenance function are constant values; the time required for maintenance and failure recovery follows an exponential distribution; the distribution of failures and the recovery rate of the CTS are constant values.

To develop the equations of the maintenance model, we will use the following notations: n – the number of maintenance operations performed per unit of time; $1/\Theta$ – the average duration of maintenance; $C_{\text{прб}}$ - the profit from operating the CTS excluding the downtime due to maintenance, per unit of time; $\overline{C}_{\text{TO}}$ - the average cost of maintenance of the CTS per unit of time; $\overline{C}_{\text{B}}$ – the average cost of failure and malfunction elimination of the CTS per unit of time; $\lambda(t)$ – the intensity of failure and malfunction occurrence in the CTS; μ – the rate of failure and malfunction elimination.

The profit from operating the CTS is determined by the following formula:

$$C_{\text{прб}} = C_{\text{дх}} - C_{\text{прс}} \cdot \overline{\overline{T}}_{\text{TO}} - C_{\text{прс}} \cdot \overline{\overline{T}}_{\text{B}} - \overline{C}_{\text{TO}} - \overline{C}_{\text{B}} = \\ = C_{\text{дх}} - \frac{C_{\text{прб}}^{\text{пл}} \cdot n}{\Theta} - \frac{C_{\text{прб}}^{\text{пл}} \cdot \lambda(t)}{\mu} - \frac{n \cdot S_{\text{TO}}}{\Theta} - \frac{S_{\text{B}} \cdot \lambda(t)}{\mu}. \quad (24)$$

where $C_{\text{дх}}$ – revenues from the operation of the CTS; $C_{\text{прс}}$ – the cost of one hour of CTS downtime; $\overline{\overline{T}}_{\text{TO}}$ – downtime of the technical system due to maintenance; $\overline{\overline{T}}_{\text{B}}$ – downtime of the CTS due to failure and malfunction elimination; $\overline{C}_{\text{TO}}$ – average cost of performing maintenance; $\overline{C}_{\text{B}}$ – average cost of failure and malfunction elimination; S_{TO} – cost of each maintenance operation of the complex technical system; S_{B} – cost of each failure and malfunction elimination; $C_{\text{прб}}^{\text{пл}}$ – planned profit from the intended use of the CTS, in UAH per year of system operation.

By differentiating equation (24) with respect to *n*, we obtain:

$$\frac{dC_{\text{прб}}}{dn} = -\frac{C_{\text{прб}}^{\text{пл}}}{\Theta} - \frac{C_{\text{прб}}^{\text{пл}} d\lambda(t)}{\mu dn} - \frac{S_{\text{TO}}}{\Theta} - \frac{S_{\text{B}} \cdot d\lambda(t)}{\mu dn}. \quad (25)$$

Equating expression (25) to zero and performing subsequent transformations yield the following equality:

$$\frac{d\lambda(t)}{dn} = -\left[\frac{1}{\Theta}\left(C_{\text{прб}}^{\text{пл}} + S_{\text{TO}}\right)\right] \Big/ \left(\frac{C_{\text{прб}}^{\text{пл}}}{\mu} + \frac{S_{\text{B}}}{\mu}\right). \quad (26)$$

The number of maintenance operations n for the CTS will be optimal when both sides of equation (26) are equal. In this case, the profit will be maximized.

Let us assume that the intensity of malfunction occurrence in the CTS is determined by equation (20). Substituting equation (20) into equation (26) yields the following equality:

$$-f \cdot e^{t} = -\left[\frac{1}{\Theta}\left(C_{\text{прб}}^{\text{пл}} + S_{\text{TO}}\right)\right] \Big/ \left(\frac{C_{\text{прб}}^{\text{пл}}}{\mu} + \frac{S_{\text{B}}}{\mu}\right). \quad (27)$$

Transforming the expression (26), we obtain:

$$n^{opt} = \ln\left[\frac{\lambda(t) \cdot \Theta \cdot \left(C_{\text{прб}}^{\text{пл}} + S_{\text{TO}}\right)}{\mu \cdot e^{-t} \cdot \left(C_{\text{прб}}^{\text{пл}} + S_{\text{B}}\right)}\right]. \quad (28)$$

where n^{opt} – optimal number of maintenance operations for the CTS over a given period of time; $\lambda(t)$ – failure intensity of the CTS; S_{TO} – cost of each maintenance operation of the CTS; S_{B} – cost of each failure and malfunction elimination of the CTS; $C_{\text{прб}}^{\text{пл}}$ – planned profit from the intended use of the CTS, in UAH per year of system operation.

This model can be used to calculate the optimal maintenance periodicity of the CTS, under which maximum profit from its operation will be achieved.

Conclusions and Prospects for Further Research. Maintaining the specified level of reliability and operational fitness of aging complex technical systems, in which scheduled preventive maintenance and repair strategies are implemented, requires further investigation into the issue of adjusting maintenance parameters, specifically, the frequency and duration of maintenance activities.

To address such tasks, it is necessary to develop downtime models for complex technical systems that take into account the impact of system reliability on the total downtime.

Models of downtime for aging complex technical systems have been developed, and analytical formulas have been derived to determine the optimal number and duration of their maintenance operations.

The novelty of the study lies in the fact that many complex technical systems of long-term use require work to maintain their suitability for operation by reducing the frequency of maintenance, and work to assess the condition of such systems.

Future research may focus on improving the maintenance of complex technical systems during prolonged periods of operation.

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