Mathematical Model of Reliability of Restored Technical System

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Abstract- It offers a discrete mathematical model of reliability and aging of the technical system, whose state is getting worse over time, increasing the probability of failure. It is assumed that in order to optimize system performance at random times conducted preventive maintenance of different depths. The purpose of the work - to justify the selection rule of such repairs, providing the optimum level of performance.

I. INTRODUCTION

I t is known that all the technical systems in the process of observation and operation impair their characteristics, as well as increases the probability of their failure. In many cases, the probability of failure is the most important for modeling, since it leads to a long downtime of the system and significant costs for its restoration. The probability of failure can be reduced and adjusted to an optimum level with the help of preventive repairs. Typically, these repairs are defined by regulations at predetermined time points. In fact, for various reasons, their implementation happens at random times. The model that will be built is taken into account this circumstance [1-3].

The purpose of the research is to build a mathematical model of reliability and availability-driven technical system with a finite number of states. The article discusses the most promising approach to modeling the reliability of technical systems, involving the introduction of the state, which determines the level of efficiency and the probability of failure. This approach allows us to take into account the individual characteristics of the system, for example, the wear rate, which in turn will enable more adequate to make decisions on its preventive maintenance. Existing modeling methods [4-6] to select the optimal solutions use statistical data collected by a large group of similar systems. The main value in this case is "time to failure." It is understood that the individual features of the particular system in this case is not counted. The purpose of modeling is to maintain a separate system for optimum performance with regard to its status on an unlimited time interval. The basis of the simulation puts a Markov random process. This work is the result of a series of researches [7-13]

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In this paper, the author develops an approach to modeling the reliability of technical systems presented in [14].

II. MATHMATICAL MODEL

Let stochastic system S is controlled by a random period of time $\zeta = \min(\xi, \tau)$, where ξ - random time to failure, depending on the observed condition of the last time control; τ - the planned period of random control, having an Erlang distribution of order k. In every moment of the control system can be in one of the states of a finite set $E'=\{x_1, ..., x_N\}$ [15-18]. We assume that the best state, in which the probability of failure is minimal, is x_1, and the worst - the state x_N. Status x_1 corresponds to the new system, and the state x_N - the most worn. All other states - intermediate, the probability of failure in which it is ordered by ascending from the minimum to the maximum. It is convenient to expand the set of states, providing each element $x_i \in E$ second index s, s = 1, ...,k +1. In this case s = 1, …, k indicates the phase Erlang distribution [7] period τ, and $a_s = k+1$ indicates the status of the planned monitoring. Let:

$$E''=\{x_{is}\},\ i = 1, ..., N,\ s = 1,...,k+1.$$

Thus, a complete set of states $E = E'' \cup \{x_0\}$ [19-22].

Let a scheduled time control system is in state x_{jk+1}, j = 1, ..., N, which uses one of the possible preventive repairs. Let us assume that the set of admissible preventive maintenance, which is called the set of controls and let $Y = \{y_1, ... y_m\}$, of course. An element of this set, y_i management, determines the depth of the system upgrade. It determines the intensity μ js transition of the system from the state x_{jk+1} a state x_{s1}, s = 1, ... j.

We assume that the deeper control provides system upgrade, the greater the intensity of the transition to a state with a lower number s. But let's keep in mind that the deeper system upgrade, the more it is worth managing [23-27].

It is natural to assume that the failure of the system is possible in any state x js, j = 1, ..., N, s = 1, ..., K, and the failure rate ν j do not depend on the phase of s. We consider it formally, that the failure of the system leads to a transition in its state x_0. In the state x_0 system is restored to one of the states x j1, with the intensity φ j, j = 1, ..., N.

Let the intensity of the transition between the phases through l. The main simulation task will consist in choosing the optimal control strategy, i.e in selecting the type of preventive maintenance for each state at each control point [28-30].

Kolmogorov equations for the probabilities of states of the model proposed above is as follows [7]:

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$$
\begin{aligned}
&\frac{d}{dt}P_{11}(t) = -(v_1+\lambda_1+1)P_{11}(t)+\phi P_0(t)+\sum_{i=1}^{N}\mu_{i1}Pi_{k(t)} \\
&\frac{d}{dt}P_{s1}(t) = -(v_s+\lambda_s+1)P_{s1}(t)+\phi_s P_0(t)+\sum_{i=s}^{N}\mu_{is}P_{ik+1}(t)+\lambda_{s-1}P_{s-11}(t), s=2,\dots,N-1 \\
&\frac{d}{dt}P_{N1}(t) = -(v_N+1)P_{N1}(t)+\phi_N P_0(t)+\mu_{NN}P_{Nk+1}(t)+\lambda_{N-1}P_{N-11}(t) \\
&\frac{d}{dt}P_{1s}(t) = -(v_1+\lambda_1+1)P_{1s}(t)+1P_{1s-1}(t), s=2,\dots,k \qquad (1) \\
&\frac{d}{dt}P_{qs}(t) = -(v_q+\lambda_q+1)P_{qs}(t)+1P_{qs-1}(t)+\lambda_{q-1}P_{q-1s}(t),\quad q=2,\dots,N-1, s=2,\dots,k \\
&\frac{d}{dt}P_{Ns}(t) = -(v_q+1)P_{Ns}(t)+1P_{Ns-1}(t)+\lambda_{N-1}P_{N-1s}(t),\quad s=2,\dots,k \\
&\frac{d}{dt}P_{qk+1}(t) = -\sum_{i=1}^{q}\mu_{qi}P_{qk+1}(t)+1P_{qk}(t),\quad q=1,\dots,N \\
&\frac{d}{dt}P_0(t) = -\sum_{i=1}^{N}\phi_i P_0(t)+\sum_{i=1}^{N}\sum_{j=1}^{k}v_i P_{ij}(t) \\
&P_0(t)++\sum_{i=1}^{N}\sum_{j=1}^{k+1}P_{ij}(t)=1
\end{aligned}
$$

Note that one of the equations except the normalization condition may be omitted when the solution.

Suppose that at the initial time the system is in a state of x_{11}. Then, the initial probability distribution is as follows:

$P_{11}(0) = 1$, $P_0(0) = 0$, $P_{ij}(0) = 0$ for all i, j, except i = j = 1.

Consider the case where there is a steady-state mode of functioning of the system [10]. At the same time there are limits to the state probabilities $P_{ij}(t)$, $P_0(t)$ as $t \to \infty$.

Therefore, in this mode, all the derivatives of these probabilities are equal to 0. Then, given a system of differential equations go into a heterogeneous system of linear algebraic equations. Such a system can be solved, for example, using a computer program Matlab [31-35].

III. DETERMINATION OF THE SYSTEM PARAMETERS

System status is determined by a set of monitoring parameters containing information about the reliability of the system, and in practice can often be reduced by using a weighting function of the scalar quantity. The dimension of the model at the same time significantly reduced. Note that the selection of the informative parameter set may be performed, for example, using methods of pattern recognition theory [8].

The process of the technical system wears adequately described by the transition intensities λ_i, i = 1, ..., N -1, between adjacent states $x_{ij} \to x_{i+1j}$, i = 1, ...,N -1, j = 1, ..., k. Indeed, in the state of x11 system is a random time, distributed exponentially, which corresponds to the absence of wear and tear, and the transition to a state of failure due to "random" factors, i.e., Constant conditional probability. Increasing the degree of aftereffect due to the transition to the new state reflects the increase in the degree of wear and, consequently, an increase over time, the conditional probability of failure [1]. Evaluation of intensity λ_i, i = 1,...,N -1, the transition between the states can be readily obtained by the methods of mathematical statistics on the basis of the available information [7].

Intensity ν_i, i = 1, ..., N, can be prepared by methods of mathematical statistics on the basis of available information [35-45].

Obtain estimates of the intensity l transition between the phases and the order k of the random variable η, has a distribution of FSD Erlang of order k. Let t_1, t_2, ...,t_n - the implementation period of time between the planned system stops for repairs. Since: $M\eta = \frac{k}{1}$, and the variance $D\eta = \frac{k}{1^2}$,the method of moments gives the following assessment parameters l and k : $1 = \frac{\bar{t}}{\tilde{\sigma}^2}$, $1 = \left[\frac{\bar{t}^2}{\tilde{\sigma}^2}\right]$ when $\bar{t} = \frac{1}{n}\sum_{i=1}^{n} t_i$, $\tilde{\sigma}^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(t_i - \bar{t}\right)^2$ the square brackets denote the integer part.

The intensity of repair at x_0 state can be evaluated by methods of mathematical statistics. It should be noted that it is convenient to assess the intensity φ separately from state x_0 output and transition probability π_i of the state of the status x_{i1}, i=1,...,N, $\sum_{i=1}^{N}\pi_i = 1$. Then the desired intensity should be set equal to $\varphi_i = \varphi\pi_i$.

Define further control parameters. Management, i.e. Preventive maintenance of different depth upgrade system, as a rule, does not worsen her condition.

Therefore, we assume that the state of x_{ik+1}, i=1, ..., N, under the influence of a transition management only in the state x_{j1}, j=1,...,i. Similarly to the above, statistical methods easily allow us to estimate the probability $p_j(y)$,j = 1,...,i, such that $\sum_{j=1}^{i} p_j = 1$, for each y∈Y, each prevent-ing a condition x_{ik+1} and the intensity μ of the output x_{ik+1} state. Then the desired intensity of the output state x_{ik+1} equal $\mu_{ij}(y) = \mu p_j(y)$, j = 1,...,i.

The system is connected with some costs, ensuring its functioning, in particular with the implementation of preventive repairs. In addition, the system in normal mode brings as usually a certain income per unit of time, possibly depending on the state. Let the system income per unit of time in a state of x_{ij} through w (x_{ij}). Let the cost of repair, maintenance works in the unit of time in a state x_{ik+1} is the value of r (x_{ik+1}, y), where y∈Y – control of defining the depth of the preventive maintenance (control room), and the cost of restoring the system from a state of failure per unit time in the state x_0 - value r_0.

IV. SYSTEM OPTIMOZATION

Displaying E → Y is said to be the crucial function and let f, while the sequence of decision functions $\pi = \{f_1, f_2, ...\}$ is called a strategy. Strategy type $\pi^{(\infty)} = \{f, f,...\}$ is called stationary. For a given stationary strategy $\pi^{(\infty)}$ the average revenue per unit time L at steady state for the system is defined as follows:

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$$L(\pi^{(\infty)}) = \sum_{i=1}^{N} W(X_{ij}) \left(\sum_{j=1}^{k} P_{ij} \right) - \sum_{i=1}^{N} r(X_{ik+1}, f(X_{ik+1})) P_{ik+1} - r_0 P_0$$

Where $f(x_{ik+1}) \in Y$ - control depends crucially function f at π strategy $\pi^{(\infty)}$.

The challenge is to find a strategy $\pi^{(\infty)}$, maximizes the function L.

A stationary finite set of strategies, so such a strategy exists. In this case, it can easily be found using computer programs Matlab. Next, we consider a model example. All cumbersome calculations be held in the Matlab system [11].

Suppose that as a result of statistical data processing found that the duration of the period of scheduled preventive maintenance is a random variable distributed according to the Erlang of order k with parameters l = 1.5 and k = 2. This system defines a set of states $E=\{x_0,x_{ij}\}$,i = 1,...,3, j=1,...,3. In states x_{i3}, i=1,...,3 ,carry out preventive repairs and able x_0 - system failover.

The system of equations for the state probabilities in stationary mode from (1). It takes the following form:

$$\begin{aligned}
&-(\nu_1+\lambda_1+1)P_{11}+\mu_{21}P_{23}+f_1P_0+\mu_{11}P_{13}+\mu_{31}P_{33}=0\\
&-(\nu_2+\lambda_2+1)P_{21}+\mu_{32}P_{33}+f_2P_0+\mu_{22}P_{23}+\mu_{31}P_{33}+\lambda_1P_{11}=0\\
&-(\nu_{31}+1)P_{31}+\mu_{21}P_{23}+f_3P_0+\mu_{33}P_{33}+\lambda_2P_{21}=0\\
&-\mu_{11}P_{13}+1P_{12}=0\\
&-(\mu_{21}+\mu_{22})P_{23}+1P_{22}=0\\
&-(\mu_{31}+\mu_{32}+\mu_{33})P_{33}+1P_{32}=0\\
&-(f_1+f_2+f_3)P_{33}+\nu_1(P_{11}+P_{12})+\nu_2(P_{21}+P_{22})+\nu_3(P_{31}+P_{32})=0\\
&-(\nu_2+\lambda_2+1)P_{22}+1P_{21}+\lambda_1P_{12}=0\\
&-(\nu_3+1)P_{32}+\lambda_2P_{22}=0\\
&P_0+p_{11}+p_{12}+p_{13}+p_{21}+p_{22}+p_{23}+p_{31}+p_{32}+p_{33}=1
\end{aligned}$$

In states x_{i3}, i=1,...,3, an idle system, preventive repairs are carried out in them. The total intensity output from each state xi3, i =1,...,3 is μ=3. The probabilities of the transitions of these states in the operating states depend on the depth of preventive maintenance. Suppose that y_1 control the most updated systems, y_2 management - to a lesser extent, and y_3 management - to a lesser extent. Intensity μ_{ij} x_{i3} defines a transition from state to x_{j1}, j = 1, ..., i.

Intensity values to control y_1: $\mu_{11} = \mu$, $\mu_{21} = 0.9\mu$, $\mu_{22} = 0.1\mu$, $\mu_{31} = 0.75\mu$, $\mu_{32} = 0.15\mu$, $\mu_{33} = 0.1\mu$; management y_2: $\mu_{11} = \mu$, $\mu_{21} = 0.5\mu$, $\mu_{22} = 0.5\mu$, $\mu_{31} = 1/3\mu$, $\mu_{32} = 1/3\mu$, $\mu_{33} = 1/3\mu$; management y3: $\mu_{11} = \mu$, $\mu_{21} = 0.15\mu$, $\mu_{22} = 0.85\mu$, $\mu_{31} = 0.1\mu$, $\mu_{32} = 0.15\mu$, $\mu_{33} = 0.75\mu$.

Preventive maintenance cost per unit time is of the state x_{i3} $r(x_{i3}, y_j)$, if the control is applied $y_j \in Y$, j =1,...,3. These values are selected as follows: r $(x_{13},y_1) = 5$, $r(x_{23}, y_1) = 5.5$, r $(x_{33}, y_1) = 6$; r $(x_{13}, y_2) = 4$, r $(x_{23}, y_2) = 4.2$, r $(x_{33}, y_2) = 4.6$; r $(x_{13}, y_3) = 3$, r $(x_{23}, y_3) = 3.2$, r $(x_{33}, y_3) = 3.4$.

Let the selected unit of measurement of income and expenses. The system generates income per unit of time in the states of x_{11}, x_{12} is 30, in the states of x_{21}, x_{22} is 22, in the states of x_{31}, x_{32} is equal to 14 units. Recovery of a failed system cost r_0= 18 arbitrary units per unit time.

For other parameters, the following values are chosen. The intensity of the transition between states λ_1= 0.5, λ_2= 2. Intensity of refusal states x_{ij}: for i=1 and j = 1,2 is $\nu_1 = 0.1$, for i = 2 and j = 1,2 $\nu_2 = 0.2$, for i = 3 and j = 1,2 $\nu_3 = 1$. The intensity of the recovery from the failure of a state of x_{11} is φ_1= 0.6, in the state x_{21} is $\varphi_2 = 0.4$, in the state of x_{31} is φ_3= 0.3.

The following result. The best strategy is the one that requires management y_1 in all states in which preventive maintenance is provided. Using Matlab to solve the problem given the following result.

Application y_1 management leads to income 15.25437722, management y_2- 14.53419191 to income, management y_3 - in 14.00128186 income per unit time for an unlimited period of operation of the system.

V. CONCLUSIONS

A new approach to modeling the aging of technical systems, the likelihood of which increases with the time of failure. It is introduced that a sequence of states, which in turn passes it to describe the evolution of aging of the technical system. At the same time an indicator of the system as the failure rate increases monotonically. It is shown that under certain conditions the evolution of the system can be described by a Markov process, and hence, the model may be based on a system of equations Kolmogorov.

The aim of the simulation was to find a preventive strategy update that would optimize its performance and reliability. The practical significance of the results is that the solution to this urgent problem can be easily obtained with the help of mathematical computing software such as Matlab. Note that in the model adopted random control period. Last expands the range of systems that can adequately be described by the proposed model.

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