DOI: 10.12731/2227-930X-2022-12-3-22-39
UDC 621.396.6.07.019.3

MATHEMATICAL MODEL OF RISK CONTROL ARISING FROM THE FUNCTIONING OF COMPLEX TECHNICAL SYSTEMS FOR CRITICAL PURPOSES IN CONDITIONS OF UNCERTAINTY OF INFORMATION ABOUT THE VALUES OF PARAMETERS AND THE PHASE STATE

P.V. Kalashnikov

Introduction. *The paper presents a description of the process of constructing a mathematical model for managing risks arising from the operation of complex technical unique systems for critical purposes under conditions of uncertainty of information about the parameters and phase state. The* ***purpose*** *of the study is to create an individual optimal strategy for managing risk events that occur during the operation of complex technical systems, which minimizes the cost of preventive work, as well as the amount of damage that may result from the occurrence of relevant events. The objectives of the study include the construction of a mathematical model for control risks arising from the operation of complex dynamic unique technical systems for critical purposes under conditions of interval uncertainty of information about the values of parameters and the phase state, since as well as an analysis of existing approaches to creating an individual forecast of changes in the state of the considered class of systems.*

Materials and Methods. *The article gives a comparative description of the effectiveness of the application of the mathematical apparatus of the theory of outliers of random processes and the method of individual forecasting in solving the problem of managing risks arising from the operation of complex unique technical systems for critical purposes under conditions of uncertainty. Based on the statistical methods of interval data, a mathematical model of risk management was created,* *taking into account possible errors in measuring the values of the parameters of the considered class of complex systems at all control windows during the operation period.*

Results. *The scientific novelty of the implemented approach lies in the use of interval data statistics, which allow the most correct consideration of possible errors associated with measuring the values of the characteristics of the studied technical systems at all stages of the control process.*

Discussion and Conclusions. *The mathematical model of risk control developed in the course of the study, arising from the operation of complex technical systems for critical purposes, makes it possible to make the optimal choice of risk management strategy when using objects of this class. Along with the above, an algorithm has been developed for predicting changes in the state of a technical system during the entire period of its operation based on the mathematical apparatus of statistics of interval data, which makes it possible to take into account in the calculations the errors that occur when measuring the values of the main parameters of the system under consideration at all stages of the control process.*

Keywords: *risk management; statistics of interval data; complex technical system for critical purposes; theory of outliers of random processes; guaranteed forecast method*

МАТЕМАТИЧЕСКАЯ МОДЕЛЬ УПРАВЛЕНИЯ РИСКАМИ, ВОЗНИКАЮЩИМИ ПРИ ФУНКЦИОНИРОВАНИИ СЛОЖНЫХ ТЕХНИЧЕСКИХ СИСТЕМ ОТВЕТСТВЕННОГО НАЗНАЧЕНИЯ, В УСЛОВИЯХ НЕОПРЕДЕЛЕННОСТИ ИНФОРМАЦИИ О ЗНАЧЕНИЯХ ПАРАМЕТРОВ И ФАЗОВОМ СОСТОЯНИИ

П.В. Калашников

В работе приводится описание процесса построения математической модели управления рисками, имеющими место во

время работы сложных технических уникальных систем ответственного назначения в условиях неопределенности информации о параметрах и фазовом состоянии. ***Целью исследования*** *является создание индивидуальной оптимальной стратегии управления рисковыми событиями, имеющими место в ходе процесса функционирования сложных технических систем, при которой сводятся к минимуму затраты на профилактический ремонт, а также величина ущерба, который может возникнуть в результате возникновения соответствующего события. К задачам проводимого исследования следует отнести построение математической модели управления рисками, имеющими место в ходе работы сложных динамических уникальных технических систем ответственного назначения в условиях интервальной неопределенности информации о значениях параметров и фазовом состоянии, а также анализ существующих подходов к созданию индивидуального прогноза изменения состояния рассматриваемого класса систем*

Материалы и методы. *В статье дается сравнительная характеристика эффективности применения математического аппарата теории выбросов случайных процессов и метода индивидуального прогноза при решении задачи управления рисками, возникающими в ходе работы сложных уникальных технических систем ответственного назначения в условиях неопределенности. На основе методов статистики интервальных данных создается математическая модель управления рисками, учитывающая возможные погрешности при измерении значений параметров рассматриваемого класса сложных систем на всех окнах контроля в течение периода эксплуатации.*

Результаты исследования. *Научная новизна реализуемого подхода состоит в использовании статистики интервальных данных, позволяющих наиболее корректно учитывать имеющие место возможные погрешности, связанные с измерением значений характеристик изучаемых технических систем на всех этапах процесса управления.*

Обсуждение и заключение. *Разработанная в ходе выполненного исследования математическая модель управления рисками, возникающими в ходе работы сложных технических систем ответственного назначения, позволяет делать оптимальный выбор стратегии управления рисками при использовании объектов данного класса. Наряду с вышеизложенным, разработан алгоритм прогноза изменения состояния технической системы в течение всего периода ее работы на основе математического аппарата статистики интервальных данных, позволяющий учитывать при расчетах погрешности имеющие место при замерах значений основных параметров рассматриваемой системы на всех этапах процесса управления.*

Ключевые слова: *управление рисками; статистика интервальных данных; сложная техническая система ответственного назначения; теория выбросов случайный процессов; метод гарантированного прогноза*

Introduction

This paper is a generalization and development of previously obtained results of calculations on the aspects of mathematical modeling of risk management, development during the operation of complex technical systems for responsible purposes, set out in the works [1, 2]. The main element of the scientific novelty of this article is the addition of previously obtained results by comparing the effectiveness of the methods of the theory of outliers and the method of guaranteed prediction in solving the problem of risk management. The work of complex critical systems in various fields of technology and economics is associated with emergencies, accidents, failures, as well as disruption of the normal operation of individual organizational structures, industries, which in turn damages the national economy and the population. The main approaches to the theory of risk control in technical systems are described in the works [1-5].

The magnitude of the risk arising in the course of the functioning of technical systems is given by the ratio

$$R = P_r B \tag{1}$$

where

R – the magnitude of the risk arising in the course of the functioning of the technical system

P_r – the probability of a risk event

B – the amount of damage in the event of a risk event.

The total value of risk R arising from the operation of complex technical systems for critical purposes, which can be described by the presence of various combinations of the magnitude of damage and the probability of their occurrence, is found by the formula

$$R_i = \sum_{i=0}^{n} P_{r_i} B_i \tag{2}$$

Summation is performed over all possible elements of the event tree.

The considered values of the amount of damage and the probability of the occurrence of a risk event are functions of time t. Risk, as a rule, is understood as a random variable of the form (, B), where – the moment in time at which a risk event occurs (equipment failure, accident, catastrophe). The approach based on the use of the standard apparatus of the theory of probability and mathematical statistics in managing risks arising in the course of the functioning of complex unique critical systems is ineffective, since it does not take into account the individual characteristics of each specific system, and also does not provide reliable results and statistical assessments under conditions lack, incompleteness and indistinctness of information about the parameters and phase state of the objects under consideration.

To solve the above problems it is necessary to use the concept of a functional-parametric approach to managing the reliability of complex systems, which is described in the works [6-10].

The main idea of the functional-parametric approach is based on the assumption of a gradual nature of the occurrence of failures in the operation of technical systems. The reason for the occurrence of failures in the operation of complex objects is the output of parameter values beyond the limits of the operability area. Forecasting the state and controlling the parameters of complex technical systems makes it possible to solve the problem of ensuring the stable operation of the structures under consideration throughout the entire period of operation.

The functional-parametric approach is focused on solving the problem of predicting changes in the values of the parameters of the system under consideration, as well as determining the optimal strategy for preventive measures, which allows, at minimal cost, to implement a set of measures to assess the state and adjust the operation of units and assemblies that ensure trouble-free operation of the facility during the entire period of its operation.

The task of risk control in the operation of critical technical systems is to determine a set of preventive measures and search for optimal control actions on the system parameters that minimize the amount of damage from the implementation of a risk event. A risk event is understood as the exit of the values of the system state parameters beyond the limits of the operability area.

Mathematical model of risk control under conditions of interval uncertainty

The state of the considered technical system S is given by a set of parameters $s=(s_1,...,s_m)$ during the period of operation $[0,T]$. Let us formulate the problem of risk management for the case of discrete control carried out at time points t_k, $k=0,...,$n, $T = t_n - t_0$. Parameter operability area number j of this technical object at the moment of time t_k is given by the relation

$$\underline{s_{jk}} \le s_{jk} \le \overline{s_{jk}} \qquad (3)$$

These parameter values determine the possible deviation from the calculated nominal values at which the system remains operational.

The vector of the state of the system at the moment of time t_k, $k=0,...,n$ has the form

$$s(t_k) = \left(s_1(t_k) \dots . s_m(t_k)\right) \qquad (4)$$

If the value of the system parameter number j at time goes beyond the region specified by relation (4), then a risk event associated with a failure occurs.

To prevent accidents and failures, the parameters of the technical system are regularly measured and monitored. A set of repair and preventive measures is carried out to ensure the stable operation of the system in question. Carrying out the indicated type of work is associated, as a rule, with significant material costs and forced downtime of equipment. The costs c_k or maintenance of the system at time $t_k \in T$ are given by the ratio

$$\underline{c_{jk}} \leq c_{jk} \leq \overline{c_{jk}}. \tag{5}$$

The total cost C associated with the control and measurement and preventive measures is calculated based on the ratio

$$C = \sum_{i=0}^{n} c_k = [\underline{c}, \bar{c}] \tag{6}$$

$$\underline{c}, \leq C \leq \bar{c}$$

The risk control strategy involves the implementation of such a set of control actions and preventive measures, in which the amount of damage caused by a risk event is minimal.

The vector of control actions on the system parameters during the operation period [0, T] has the form

$$u=(u_{1,\dots,}u_r) \tag{7}$$

The set of values of the control correcting action number j on the parameters of the system at the moment of time t_k, k=0…n given by the ratio

$$\underline{u_{jk}} \leq u_{jk} \leq \overline{u_{jk}} \tag{8}$$

The vector of control actions at the moment of time t_k, k=0,...,n has the form

$$u(t_k) = \left(u_1(t_k) \dots . u_r(t_k)\right) \tag{9}$$

Let B_k=B_k $(s(t_k), s(t_{k+1}\}, u(t_k), t_k)$ costs associated with the chosen risk control strategy at time t_k. Then the optimal control $u^*(t_k)$, leading to the minimum costs of operation of the technical system are determined for the time t_k on the basis of the relation

$$B_k\ (s(t_k), s(t_{k+1}\}, u^*(t_k), t_k) \leq B_k\ (s(t_k), s(t_{k+1}\}, u(t_k), t_k) \tag{10}$$

During the period of operation $T= t_n - t_0$ we have a set of optimal control actions in the form

$$U^*(t_0,t_n)=\{u^*(t_0 \dots ,u^*(t_n)\} \tag{11}$$

The optimal risk management strategy is to determine such a set of control actions on the system parameters, in which the amount of damage in the event of a risk event will be minimal.

$$J = \sum_{k=0}^{n-1} B_k \,(s(t_k), s(t_{k+1}\}, u(t_k), t_k) \dashrightarrow \min \qquad (12)$$

$$\sum_{k=0}^{n} c_k = C \dashrightarrow \min \qquad (13)$$

Application of the theory of emissions of random processes to the problem of risk management arising from the functioning of critical systems

An important role in solving the problem of risk management in the operation of critical systems is played by the problem of determining the first moment in time at which a random process goes out outside the area of operability. To solve the indicated problem it is necessary to use elements of the theory of emissions of random processes, which are described in the paper [11].

Suppose that the change (drift) of the parameters of the system S is described by a random process S (t) and the first exit of the process under consideration outside the range of operability W leads to a failure (an emergency situation in which the operability of the system is disrupted). We denote by P (t) the probability of failure-free operation of the system, where $P(t)= P\,(S(\tau)\in W)$, $\tau\in[0, t]$.

For a stationary differentiable process $P(t)$ has the form

$$P(t) = P_0 - n \int_0^t (1 - L(\tau))\, d\tau \qquad (14)$$

where

P_0 – the probability of the process being in the operability area at the initial moment of time;

n – the average number of emissions of the process under consideration per unit of time outside the region;

$L(\tau)$ – distribution function of the duration of the residence time of the process in a given region W from the moment it hits it until the moment it leaves it for the first time.

Let us consider the case in which the performance area W is specified using an interval of the form $W =[\underline{a}\,, \overline{a}\,]$. In this case, expressions for calculating the value $P(t)= P\,(\underline{a} < S(\tau) < \overline{a})$, $\tau \in [0, t]$ has the form

$$P(t) = F(\overline{a}) - F(\underline{a}) - n_{\underline{a}\overline{a}} \int_0^t (1 - L_{\underline{a}\overline{a}}(\tau))\, d\tau \qquad (15)$$

where

F (...) – the distribution function of the ordinate of the considered random process describing the functioning of the system.

$n_{\underline{a}\overline{a}}$ – the average number of times a random process leaves the range of operability per unit time *W;*

$L_{\underline{a}\overline{a}}$ – the distribution function of the duration of the residence time of the process in a given region W from the moment it hits it until the moment it leaves it for the first time.

We introduce into consideration the following random variables.

τ – time since the beginning of observation of the considered random process until the moment of its first exit from the domain W;

μ – duration of time passing from the moment of the first hit of the process in the area W to the moment of the 1st exit from it;

ρ – the duration of the time elapsing from the moment a random process enters the domain W until the moment it begins to observe it.

The magnitude μ = τ+ ρ. Let *K*(τ) = 1 – *L*(τ)*,*φ(τ) – distribution density of a random variable τ. In the introduced notation

$$\varphi(\tau) = -\frac{dP}{d\tau},\ \varphi(\tau) = n_{\underline{a}\overline{a}}\, K(\tau) \qquad (16)$$

Consider the expressions *K*(*t*)=*P*(μ>*t*) и *P*(*t*)=*P*(τ>*t*). Between realizations of random variables и the relation is true μ>τ. Hence, *K*(*t*) ≥ *P*(*t*).

$$\frac{dP}{dt} = -n_{\underline{a}\overline{a}}\, K(t) \qquad (17)$$

Dividing the left and right sides of relation (17) by *P*(*t*), we obtain the expression

$$\frac{dP}{Pdt} = -n_{\underline{a}\overline{a}} \frac{K(t)}{P(t)} \qquad (18)$$

Let us introduce the notation

$$\delta(t) = -\frac{dP}{Pdt},\ b(t) = \frac{K(t)}{P(t)} \qquad (19)$$

In the introduced notation, we have

$$\delta(t) = n_{\underline{a}\overline{a}}\, \mathrm{b(t)} \qquad (20)$$

Due to the inequality *K*(*t*) ≥ *P*(*t*) variable *b*(*t*) ≥ 1, hence, $\delta(t) \geq n_{\underline{a}\overline{a}}$,

Let us construct estimates for the quantity *P*(*t*). Let *K*(τ) = 1 – *L*(τ) =1. In this case, we have the estimate

$$P(t) \geq F(\overline{a}) - F(\underline{a}) - n_{\underline{a}\overline{a}} t, \quad t \leq \frac{F(\overline{a}) - F(\underline{a})}{n_{\underline{a}\overline{a}}}. \qquad (21)$$

For the case of one-sided boundaries, we have the following estimates

$$P(t) \geq F(\overline{a}) - n_{\overline{a}}t, \quad t \leq \frac{F(\overline{a})}{n_{\overline{a}}} \tag{22}$$

$$P(t) \geq 1 - F(\underline{a}) - n_{\underline{a}}t, \quad t \leq \frac{1-F(\underline{a})}{n_{\underline{a}}} \tag{23}$$

When solving practical problems, random processes are often considered, which are the sum of a deterministic function and random noise, which are described by the relation

$$S(t) = Y(t) + \beta(t) \tag{24}$$

where

$Y(t)$ – random noise;

$\beta(t)$ – deterministic function.

Formulas for estimating the probability of no-failure operation P (t) for random processes of the form (24) are presented in the paper [12].

To estimate the probability of a random process staying in a given area, it is necessary to know the one-dimensional distribution law of the ordinate of this process, as well as the average number of outliers of this process outside the band per unit time *W*.

The use of the above mathematical apparatus allows one to obtain approximate estimates of the value $P(t)$ of the probability of failure-free operation of the system under consideration, as well as tentatively determine the moment of the onset of a risk event (the first outburst of a random process outside the area W), at which a failure occurs in the operation of the technical object under study. The use of this kind of methods is suitable for groups of technical objects characterized by statistical homogeneity and does not take into account individual characteristics and unique features characteristic of critical systems.

To solve the indicated problem, the method of individual forecast is used [6].

At a moment in time t_p information on the progress of changes in the process of system functioning is available in the form of a sequence of observations $\{d_k\}$,_$k=0...p$. As a rule measurement of system parameters at various stages of control is associated with the presence of errors (inaccuracies in the operation of measuring equipment, rounding errors, etc.).

Results of the research

Making decisions on the choice of control actions that minimize risk in unique systems of responsible assignment is associated with the presence of incompleteness and uncertainty of information. The most appropriate tool for mathematical modeling in such a situation is the statistical apparatus of interval data [13-16].

When using this type of mathematical apparatus, it becomes possible to make optimal decisions in conditions of incompleteness and lack of information about the system parameters, since the sample volumes with which the interval data statistics apparatus operates are much smaller than in the case of traditional methods of mathematical statistics.

Consider the formulation of the problem of constructing an individual forecast of changes in the state of a critical technical system.

Let, $S(t)$ be a random process describing the change in the values (drift) of the parameters of a critical technical system S during a time interval $[0,t_p]$ and define the further trajectory of the system parameters change over the time interval $T\text{-}t_p$.

Suppose that the model of the random process $S(t)$ has the form

$$S(t)=F(t)+h(t) \qquad (25)$$

where

$F(t)$ – the form of the process under consideration (scalar, linear, monotonic);

$h(t)$ – model error, which may be absent, random or interval given.

Consider a specific form of a random process given by the relation

$$S(t)=a'b(t)+h(t),\ t \in [0,T] \qquad (26)$$

where

$a=\{a_j\},\ j=0,\dots n$ – vector of random coefficients;

$b(t)$ – continuously specified deterministic functions of time $t\in[0,T]$;

$h(t)$ – model error given by interval $\underline{h(t)}\leq h(t)\leq \overline{h(t)}$ time function $t\in[0,T]$;

On a time interval $T_p\in T$ consider the implementation $s(t)$ of the process $S(t)$, observed with measurement error $e(t_k)$ for the moment of control t_k, given by the interval ratio

$$\underline{e(t_k)} \leq e(t_k) \leq \overline{e(t_k)} \quad (27)$$

In accordance with model (15), the implementation of the process $S(t)$ on the time interval $[0, T_p]$ has the form

$$s(t) = a'b(t) + [\, \underline{h(t)}, \overline{h(t)}] \quad (28)$$

For the moment of control t_k set of valid process implementations $s(t_k)$ described by the expression

$$\underline{e(t_k)} + \underline{h(t_k)} + d(t_k \leq s(t_k \leq \overline{e(t_k)} + \overline{h(t_k)} + d(t_k,), t_k \epsilon T_{p\_} \quad (29)$$

Condition (18) describes the forecast tube, which is guaranteed to contain the values of the realization $s(t_k)$ at the moment $t_k \in T_p$.

Let us single out among the admissible implementations $s(t_k)$ extreme $s(t_k)^+$, $s(t_k)^-$ based on solving a minimax optimization problem of the form

$$'b(\backslash t^*) + h(t^*) \rightarrow \max \quad (30)$$

$$a'b(t^*) + h(t^*) \rightarrow \min\ t^* \epsilon\ [T_p, T] \quad (31)$$

With restrictions

$$\underline{e(t_k)} + \underline{h(t_k)} + d(t_k \leq a'b(t_k) + h(t_k) \leq \overline{e(t_k)} + \overline{h(t_k)} + d(t_k, k=0 \ldots p \quad (32)$$

Approaches to solving the problem under consideration are described in the paper [15].

Suppose that, based on the solution to problem (19-21), extreme realizations are determined $s(t_k)^+$, $s(t_k)^-$, $t_k > t_p$.

Let the boundaries of the operability area be given in the form

$$A(t_k) = (\underline{s_{1k}}, \ldots, \underline{s_{mk}}),, \ k=0 \ldots n \quad (33)$$

$$B(t_k) = (\backslash \overline{s_{1k}}, \ldots, \overline{s_{mk}}), \ k=0 \ldots n \quad (34)$$

To solve the problem of risk management, it is necessary to determine the closest moment in time at which a risk event (failure) is possible, and also to reduce, if possible, the number of preventive measures associated with measuring and monitoring the state of the system..

In this regard, as the next point in time at which it is necessary to monitor the system state, it is advisable to choose $t_{p+1} = \min\backslash\{\tau_{A_k}, \tau_{B_k}\}$, where are the moments in time τ_{A_k}, τ_{B_k} are determined by solving equations of the form

$$A(t_k) = s(t_k)^-,, \ B(t_k) = s(t_k)^+ \quad (35)$$

Relations (24) specify the condition for the intersection of extreme trajectories and boundaries of the system operability region at the moment $t_k > t_p$.

For a period of time t_c=$t_{p+1} - t_p$ it is possible to guarantee that the system parameters are within the operability range and that there are no failures.

The considered process of predicting the state of the system is iterative in nature. The next step is to determine the moment in time t_{p+d} monitoring the state of the system based on the calculation of extreme trajectories based on the available observable information (d_{p+1}, t_{p+1}).

If the period of operation before the onset of the next risk event is less than the minimum guaranteed reasonable interval of time for maintaining operability t_c^{min}, t_{p+d}- $t_{p+1} < t_c^{min}$, then it is necessary to stop the system at the moment t_{p+1} and take the necessary preventive measures to correct the values of the parameters of the considered technical object.

Discussion and conclusions

In the course of the work carried out, the main approaches to managing risks arising from the operation of complex technical systems for critical purposes were studied, and a mathematical model was developed that allows choosing the optimal strategy for monitoring and adjusting the values of the parameters of systems of this type under conditions of interval uncertainty. An algorithm has been developed for predicting changes in the state of a technical system during the entire period of its operation based on the statistical apparatus of interval data, which makes it possible to take into account the measurement errors of the main parameters of the system when taken into account at all stages of the control process. The use of the mathematical apparatus of the theory of bursts of random processes makes it possible to find approximate estimates of the probability of failure-free operation of a critical technical system under conditions of uncertainty, as well as to calculate the moment of the first release of the process outside the acceptability region.

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DATA ABOUT THE AUTHOR

Pavel V. Kalashnikov, junior researcher

Institute for Automation and Control processes, Far Eastern Branch of Russian Academy of Sciences
5, Radio Str., Vladivostok, 690041, Russian Federation
ORCID: http://orcid.org/0000-0003-5424-1635
kalashnikovpv@iacp.dvo.ru

ДАННЫЕ ОБ АВТОРЕ

Калашников Павел Викторович, младший научный сотрудник

Федеральное государственное учреждение науки Институт автоматики и процессов управления Дальневосточного отделения Российской академии наук (ИАПУ ДВО РАН)
ул. Радио, 5, г. Владивосток, 690041, Российская Федерация
kalashnikovpv@iacp.dvo.ru

Поступила 10.05.2022 Received 10.05.2022
После рецензирования 30.05.2022 Revised 30.05.2022
Принята 05.06.2022 Accepted 05.06.2022