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STUDY OF TECHNOLOGY FOR THE RELIABILITY AND SURVIVABILITY MODELLING OF ONBOARD CONTROL SYSTEM OF SMALL SPACECRAFT OPERATING IN COMPLEX MODES

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The technology of system modeling of reliability and survivability of the onboard control system (OCS) of the spacecraft is presented in the study of various options for the activation of operating modes. The technology of spacecraft functioning based on the concept of digital twins currently takes a leading position. That's concept allows you to create realistic virtual copies of spacecraft, to simulate not only the objects themselves, but also the processes of their design and operation in various conditions of a priori uncertainty. Such conditions, first of all, should include the destructive effects of an aggressive external environment (outer space) and the multi-mode nature (sequence and intensity of the modes involved) of the functioning of onboard spacecraft systems. The implementation of the requirements of multi-purpose and multi-mode control in these conditions is closely related to the study of the reliability and survivability of such objects from the standpoint of considering their structural construction. The proposed article discusses an approach to assessing the reliability and survivability of onboard systems of small spacecraft (SS), which is based on the concept of a parametric genome structure, taking into account the multi-mode operation in an aggregated form.

Keywords: modes of functioning, parametric genome of structure, structural and functional survivability, motion control system, small spacecraft, onboard control complex

1 INTRODUCTION

Ensuring the sustainability of the OCS is undoubtedly one of the determining conditions the onboard systems, including sufficient structural and functional resources required to achieve the intended objectives, the capacity of onboard power sources, the mass of the working body for rocket engines, is established to fulfill the flight program [1-2]. However, during its active existence, the spacecraft is significantly affected by various external factors and specific conditions of being in space, which may include: weightlessness, electromagnetic radiation, special temperature conditions, impact of electrostatic and magnetic fields, vacuum, vibration, aerogasdynamic effects, heavy charged particles, radio noise, etc. Despite a large volume of ground tests, it is impossible to take into account all possible factors, leading to loss of design life of OCS in flight due to abnormal flight situations. Firstly, not all conditions of a space flight can be reproduced on Earth during complex tests, in particular, conditions of weightlessness, impacts of ionizing radiation and others [3]. Secondly, each SS is a "product" of small-scale or even single production, which also does not allow a full flight qualification of the reliability of the systems [4].

It is important to note that, among other things, the functional elements and subsystems of OCS of SS can operate in different modes to support the mission's mission objectives [5]. Moreover, the modes of operation differ in terms of the nature and intensity of their use. Depending on SS target mission and interoperability, the modes of operation of OCS can be performed in time both sequentially and in parallel, as well as have different intensity of activation.

Therefore, an important and indispensable condition of research dedicated to ensuring the sustainability of OCS of SS is the analysis of such an important property of SS as structural and functional sustainability under conditions of multi-mode and negative impacts of the external environment [5-7]. Hereinafter, under structural and functional stability of OCS of SS we will understand the ability of an object to preserve within certain limits the quality of its target functioning (implementation of functioning modes) (or to restore such ability) by changing (forming) the structural and functional configuration of OCS configurations. And the study of this property should be conducted taking into account the possibility of joint application of modes of functioning, the equivalence of intensities of engagement of modes of functioning and homogeneity of the structure of elements and subsystems of the OCS.

2 METHODOLOGY

2.1 Evaluating the stability of a small spacecraft onboard control system

The entire process of calculating the generalised stability index of an OCS can be divided into several stages.

Stage I. The study of structural and functional reliability of OCS of a SS, including the construction of parametric genome of the investigated structure [8,9] and calculation on its basis of integral indices of structural and functional reliability for different variants of structure elements description [10-13] (the structure consists of homogeneous or non-uniform elements by probability of failure-free operation, elements have homogeneous fuzzy-possible description of functioning), and also consideration of possibility of joint or non-combined use of functioning modes.

Stage II. Identification of the different reconfiguration trajectories of the structure under study: pessimistic, optimistic and random.

Stage III. Conduct a series of computational experiments to determine the values of structural and functional stability indicators in the form of a fuzzy triangular number.

Before performing the first step, it is advisable to conduct a preliminary analysis of the possible schemes and modes of operation of OCS of SS. The methods and approaches to such analysis are the subject of a separate study and are not considered in this paper. This topic and its individual aspects are discussed in more detail in [5-9]. For this reason, it is assumed that the preliminary stage of the analysis has been carried out and its results are summarized in the form of three schemes shown in Figures 2-4.

Let us now elaborate on each step of the procedure for calculating a generalised indicator of the structural and functional stability of an OCS.

To investigate the structural and functional reliability of the OCS, it is reasonable to use the capabilities of the general logical and probabilistic method (GLPM) and construct a functional integrity diagram (FID) of OCS of SS [14]. It should be noted that in the presence of groups of incompatible events (GIE) [14], used to reflect the separate (sequential) involvement of both modes of operation and elements of the OCS of SS, in the construction of logical and probabilistic models, their consideration is carried out automatically.

Using the automated structural-logical probabilistic modelling software package "Arbiter" [14], we obtain two probabilistic polynomials of its successful functioning (implementation of functioning modes) (1) for FID of the OCS of a SS

$$\begin{gathered}\Re_c(P_1,\dots,P_n,P_{n+1},\dots,P_{n+m},Q_1,\dots,Q_n,Q_{n+1},\dots,Q_{n+m})\\ \Re_p(P_1,\dots,P_n,P_{n+1},\dots,P_{n+m},Q_1,\dots,Q_n,Q_{n+1},\dots,Q_{n+m})\end{gathered} \tag{1}$$

where $\Re_c(P_1,\dots,P_n,P_{n+1},\dots,P_{n+m},Q_1,\dots,Q_n,Q_{n+1},\dots,Q_{n+m})$ - the probability function of the implementation of modes of operation of the OCS of SS, which are not a group of incompatible events;$\Re_p(P_1,\dots,P_n,P_{n+1},\dots,P_{n+m},Q_1,\dots,Q_n,Q_{n+1},\dots,Q_{n+m})$ - the probability function of the implementation of modes of operation of the OCS, representing a group of incompatible events;$P_i(Q_i), i=1,\dots,n$ - the probability of failure-free operation (failure) of functional elements (FE) of OCS of SS, and $P_{n+i}(Q_{n+i}), i=1,\dots,m$ - the intensity of demand (not demand) for the implementation of the operational modes of OCS. We will denote the intensity of the requirements for the implementation of modes of operation by $\beta_i=P_{n+i}, i=1,\dots,m$. Then, using the parametric genome [5] for a structure without GIE

$$\begin{gathered}\vec{\chi}_c(\beta_1,\dots,\beta_m)=(\chi_{c0}(\beta_1,\dots,\beta_m),\\ \chi_{c1}(\beta_1,\dots,\beta_m),\dots,\chi_{cn}(\beta_1,\dots,\beta_m))^T\end{gathered}$$

and a parametric genome for a structure with GIE

$$\vec{\chi}_p(\beta_1,\dots,\beta_m)=(\chi_{p0}(\beta_1,\dots,\beta_m),\chi_{p1}(\beta_1,\dots,\beta_m),\dots,\chi_{pn}(\beta_1,\dots,\beta_m))^T \text{ [9]},$$

Let us calculate estimates of structural and functional reliability of OCS, depending on the parameters $\beta_1,\dots,\beta_m$ of intensities of separate (GIE) or joint use of modes of operation.

In case of probabilistic description of failure-free operation of elements for the case, when the probability of failure-free operation of FE of the onboard control system is the same (homogeneous structure) [9], the structural and functional reliability indicator can be calculated according to the formula (2)

$$\begin{aligned}&F_{hom\,og}(\vec{\chi}(\beta_1,\dots,\beta_m))=\int_0^1\Re(P,\beta_1,\dots,\beta_m)dP=\\ &=\vec{\chi}(\beta_1,\dots,\beta_m)\cdot(1,\frac{1}{2},\frac{1}{3},\dots,\frac{1}{n+1})^T,\end{aligned} \tag{2}$$

Where $\Re(P,\beta_1,\dots,\beta_m)$ is a polynomial either $\Re_p(P_1,\dots,P_n,P_{n+1},\dots,P_{n+m},Q_1,\dots,Q_n,Q_{n+1},\dots,Q_{n+m})$, or $\Re_c(P_1,\dots,P_n,P_{n+1},\dots,P_{n+m},Q_1,\dots,Q_n,Q_{n+1},\dots,Q_{n+m})$ considering what $P_1=P_2=\dots=P_n=P, P_{n+1}=\beta_1, P_{n+2}=\beta_2,\dots,P_{n+m}=\beta_m$, a $\vec{\chi}(\beta_1,\dots,\beta_m)$ the corresponding parametric genome for a structure with GIE or without GIE.

In the case of a heterogeneous structure (different values of the probability of failure-free operation of FE), it is proposed to use the expression presented by formula (3) as an indicator of structural and functional reliability

$$\begin{aligned}&F_{heterog}(\vec{\chi}(\beta_1,\dots,\beta_m))=\\ &=\vec{\chi}(\beta_1,\dots,\beta_m)\cdot(1,\frac{1}{2},\frac{1}{2^2},\dots,\frac{1}{2^n})^T.\end{aligned} \tag{3}$$

If it is impossible to identify a well-defined stochastic pattern of failure-free performance when performing functions of FE of OCS, it is considered appropriate to use a fuzzy-possibility approach to describing the behavior of elements, based on the notion of a space with a measure of possibility [14,16].

Then, applying the operation of fuzzy integration on a possible measure [16] to calculate the integral index of structural and functional reliability of OCS, we obtain

$$F_{hom\ \mathrm{poss}}(\vec{\chi}(\beta_1,\ldots,\beta_m)) = \sup_{\mu\in[0,1]} min\{R(\mu,\beta_1,\ldots,\beta_m)$$
$$g(\mu)\} = \sup_{\gamma\in[0,1]} min\{\gamma, G(\{\mu|R(\mu,\beta_1,\ldots,\beta_m)\geq\gamma\})\} \tag{4}$$

It should be noted that the following constraints are imposed on the parameters $\beta_1,\ldots,\beta_m$ in the most general case when simultaneous (parallel, joint) operation modes are involved $0\leq\beta_i\leq1, i=1,\ldots,m$. If these modes are used separately, these restrictions must be supplemented by the following $\sum_{i=1}^{m}\beta_i\leq1$.

In addition to the jointness of the modes of operation, it should be noted that the intensity of their operation can be both the same (modes of equal intensity, that is $\beta_1=\beta_2=\ldots=\beta_m=\beta$) and different (modes of unequal intensity). This means that when the modes of equal intensity are used separately, the constraint $\sum_{i=1}^{m}\beta_i\leq1$ will be $\beta\leq\frac{1}{m}$. Taking all of the above into account, in order to investigate the structural and functional reliability of an object, let us introduce the integral indicators represented by formulas (5)- (8)

$$J_{pp} = m\cdot\int_0^{1/m\int} F_*(\vec{\chi}_p(\beta))d\beta \tag{5}$$

$$J_{cp} = \int_0^1 F_*(\vec{\chi}_c(\beta))d\beta, \tag{6}$$

$$J_{pn} = m!\cdot\iiint_{\substack{\beta_1+\ldots+\beta_m\leq1\\0\leq\beta_i\leq1,i=1,\ldots,m}} F_*(\vec{\chi}_p(\beta_1,\ldots,\beta_m))d\beta_1d\beta_2\ldots d\beta_m\,, \tag{7}$$

$$J_{cn} = \int_0^1\int_0^1\ldots\int_0^1 F_*(\vec{\chi}_c(\beta_1,\ldots,\beta_m))d\beta_1d\beta_2\ldots d\beta_m, \tag{8}$$

where indicators (5) and (6) allow estimating generalized structural and functional reliability of the object at separate and joint use of modes of functioning equal in intensity, and indicators (7) and (8) - at separate and joint use of modes of functioning unequal in intensity, respectively. In formulas (5)-(8), $F_{hom\,og}$, $F_{heterog}$ or $F_{hom\ \mathrm{poss}}$ can obviously be used as the F_* function.

To calculate the generalized structural and functional stability indicator of the OCS, we will use the approach outlined in [8]. Let us briefly clarify the essence of this approach.

The process of reconfiguration (degradation or restoration) of structure of OCS will be correlated with operations of removal $\left(P_j=0\right)$ or restoration $\left(P_j=1\right)$ of the FE of the OCS from some set $\{P_{j_1},P_{j_2},\ldots,P_{j_N}\}=\tilde{P}\subseteq\{P_1,P_2,\ldots,P_n\}$. In the process of FE removal (recovery), the structure of OCS may be in one of its intermediate states S_α, characterised by the corresponding parametric genome $\vec{\chi}_\alpha(\beta_1,\ldots,\beta_m)$. One possible reconfiguration trajectory of the OCS structure during the failure (recovery) process can be described by the following chain of transitions $\vec{\chi}_{\alpha_0}(\beta_1,\ldots,\beta_m)\xleftrightarrow{P_{j1}}\vec{\chi}_{\alpha_1}(\beta_1,\ldots,\beta_m)\xleftrightarrow{P_{j2}}\ldots\ \ldots\xleftrightarrow{P_{jN}}\vec{\chi}_{\alpha_N}(\beta_1,\ldots,\beta_m)$, where $\vec{\chi}_{\alpha_0}(\beta_1,\ldots,\beta_m)=\vec{\chi}_0(\beta_1,\ldots,\beta_m)$ - is an initial state, $\vec{\chi}_{\alpha_N}(\beta_1,\ldots,\beta_m)=\vec{\chi}_f(\beta_1,\ldots,\beta_m)$ - is a final state, $\vec{\chi}(\beta_1,\ldots,\beta_m)\xleftrightarrow{P_j}\vec{\chi}_\alpha(\beta_1,\ldots,\beta_m)$ - the directly related structural states of OCS S and S_α, when a functional element P_j fails (recovers). Denote by $X(\vec{\chi}(\beta_1,\ldots,\beta_m))$ the set of all structural states directly related to the state $\vec{\chi}(\beta_1,\ldots,\beta_m)$.

In order to construct an optimistic (pessimistic) trajectory for the reconfiguration of the OCS, the following optimization problems must be solved (9)

$$\sum_{j=0}^{N} F_{stab}^{\alpha_j} \rightarrow \max_{\substack{\vec{\chi}_{\alpha_j}(\beta_1,\ldots,\beta_m)\in X(\vec{\chi}_{\alpha_{j-1}}(\beta_1,\ldots,\beta_m))\\ \vec{\chi}_{\alpha_0}(\beta_1,\ldots,\beta_m)=\vec{\chi}_0(\beta_1,\ldots,\beta_m),\\ \vec{\chi}_{\alpha_N}(\beta_1,\ldots,\beta_m)=\vec{\chi}_f(\beta_1,\ldots,\beta_m),\\ \{P_{j_1},P_{j_2},\ldots,P_{j_N}\}=\tilde{P}}} (\min)\ . \tag{9}$$

The following integral indicators of structural and functional reliability of OCS of SS can be used here as

$$F_{stab}^{\alpha_j} - m\cdot\int_0^{1/m} F_*(\vec{\chi}_{p\alpha_j}(\beta))d\beta, \int_0^1 F_*(\vec{\chi}_{c\alpha_j}(\beta))d\beta,\ m!\cdot\iiint_{\substack{\beta_1+\ldots+\beta_m\leq1\\0\leq\beta_i\leq1,i=1,\ldots,m}} F_*(\vec{\chi}_{p\alpha_j}(\beta_1,\ldots,\beta_m))d\beta_1d\beta_2\ldots d\beta_m,$$
$$\int_0^1\int_0^1\ldots\int_0^1 F_*(\vec{\chi}_{c\alpha_j}(\beta_1,\ldots,\beta_m))d\beta_1d\beta_2\ldots d\beta_m.$$

In [8], a combined method of random directed search for variants of the solution of the given problem is presented and an algorithm that implements the above method and allows finding both optimistic and pessimistic trajectories, as well as intermediate trajectories constructed at random, is developed.

Figure 1 shows the trajectory $\mu^{(k)}$ of the reconfiguration of OCS structure. Here, the abscissa axis shows the intermediate states of OCS of SS, and the ordinate axis shows the values of structural and functional reliability of OCS in these states. The area S_0 equal to $1 \cdot N$, is directly proportional to the maximum total index of structural and functional reliability of functioning of OCS in case of failure of N elements. The calculated area $S^k = \sum_{j=0}^{N-1} \frac{F_{stab}^{\alpha_j(k)} + F_{stab}^{\alpha_{j+1}(k)}}{2}$ equals the total structural and functional reliability of the functioning of OCS during the reconfiguration process under scenario $\mu^{(k)}$.

We obtain that the ratio of these areas $J^k = \frac{S^k}{S_0} = \frac{S^k}{N}$ allows us to quantify the structural and functional stability indicator of OCS of SS during its structural reconfiguration according to scenario$\mu^{(k)}$.

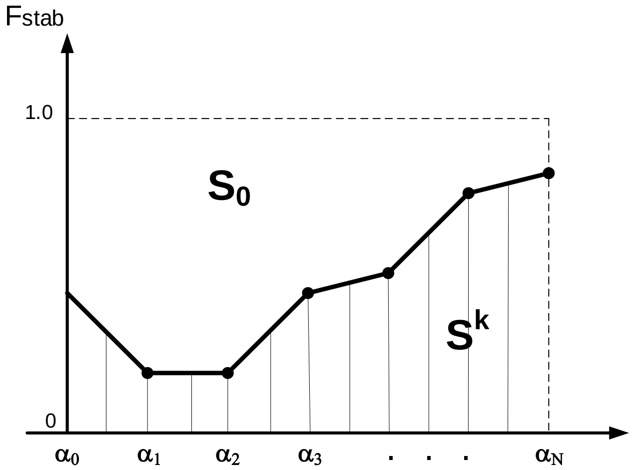


Fig. 1. Graphical interpretation of the calculation of the generalized stability indicator of the OCS along the reconfiguration trajectory

As a result of a series of M experiments for the construction of arbitrary reconfiguration traces, the average value of the stability indicator $J^0 = \frac{1}{M}\sum_{k=1}^{M} J^k$ is calculated.

Then [8] the maximum J^{max} value of the generalized structural and functional stability indicator of the OCS J will be achieved in the optimistic scenario of OCS reconfiguration, and the minimum J^{min} value - in the pessimistic scenario.

It is easy to see that the real values of J will lie in the interval $[J^{min^{max}}$ and the most expected value will be J^0. The values of J can be represented by a fuzzy triangular number (a, α, β), where $a = J^0$, $\alpha = J^0 - J^{min}$,$\beta = J^{max^0}$ [8,16].

Experimental researching of the motion control system of the small spacecraft for solving orientation problems in different modes of operation

As an example, let us consider the motion control system (MCS) of the Aist-2D spacecraft [17-19]. To study the structural and functional reliability, we will use the results from [9]. In [9], 4 modes of angular motion control were considered: angular velocity damping (AVD); uniaxial solar orientation (USO); three-axial orientation in the orbital coordinate system (OOCS); conducting experiments (CE). In addition, FID of three variants of the design solutions for the construction of MCS of SS, taking into account the orientation of the angular velocity sensitivity axes for the four uniaxial angular velocity meters (UAVM) were developed [17,19]: cubic configuration (three UAVM are coaxial to the axes of SS and the fourth on the diagonal of the cube), conical configuration with one axis meter (three UAVM are located in planes formed by the heights of tetrahedron faces and one UAVM is coaxial to the SS axis), exclusively conical configuration (all axes are located on planes formed by the heights of pyramid faces). In accordance with the above diagrams of the location of the devices of UAVM and the logic of the operation of MCS for different modes of SS [5,9], the FID of MCS to perform the task of determining the orientation of the SS will look as shown in Figures 2, 3, and 4.

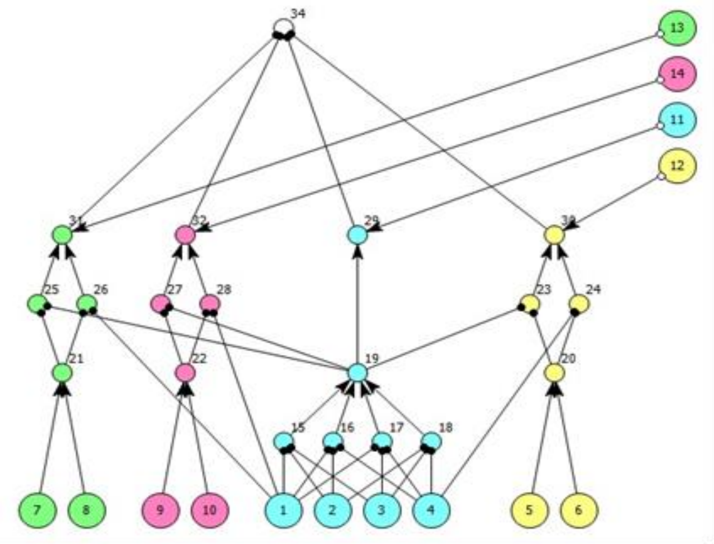


Fig. 2. FID of MCS for Cube configuration

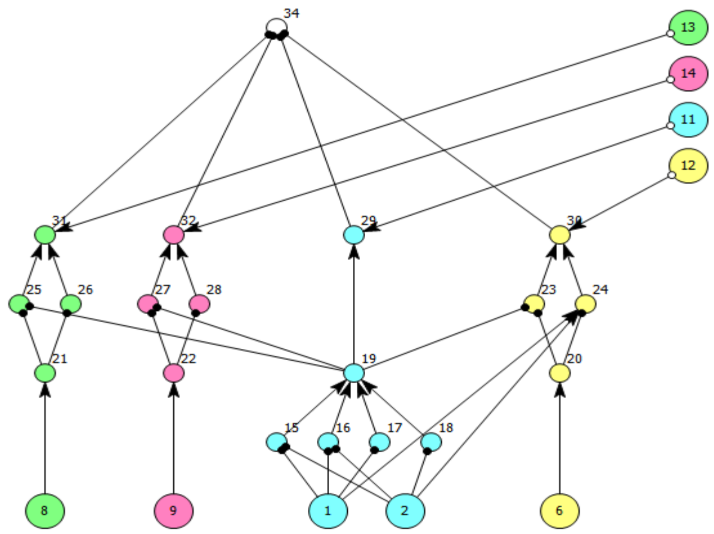


Fig. 3. FID of MCS for “Cone+Axis” configuration

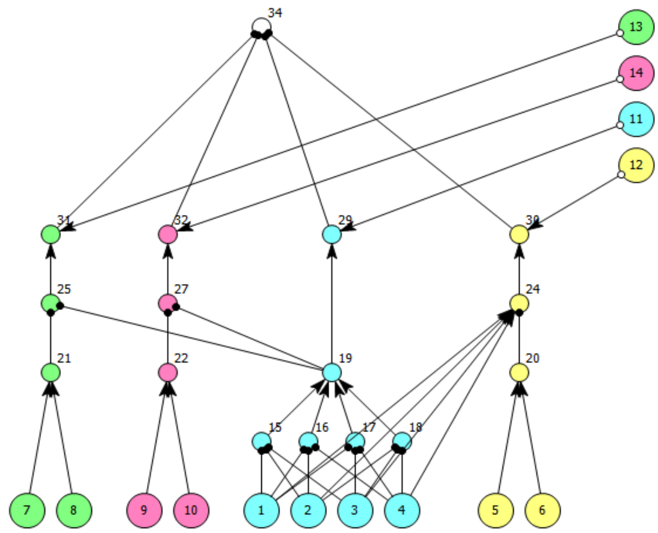


Fig. 4. FID of MCS for Cone configuration

Further, using the Arbiter [14], we obtain the probability polynomials (PP) of these FID, taking into account that the modes (nodes 11, 12, 13, 14) can represent a group of incompatible events (they are activated sequentially, separately) or not have this property. For example, for FID with a cube configuration, where modes can be triggered jointly, PP consists of 159 members. A fragment of PP is shown below:

$$P_1 * Q_2 * P_3 * P_4 * Q_5 * Q_6 * Q_7 * Q_8 * Q_9 * P_{10} * P_{12} * P_{13} +$$
$$+ P_1 * Q_2 * P_3 * P_4 * Q_5 * Q_6 * Q_7 * P_8 * Q_9 * Q_{10} * P_{12} * P_{14} +$$
$$+ Q_1 * P_2 * P_3 * P_4 * Q_5 * Q_6 * Q_7 * Q_8 * Q_9 * P_{10} * P_{12} * P_{13}$$

$$SS + P_1 * P_2 * Q_3 * P_4 * Q_5 * Q_6 * Q_7 * Q_8 * Q_9 * P_{10} * P_{12} * P_{13} +$$
$$+ P_1 * P_2 * Q_3 * P_4 * Q_5 * Q_6 * Q_7 * P_8 * Q_9 * Q_{10} * P_{12} * P_{14} +$$
$$+ Q_1 * P_2 * P_3 * P_4 * Q_5 * Q_6 * Q_7 * P_8 * Q_9 * Q_{10} * P_{12} * P_{14} \dots$$

The input data for assessing the structural and functional stability of MCS of SS with regard to multi-mode operation are the probability polynomial of such a system, taking into account the joint or separate (parallel or sequential) engagement of modes, as well as the equivalence of the engagement of modes of operation [5,20].

As mentioned earlier, the theoretical basis of the “Arbiter” is the general logical probabilistic method (OLVM) for analyzing structurally complex objects and processes of various types, classes and purposes, which includes the following provisions:

- For the structural and logical description of the studied properties of reliability (reliability) and safety (technical risk), OLVM uses a graphical apparatus of FID, which allows, on the basis of a functionally complete set of logical operations "AND", "OR", "NOT", to correctly represent almost all types of structural modeling — block diagrams, bounce trees and event trees.
- A complete set of logical operations "AND", "OR", "NOT" allows the analysis of both monotonic (coherent) and non-monotonic (incoherent) structural models of reliability, survivability and safety of complex systems and processes for various purposes.
- The logical versatility of the OLVM and the FID apparatus provide the user of the “Arbiter” with the opportunity to build both structural models of reliability (trouble-free) of the object under study and structural models of failure (accident) of the system.
- At the probabilistic level, the OLVM allows using not only the hypothesis of the independence of binary events, but also correctly taking into account groups of incompatible events, as well as implementing various models of failures for common reasons.

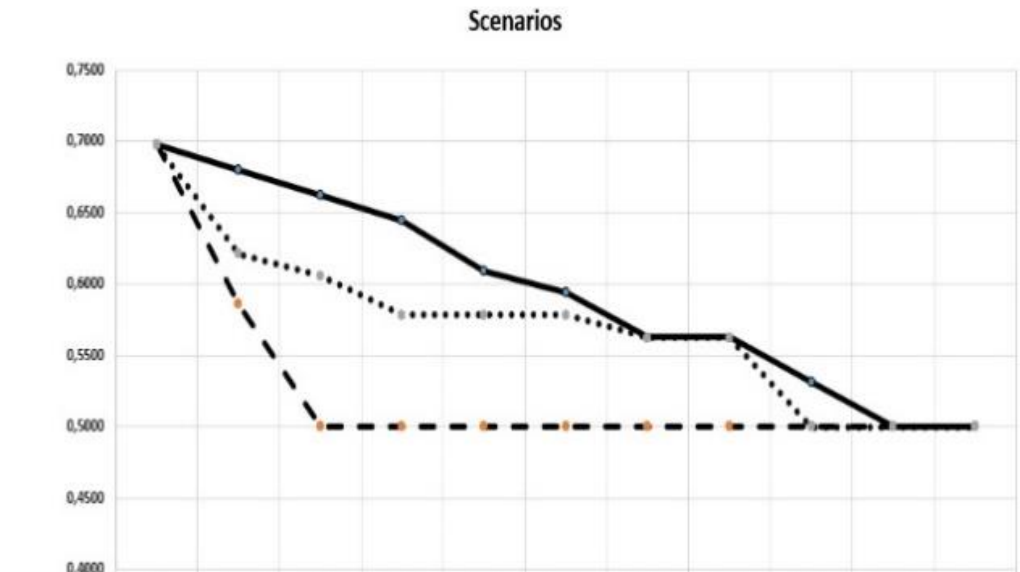
3 RESULTS AND DISCUSSION

3.1 Case 1

Let's calculate the values of structural and functional stability using the example of FID of MCS «Cube».

Case 1: *Incompatible angular motion control modes.*

The MCS reconfiguration trajectories for the variant considering equal intensity of engagement of incompatible angular motion control modes and heterogeneity of MCS of the SS structure are shown in Figure 5. The abscissa axis indicates the numbers of FE, whose failure led to a change in the generalized structural and functional reliability according to the optimistic (arbitrary; pessimistic) scenario.



	0	5(4;1)	7(8;4)	9(3;2)	2(2;3)	3(5;5)	4(6;6)	6(9;7)	8(1;8)	1(7;9)	10(10;10)
optimistic	0,6973	0,6797	0,6621	0,6445	0,6094	0,5938	0,5625	0,5625	0,5313	0,5000	0,5000
pessimistic	0,6973	0,5859	0,5000	0,5000	0,5000	0,5000	0,5000	0,5000	0,5000	0,5000	0,5000
arbitrary	0,6973	0,6211	0,6055	0,5781	0,5781	0,5781	0,5625	0,5625	0,5000	0,5000	0,5000

Fig. 5. Scenarios for the reconfiguration of the motion control system "Cube" (the structure is heterogeneous; modes are incompatible and equivalent)

The calculation of structural and functional stability for the variant under consideration (equal intensity of incompatible modes and heterogeneity of the structure) gave the following results: maximum value is J^{max}, minimum value is J^{min}, and the robustness of the arbitrary scenario given is $J^{k} = 0{,}5685$. In order to find the most expected value of J^{0} a series of 1000 experiments were carried out. As a result of these experiments the following estimate of $J^{0} = 0{,}5602$ is obtained. Then the generalised value of the structural and functional stability indicator of MCS for the variant under consideration, represented by a fuzzy triangular number, is as follows: $(a, \alpha, \beta) = (0.5602, 0.0417, 0.0342)$, where $a = 0.5602$, $\alpha = 0.5602 - 0.5185 = 0.0417$, $\beta = 0.5944 - 0.5602 = 0.0342$.

The results of values of the indicator of structural and functional stability of the motion control system of the SS with the Cube configuration for other options of intensity of engagement of angular motion control modes and homogeneity of MCS structure are presented in Table 1 (the cells of Table 1 show the values of $J^{min^{0^{max}}}$).

Table 1. Structural and functional stability of the orientation determination of SS for the Cube configuration (case 1)

Intensity of use of incompatible modes	Cube configuration (pessimistic, expected, optimistic impact scenario)	
	Homogeneous structure	Heterogeneous structure
Equal	0.5253; 0.5849; 0.6198	0.5185; 0.5602; 0.5944
Unequal	0.2405; 0.3397; 0.3917	0.2295; 0.2986; 0.3511

3.2 Case 2

Case 2: *Joint angular motion control modes.*

In this case, the reconfiguration trajectories of MCS of SS for the equal intensity of the joint angular motion control modes and the heterogeneity of the structure are shown in Figure 6.

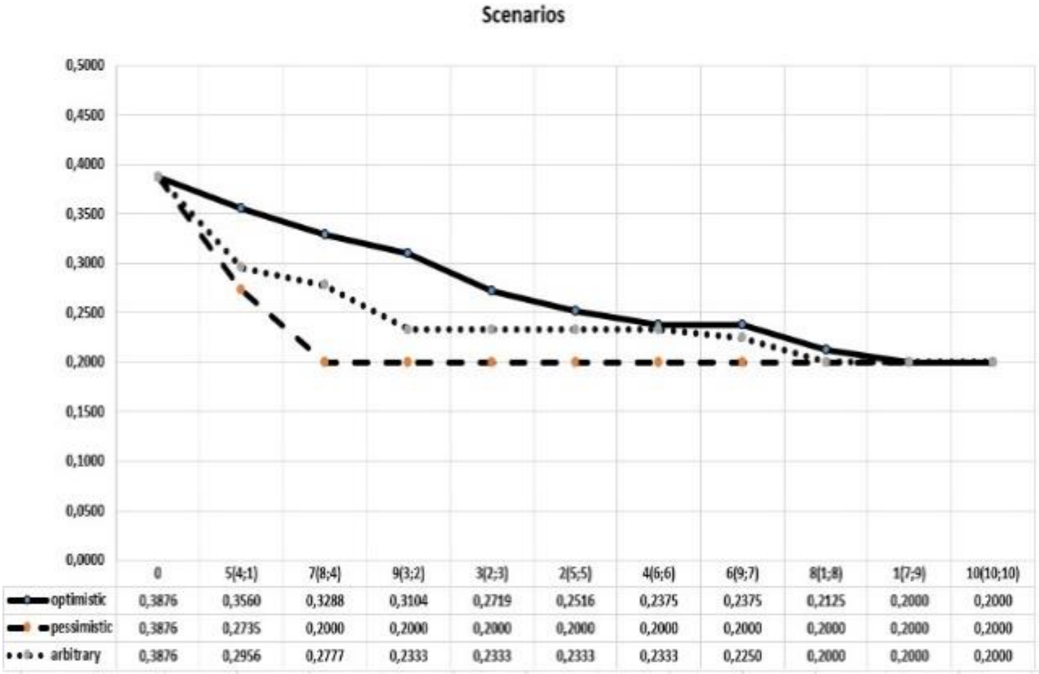


Fig. 6. Scenarios for reconfiguration of MCS of SS "Cube" (the structure is heterogeneous; modes are joint and equivalent)

The values of the structural and functional stability indicator of MCS with the Cube configuration for the case in question are shown in Table 2.

Table 2. Structural and functional stability of the orientation determination of SS for the Cube configuration (case 2)

Intensity of use of joint modes	Cube configuration (pessimistic, expected, optimistic impact scenario)	
	Homogeneous structure	Heterogeneous structure
Equal	0.2332; 0.2704; 0.3319	0.2163; 0.2411; 0.2700
Unequal	0.1022; 0.1521; 0.2215	0.0837; 0.1195; 0.1550

3.3 Discussion

In the course of this investigation, it was found that the stability of a motion control system of a SS, in addition to the homogeneity and heterogeneity of the structure, depends significantly on the way the modes of orientation are engaged. For example, the stability of MCS of SS is $\approx 22-29\%$ higher, when equal modes are not used than if unequal modes are used. The stability of MCS of SS increases by $\approx 12\%$ when equivalent modes are used together as opposed to when unequal modes are used.

4 CONCLUSIONS

4.1 Model limitations

The peculiarity and novelty of the method proposed in this article is that on a single methodological basis (the original concept of parametric genome of the structural construction of complex objects) it is possible to conduct research on the structural and functional properties and carry out rapid calculation of interval, optimistic and pessimistic assessments of structural and functional stability indicators of both homogeneous and heterogeneous structures of the OCS of a SS and various options for engaging modes of operation of complex objects.

A series of new indicators of structural and functional reliability and stability, reflecting the joint and separate use of modes of operation with different intensities, have been introduced. The proposed indicators of structural and functional stability of OCS of SS allows to analyze the stability of various configurations of onboard systems of a SS.

However, the proposed methodology and model have limitations. The introduction of multimode OCS into the structural model of reliability as functional vertices of the operation modes leads to the fact that it becomes incoherent (nonmonotonic), and the modes themselves can form groups of both incompatible and joint events. To identify the possibilities of such interaction, further development and research of the parametric genome concept is required.

4.2 Directions for future research

As promising areas for further research in the field of structural dynamics of complex multimode objects, we propose to develop a universal methodology for designing configurations of OCS of SS and their planned changes under conditions of uncertainty, limited onboard resources, and structural parameter degradation, in order to extend the active life of SS by uniformly loading their FE during operation.

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