SAFETY OF BUILDING CRITICAL INFRASTRUCTURES AND TERRITORIES

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METHODOLOGY OF ASSESSING INDIVIDUAL RELIABILITY OF UNIQUE STRUCTURES

Abstract. The paper describes the author’s methodology of quantitative reliability assessment of unique systems that are components of very expensive critical/strategic infrastructures, manufactured in very small series/batches, or even as single, unique structures. It was dubbed “theory of individual structural reliability — TISR”. With the development of the 3D digital technology and digitization that opened the door to creating digital twins in design, the share of unique products is growing non-stop in all branches of contemporary heavy industry and machine-building (rotor excavators, continuous casting plants, drilling rigs), adjacent sectors of industry (ship-building, aircraft building), and construction industry (large span bridges, super high skyscrapers, exhibition pavilions etc.). In this paper the TISR methodology is described for a class of unique and *non-renewable* objects using as an example a one-time-deployed-when-on-orbit robotic technological complex, designed to serve without interruption for 12–15 years in the near-space environment. The paper is a direct extract from preprint [1], revised and translated into English by its first author. The initial data needed for writing paragraphs 4 and 6 of this paper belongs to Yu. P. Pokhabov, published elsewhere, which made the description of implementing the TISR methodology in the field of unique spacecraft design up to date.. The author greatly appreciates and acknowledges the provided input.

Keywords: assessment methodology, individual reliability, unique structures

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МЕТОДИКА ОЦЕНКИ ИНДИВИДУАЛЬНОЙ НАДЕЖНОСТИ УНИКАЛЬНЫХ КОНСТРУКЦИЙ

Аннотация. Описана оригинальная методология количественной оценки надежности уникальных устройств/систем — компонент критических/стратегических инфраструктур, чрезвычайно дорогих технических объектов, изготавливаемых малыми сериями или даже в единичном экземпляре, которая получила название *теория индивидуальной конструкционной надежности*. Автором этой методики является С. А. Тимашев. К таким конструкциям относятся, например, уникальные большепролетные мосты, сверхвысокие небоскребы, выставочные павильоны. Доля уникальных изделий во всех отраслях современного тяжелого машиностроения (роторные экскаваторы: установки непрерывной разливки стали) и смежных секторах промышленности (судо-, авиастроении) с развитием современных цифровых 3D-технологий непрерывно растет. В данной статье метод оценки индивидуальной надежности рассмотрен на примере невосстанавливаемых складных телекоммуникационных спутников в виде робототехнических комплексов одноразового раскрытия, предназначенных для бесперебойной работы в течение не менее 12–15 лет в условиях ближнего космоса. Статья является прямой выдержкой из препринта [1], отредактированной и переведенной на английский язык ее первым автором. Исходные данные, необходимые для написания параграфов 3 и 5 настоящей статьи, принадлежат Ю. П. Похабову, были приведены им ранее в других публикациях. Эти данные позволили актуализировать описание процедуры использования TISR при создании уникальных космических аппаратов, за что автор глубоко признателен Ю. П. Похабову.

Ключевые слова: методология оценки, индивидуальная надежность, уникальные конструкции

Introduction. Current state of the art

Despite the imperative importance of the problem, assessing the reliability of individual systems still remains one of the unresolved problems of the modern theory of structural reliability.

This is largely due to the fact that among the designers of and reliability specialists of such systems a stable (but deeply erroneous) opinion was formed that the modern theory of structural reliability is fundamentally incapable of solving this problem [1, 2]. The origin of this opinion lies in the fact that classical structural reliability does not know how to construct. from a single-manufacture structure, the corresponding general sets (GS) of structural parameters values [3] that are absolutely needed for estimating their statistical distribution.

The corresponding GS for loads, impacts, and structural materials are quite accessible for construction and study, but do not exist in principle for the parameters of unique structures (US), and there are no adequate ways to create such GSs. Proposals [1, 2] to build virtual sets of such GSs based on institutional knowledge, expert judgment and common sense, or the results of computer modeling stumble upon the need to take into account the epistemic and aleatory components (that in this case are *terra incognita*) of such purely empirical models. Hence, the ad hoc construction of a virtual set of such GSs inevitably leads to unacceptably vague, fuzzy and largely speculative values of their possible stochastic properties, from which it is impossible to obtain the required robust (i. e., insensitive to small perturbations) quality estimates of highly reliable systems.

The specificity of unique systems, that must be taken into account during their design, in addition to their uniqueness and non-renewableness, is in that their designers have to [4]:

- strictly abide with the unconditional weight, size restrictions and other requirements of the customer;
- take into consideration that the US are multicomponent systems/infrastructures;
- account for the ability of such systems to fail, in general, according to a set of heterogeneous criteria of failure;
- account for the effects of combinations of various, possibly interdependent, specific loads and effects in the form of stochastic functions of time, physical characteristics of near space (in this case, part of the effects on the system is generated inside the system itself);
- keep in mind that the structures are designed out of a large number of heterogeneous structural materials and elements;
- account for the fact that the US is assembled from units, components, and parts from manufacturers with different levels of production culture, which arrive at the place of assembly product by different transportation means;
- take into consideration the heterogeneous human factor in terms of its competencies and skills at all stages of the US life time (design, manufacture, assembly, testing and debugging).

The conservatism of design and technological solutions used when creating US allows only qualitative assessments of their (supposedly high) reliability, and does not guarantee the necessary quality. Below the basics are described of the theory of individual structural reliability (TISR), originally developed for the design of such multicomponent systems as steel and reinforced concrete multi-span and multi-story frames, subjected to combinations of random Markov type loads [5–9]. Subsequently, this methodology was used to assess individual structural reliability of oil and gas main pipelines [10, 11], as well as in the design of the framework of nuclear reactors. In this paper, the TISR is described in relation to pivotal elements of unique telecommunication deployable-on-orbit sputniks.

1. The main provisions of the theory of individual structural reliability

To understand the further discussion, we briefly outline the main points of the TISR [6–9]. First, we note that the problem of accounting for various inherent uncertainties facing all scientific and engineering disciplines received its initial solution in structural mechanics, where the concept of the limit state of a system was developed. The design methodology based on this concept was called the "load — resistance/strength" calculation scheme.

Over time, it turned out that this methodology is universal and can be successfully applied not only to assessing structural reliability of any engineering structures/infrastructures, products of machine-ship-aircraft construction and space technology, but also in assessing their *functional reliability*, as well as to solve a number of important technical and economic problems [7]. The idiom "*load — resistance*" is replaced by "*demand — supply*" (in economic problems), "*demand — inventory*" in transportation and logistics tasks in manufacture, production, warehousing and storage), "*need (necessity) — possibility of satisfying it*", respectively (in resilience, security and strategic readiness of infrastructures, and provision of social services). The stochastic idiom "*supply — demand*" in economics can be considered as a probabilistic analogue of the equations of equilibrium and compatibility of deformations in the mechanics of deformable systems. Thus, in the general case, the load (*demand*, etc.) is understood as the *impact* or *stressor* on the system of any nature (physical, economic, logistic, social, etc.), which can lead to failure or affect its output effect. Accordingly, *resistance* (strength, supply, stock, satisfaction of demand, etc.) should be understood as the *inherent property* of the designed system *to withstand* the load impact [7].

For further discussion, we need an understanding of the nature of the general set for the properties of an individual product, which, as mentioned above, is still considered absent by designers of and reliability specialists in the field of the US, because, due to its uniqueness, it does not belong to any really existing GS of homogeneous structures, and it is impossible to reliably build an adequate virtual GS — a mathematical model for an US.

Nevertheless, even for a single, unique structure it is possible to build its GS, which, however, will have a completely different nature and meaning. To build such a GS, this unitary design should be comprehensively and repeatedly measured and diagnosed at each stage of its manufacture, assembly, debugging and testing. Since it is known from measurement theory that the true dimensions and any other physical indicators of an object are fundamentally immeasurable (in the sense that all measurements inevitably contain measurement errors — ME), having such sets of measurements (obtained by using non-destructive testing methods), of material properties actually used when creating the unique system, its overall geometry and the dimensions of its parts, dimensional chains, etc.) it is possible to construct corresponding histograms for the physical properties of the materials and components actually used in a unique product, and from them — the probability density function (PDF) of MEs of all the parameters that are important for reliability assessment if the US.

The more accurate the measurements, the narrower is the PDF curve (compare Fig. 1 with Figs. 2–4). It should be borne in mind that the variability of the properties of materials and critical parameters of such structures should be minimal (Fig. 3–5) and not determined by the dispersion of the properties of a real or virtual set of similar products, but exclusively by the accuracy and precision of measuring these properties and parameters at all stages of creating this *unique* product sample. With this approach, all the statistics necessary to solve the reliability problem are *in principle accessible* and can be collected during the design, construction, manufacture, assembly, testing, debugging of the device, and their subsequent interpretation. However, this knowledge (and the very possibility of applying the TISR) requires appropriate

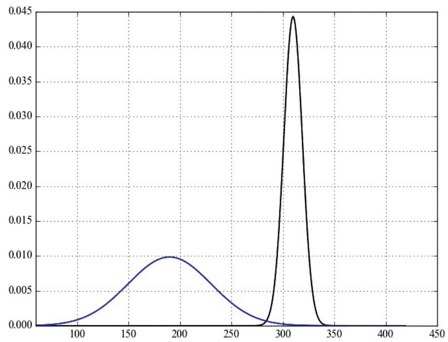

Fig. 1. Visualization of the classical problem of structural reliability according to the “load — resistance” scheme

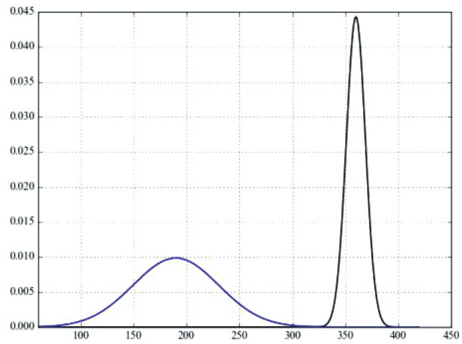

Fig. 2. Spreading (increasing the distance between the load PDF and resistance PDF) to increase product reliability

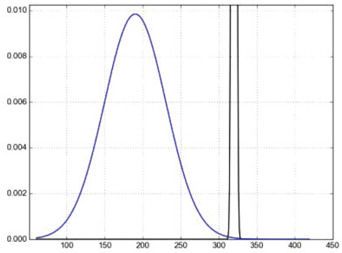

Fig. 3. The classic problem of individual reliability (the resistance PDF is obtained by measurements and diagnostics)

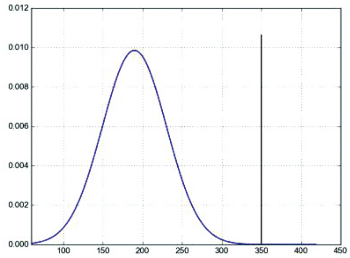

Fig. 4. Solving the problem of individual reliability using one realization (one quantile of resistance)

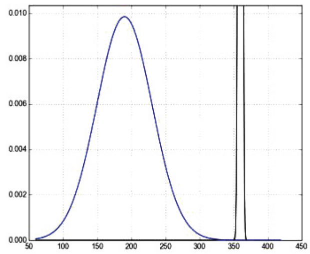

Fig. 5. Spreading of the PDFs of load and resistance in the problem of individual reliability (including by design and technological solutions)

organizational efforts and a production culture (as a rule, much higher than the existing culture).

2. The main schemes for calculating the individual structural reliability of deformable systems

We turn to the description of the basic schemes for calculating individual structural reliability of deformable systems.

The first, basic calculation scheme radically solves the dimensionality curse of the reliability problem of a multicomponent system, which is exposed to a combination of loads and influences of various nature, taking into account physical, technical, technological and operational aspects. In the classical approach, the dimension of the structural reliability problem is equal to the product of the number of structural elements of the system and the number of loads and impacts on it. In the calculation scheme described below, this dimension is equal to or less than the number of loads on the system, which can be $10–10^4$ (10^5) times less than in the classical case [6–8]. This scheme is ideally suited for the main cases of calculating the US reliability when a combination of random loads and influences acts on the structure, or when internal or external influences are more adequately described by stepwise (non-differentiable) time processes, or when the task requires calculating the probabilities of a random process not exceeding low levels [6–8]. It consists of four stages.

At the first stage, the system is schematized, i. e., the space Q of the input parameters q and the space U of the output parameters u are selected. This introduces the operator of the system L:

$$Lu = q, \quad u \in U, \quad q \in Q. \tag{1}$$

The choice of the mathematical operator L is made on the basis of technical and economic considerations, taking into account technological, operational requirements, as well as the capabilities of available computing facilities.

At the second stage, elements κ, κ_o, κ_c are distinguished in the operator L, where κ, κ_o are, respectively, elements from the space K of deterministic system properties that are not subject to (κ) and are subject to optimization (κ_o); κ_c — elements of the space K_c of those properties of the system that are considered random.

At the third stage, the subspace of quality $V \subseteq U$ is determined from the solution of the *inverse problem* of mechanics in the space U, and from it the admissible domain (AD) $\Omega_0(\kappa_c)$ in the space Q is determined. Currently, the choice of the space V is not algorithmicized and largely depends on intuition and the experience of the designer (and/or the reliability speciaist).

At the fourth stage, the conditional reliability of the system is found:

$$R_y(t) = P\left[q(\tau) \in \Omega_0(\kappa_c), 0 \le \tau \le t\right] \tag{2}$$

and using it, the complete/full reliability:

$$R(t) = \int_{\kappa_c} \ldots \int R_y(t) f(\kappa_c) d\kappa_c. \tag{3}$$

Thus, according to this scheme, the problem of individual structural reliability is always solved in the space of loads or, as will be shown below, in the space of *critical structural parameters of the system*. Using this scheme simplifies the stochastic problem as much as possible and reduces the dimension of the problem by one, two or more orders of magnitude.

In the scheme described above, the admissible region is constructed according to equation

$$v_* = H(q, \kappa_c)$$

where v_* is the maximum permissible value of the system quality vector; H is the operator inverse to operator L.

The operators L, H reflect the level of complexity of formulation of the deterministic problem (since the value of the vector κ_c is fixed). This means that each time the reliability of a specific (individual) design is considered, which is solved taking into account modern achievements in the mechanics of deformable media and the capabilities of available computing resources. Such an approach allows one to construct partial admissible regions in the space Q according to each i-th quality criterion (Fig. 6, *a*)

Their intersection gives an admissible region according to all quality criteria simultaneously.

$$\Omega_0 = \bigcap_{i=1}^{N} \Omega_0^{(i)} \tag{4}$$

where N is the number of quality criteria.

In this way, it is not difficult to find areas where any one, two, three, etc. types of failure occur simultaneously. For example, according to Fig. 6, *a*

$$\begin{aligned} \bar{\Omega}_i &= \Omega_0^{(i+1)} - \Omega_0^{(i)} \bigcap \Omega_0^{(i+1)} \\ \bar{\Omega}_{(i+1,i+2)} &= \Omega_0^{(i)} - \Omega_0^{(i)} \bigcap \Omega_0^{(i+2)} \end{aligned} \tag{5}$$

If for a multi-element system (engineering structure) it is possible to construct a permissible region for each element by some criterion (Fig. 6, *b*), their intersection will give an permissible region for the system as a whole, according to the same criterion. Performing this procedure for all quality criteria, it is possible to reduce to the diagram of Fig. 6 the problem of finding the permissible area for a system by all quality criteria.

The advantages of this approach are the visibility and ease of interpretation of the essence of the problem. Indeed, even before calculating the reliability function, the designer already knows which quality criteria are the most stringent (in Fig. 6, *a*, these are criteria i and $i + 1$), which elements do not participate in the formation of an acceptable region (for example, in Fig. 6, *b* — elements 3, 5 and 6). This allows selecting elements with excessive reliability and outline constructive measures to reduce their reliability (and, accordingly, the mass of the

US) to a level that does not affect the overall reliability of the system.

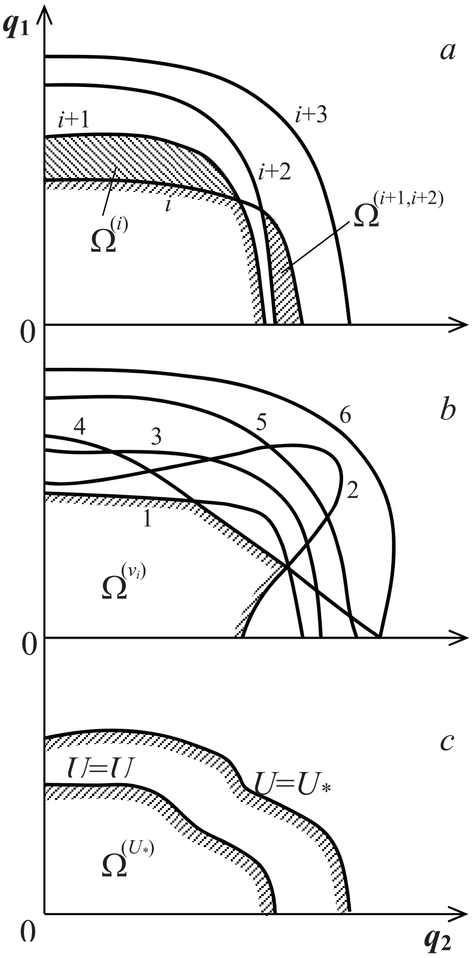

Fig. 6. Permissible areas in the space of loads

If the task is considered as managing reliability of an US system in the class of a two-level management policy, then the warning U_* and physical U_{**} failures are taken into account (Fig. 6, *c*).

A *warning failure* means a certain state of the system, that signals a possible violation of its functioning in the near future, or a failure that causes slight damage. The permissible areas for each failure are shown in Fig. 6, *c*, from which it is clear that $U_* \in U_{**}$ and $\Omega(U_{**}) > \Omega(U_*)$.

The task now is to prevent the load vector from exiting the domain $\Omega(U_*)$ or, if it already exited, to prevent the occurrence of a physical failure — the exit of q (τ) from the domain $\Omega(U_{**})$. To do this, it is needed to know what time it will take for q (τ) to cover the distance from the border $\Gamma(U_*)$ to the border $\Gamma(U_{**})$, and what method and control tool to use to implement this policy. In this paper, these tasks are not considered, but they may be necessary in assessing the reliability of a new generation of USs (equipped with self-diagnosis and monitoring subsystems) at the stage of their operation in orbit.

Since admissible regions are constructed for a *fixed value* of the random vector κ_c, the reliability function obtained with their help is conditional. Integrating it with the weight (weight ratio) $f(\kappa_c)$ gives an unconditional reliability function. Thus, all randomness is concentrated in the admissible region (its form and size). The PDF $f(\kappa_c)$ is constructed in the process of creating an individual manufacture.

Under the influence of physical and chemical stressors, the quality of structures changes over time. In this case, the *second scheme* for assessing the reliability of a mechanical device is used. The first two stages of the assessment remain the same, and the conditional reliability function is written as

$$R_y(t) = P\left[q(\tau) \in \Omega_0\left(\tau | \kappa_c\right),\ 0 \le \tau \le t\right] \tag{6}$$

i. e., it is determined at each moment of time taking into account the effect of “shrinking” of the admissible region (Fig. 7).

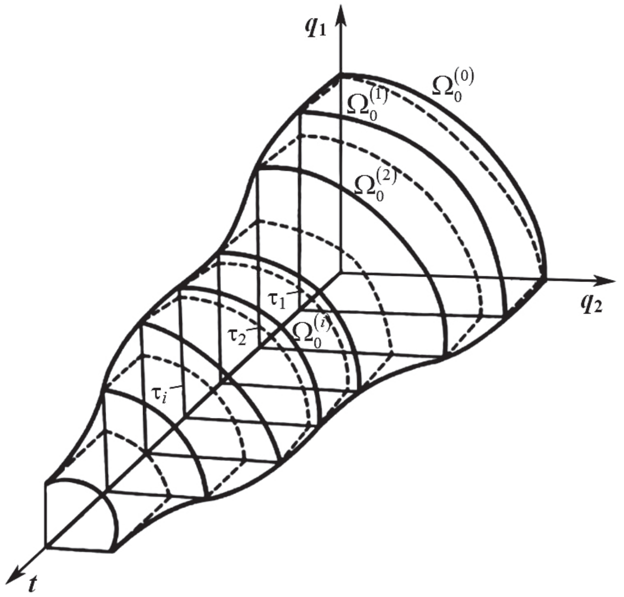

Fig. 7. Permissible time-varying region

If a conservative stepwise approximation of the admissible region in time is performed (see Fig. 7), then

$$R_y(t) = \prod_{i+1}^{n} P_{yi} \begin{bmatrix} q(\tau) \in \Omega_0^{(i)}\left(\tau_i | \kappa_c\right), \\ \tau_{i-1} \le \tau \le \tau_i \left| q(\tau) \in \Omega_0^{(k)}\left(\tau_k | \kappa_c\right),\ \tau_{k-1} \le \tau \le \tau_k \right. \end{bmatrix}$$

$$k = i-1, \ldots, 1, \qquad \tau_0 = 0 \tag{7}$$

since the reliability of a system aging in this way should be calculated according to a series connection scheme. The rule for calculating complete reliability (3) remains unchanged.

In some cases, the task is posed from the very beginning as a problem of durability, for example, when considering long-term and low-cycle strength, high-cycle fatigue, stability under creep, etc. Here the *third scheme* for calculating the system reliability is used, according to which at the first stage the deterministic durability is calculated

$$T = L(q, \kappa_c) \qquad (8)$$

where q is the vector of external influence; L is the operator.

When choosing the operator L, the quality space and the region of admissible states are automatically assigned, since without solving these issues it is not possible to uniquely determine the operator. At the second stage, elements κ_c randomness are distinguished that are carriers of in the operator L.

At the third stage, the method of conditional functions is used to find the durability PDF

$$f(T) = \int\limits_{\psi(\kappa_c)<T} f(\kappa_c)\,d\kappa_c \qquad (9)$$

where $f(\kappa_c)$ is the joint parameter density κ_c; $\psi(\kappa_c)$ is defined by equation (8).

In some cases, it is possible to immediately determine the moments of stochastic durability. Then, the durability PDF is constructed using the *robust* Gram — Charlier or Edgeworth series expansion, as well as using the maximum entropy method.

At the fourth stage, the system reliability is sought

$$R(t) = \int\limits_0^t f(T)\,dT \qquad (10)$$

The described schemes for calculating reliability of unique mechanical systems complement each other and allow giving reliability assessment for all practical cases.

In all schemes, the reliability function $R(t)$ is defined as the result of taking into account the most important environmental factors, system properties, technological and operational requirements.

In the case of predicting reliability of a single functioning system *following calculation scheme* can be used. Based on equations (1) and (4), an admissible region $\Omega_q(t)$ is constructed in a space Q of dimension m at time t and the coordinates of the image point $d(x_q)$ are determined. In this space, the depicting point $x_q = \{x_1, x_2, \ldots, x_m\}$ means the point whose coordinates are the loads and effects acting on the system at the time of analysis t. If $d(x_q) \in \Omega_q$, then the reliability of the system is $R(t) \equiv 1$, if $d(x_q) \notin \Omega_q$, then $R(t) \equiv 0$.

Based on the kinetic equations obtained from measurements and observations of the parameters x of the system over time t, the evolution equation of the admissible region is determined

$$\Omega_q(\tau) = \Omega_q(x, \tau) \qquad (11)$$

where x is the vector of parameters that determine the configuration and size of the permissible region.

Using prior data on the loads and processes of quality loss of the system $q(\tau)$ using the Bayesian approach, posterior characteristics of the same processes $q^{(a)}(\tau)$ are constructed, and from them the probability is sought

$$P(\tau, x) = P\left[q^{(a)}(\tau) \in \Omega_q(\tau|x),\ t < \tau \le T\right] \qquad (12)$$

and *predicted* reliability

$$R_p(\tau) = \int P(\tau, x) f(x)\,\mathrm{d}x \qquad (13)$$

where $f(x)$ is the joint PDF of quantities x (the integral is taken over the region of existence of x).

Another way to calculate the reliability function is as follows:

$$R_p(\tau) = P\left\{\int\limits_t^T v_d^{(a)}(\tau)\,\mathrm{d}\tau < r_t\right\} \qquad (14)$$

where r_t is the distance to the boundary of the admissible region at time t, $v_d^{(a)}(\tau)$ is the posterior relative velocity of approach of the image point and the boundary of the admissible region obtained from the measurement results during the time [0, t].

If forecasting yields unsatisfactory results, it is necessary to correct the models of the observed random processes, reduce the time between the moments of measurements, and increase the depth of control. Usually the forecast depth $(T - t) \le t/10$.

Possessing the calculation schemes described above, the designer can provide the necessary level of reliability for each admissible area (see Fig. 3, 5). If the cost of multiple measurements is too high, then use a small sample size (< 25–30) and apply to it the bootstrap/reselection procedure, that will allow obtaining the desired probabilities with the necessary consistency. It is also possible to select a quantile (say, of the order of 0.001) of material strength and solve the reliability problem with its help (see. Fig. 4). Thus, in the framework of the presented methodology, individual structural reliability is just a special kind of general theory of structural reliability. As noted above, for its use in practice it is necessary to have a technology and production culture available that allows collecting, at each technological operation, all the necessary, sufficient and consistent statistical information about the parameters of the unique structure. The costs of changing the technological culture of production quickly pay off, since they make up no more than 5–10% of the cost of one unsuccessful launch of a unique satellite. It should be noted that the concept of such a technology developed at the Science and Engineering Center "Reliability and Safety of Large Systems and Machines", Ural Branch, Russian Academy of Sciences, for assessing reliability, likelihood of failure and residual life of individual sections of trunk oil and gas pipelines, has been recognized in the global pipeline industry [10, 11].

3. The application of TISR to reliability analysis of a unique telecommunication satellite pivoting rod

To visualize the capabilities of TISR *as applied to spacecraft*, we will demonstrate them on a real-life example of evaluating the complex individual structural reliability of an one-time pivoting single-link rod of a GPS satellite magnetometer (see Fig. 8).

The structural scheme of the rod without a magnetometer is shown in Fig. 9. In the general case, instruments and equipment for various purposes, such as antennas, solar panels, orientation, stabilization devices, etc., necessary for operating the on-board systems of the spacecraft, as well as scientific equipment, can be placed on the free end of the rod.

In the folded position φ_n the rod (1) is fixed on the support base of the US using a lock (2). After stripping, lock (2) releases rod (1), which, under the action of pusher (3) and torsion spring (not shown in Fig. 9) installed in hinge (4), is rotated and fixed in its final angular position φ_k using latch (5) (not shown in Fig. 9).

The solution of the problem in a stochastic formulation using the classical reliability theory of [4, 9] reduces the problem of reliability of the rotation of the rod to ensuring two conditions:

- strength — resistance to loads, when folded and when locked in the working position;
- functioning during rotation of the rod — the excess of the driving moment on the drive over the moment of resistance forces (hinge and the final position latch) both along the entire travel path and at its very end.

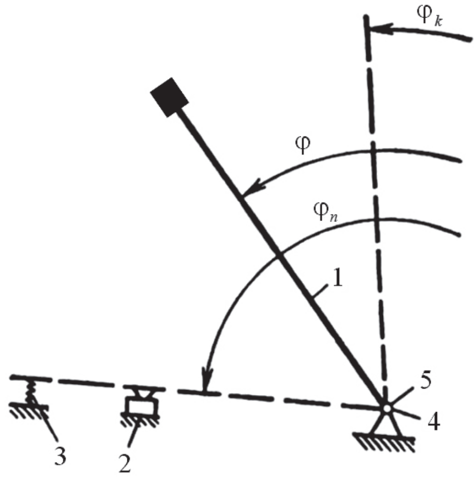

Fig. 9. US GPS with deployed open solar panels and magnetometer rod

Such solution of the problem is crucial when choosing the parameters of the rod's performance at the design stage; however, it does not take into account the structural and technological factors during final design, technological preparation and production.

The failure-free operation of the rod is ensured by the sequential execution by its structural elements of the following functions (conditions) [3, 4]:

- preservation of the strength/integrity of the rod when loaded in the folded position;
- prevention of unauthorized removal of mechanical ties in the lock;
- the passage of an electrical signal to the electric igniter of the pyro-cartridge according to a given command;


Fig. 8. US GPS with deployed open solar panels and magnetometer rod

- triggering/activating of the pyro-device;
- separation of mechanical bonds in the lock;
- separation of the rod from the support base (US);
- rotation of the rod by a given angle;
- fixing the rod in the working position;
- providing the specified parameters of the rod in the working position.

For this example, there are at least *nine* conditions that must be *unconditionally* met for a successful rod turn. Any of the conditions can be divided into a number of subconditions (as branches of the possible causes of failures of critical elements within the framework of the main functional condition), each of which should be reflected in the technical (design and technological) documentation by establishing certain requirements for manufacturing and technical control. Moreover, failure for each of the conditions (subconditions) is determined not only by the genesis of the causes of failures (accepted design and technological solutions at the pre-operational stages of the life cycle), but also by the conditions of the operating modes, which should be taken into account when analyzing and evaluating their reliability.

For a pivoting rod, the fulfillment of each of the above conditions is possible if there are no reasons for the failure of critical elements of its structure. The set of such reasons depends on the individual specifics of the rod design [3, 4]. A set of possible causes of failures for each of the conditions for the rotation of the rod, given in [3, 4] is listed below.

1. The condition for ensuring the strength/integrity of the rod from loads in the folded position. The reasons for failure during deployment of the rod due to violation of this condition may be: the destruction of structural elements of the locks and opening mechanisms (loss of bearing capacity); plastic deformations in the executive bodies and of the opening mechanisms' interfaces that worsen their work (unacceptable deformations); changes in the relative positions of the mechanism parts during vibration (insufficient vibration resistance); unacceptable thinning of the solid lubricating layer in tribo-conjugations (violation of lubrication conditions); unacceptable amplitudes of vibro-displacements, leading to the ingress of foreign objects into the mechanism of opening (deployment blocking); impaired mobility in highly loaded structural elements of mechanisms in vacuum (cold welding).
2. The condition for preventing unauthorized removal of mechanical ties in the lock. In addition to the destruction of locks, the causes of failure can be the following phenomena: electrostatic breakdown, leading to self-operation (self-opening) of the lock — the initiator of opening; unacceptable deformations in the locks (unacceptable deformation).
3. The condition for the passage of the electric signal to the electric igniter of the pyro-cartridge according to a given command. The causes of failure may be: a mechanical break in the supply wire or oxidation of the contact (open circuit).
4. The condition for triggering the pyrodevice. The reasons for its failure may be: failure of the pyro-check, non-destruction of the check, non-release of the mechanical connection between the pyrodevice and the lock (for example, due to the ingress of glue).
5. The condition of non-separation of mechanical bonds in the lock. The causes of failure may be: insufficient motion space of the actuators; insufficient energy of the lock drive springs; intrusion of isolated particles into the lock mechanism; incorrect adjustment of the lock mechanism elements (neglect of possible shifts under the influence of gravity), etc.
6. The condition for the separation of the rod from the support base. The causes of failure may be: jamming of the movable elements of the lock due to installation and thermal deformations; interference on the movement path of the detachable parts of the lock when leaving the interface zone with the immovable parts; insufficient energy of the deployment opening drives to overcome rest friction.
7. The condition for rotating the rod at a given angle. The reasons for failure under this condition can be: malfunction of the drive (failure to turn on), lack of necessary torque reserves (braking), disappearance of the radial clearance in the rotation hinge (press-in), disappearance of the axial clearance in the hinge assembly (jamming), sudden obstacles to the movement of the rod (meshing).
8. The condition for fixing the rod in the working position. The cause of failures is the insufficient energy of the drives to snap the latches of the end position of the rod, the release of the end position of the rod under the action of an external load.
9. Conditions for ensuring the specified parameters of the rod in the working position. The causes of failures under this condition may be destruction and deformation of the structural elements of the rod with the instantaneous application of mechanical ties at the time of fixating the rod; insufficient rigidity of the rod; presence of backlash in hinges; insufficient accuracy of positioning the rod in the working position; insufficient accuracy of the shape of the working surface of the equipment placed on the rod during the period of its active existence; insufficient local strength of the structural elements of the rod during operation of the propulsion system that corrects the orbit or orientation of the apparatus.

The listed conditions can be divided into groups according to the physical principles of their manifestation [3, 4]:

- conditions of the *structural strength* of the rod at various stages of its operation (at the time preceding its rotation to the working position, when locked in the final position, etc.);
- *temporal conditions* (taboo on *premature* opening of the lock with rod in the starting position; ensuring the initiation of the rod deployment

process at a *given moment of time*; removing kinematic links of the rod with the support base at a *given moment of time*, etc.);

- *kinematic conditions* (ensuring freedom of *rotation* in the hinge in any angular position of the rod, and unimpeded *movement* of the rod along a given path, etc.);
- *tribological conditions* (presence at all times of a separating lubricating layer in places of contact interaction of moving units; the lubricant resistance to abrasion during vibration exposure to the loads of the active phase of satellite launch; the lubricant resistance to abrasion after checking the functioning of opening mechanisms during ground tests, etc.);
- *energy conditions* (overcoming rest friction in the rod hinge during initial straggling and ensuring energy sufficiency for pivoting the rod to the full design angle of rotation, including for fixing in the working position, etc.);
- *conditions for positioning accuracy* (absence of backlash in the hinges after installing the rod in the working position, absence of irreversible deformations and fractures, absence of geometric distortions due to aging processes, etc.).

All these conditions are tied to strict sequence or synchronization of execution. To solve this problem, it is necessary to fulfill all the nine conditions with the same, very high probability. In a successful launch, all these probabilities become equal to unity.

Hence, the problem under consideration is reduced to assessing the *functional reliability* of a one-time action mechanism, which is much more complicated than the usual calculation of structural reliability of a mechanical system.

We now present the described procedure in more detail for the case of assessing the reliability of the process of error-free rotation of the rod (Fig. 9). To do this, we consider the algorithms for constructing admissible areas (AA) and limit state functions (LSF) for each of the nine types of failure of the bar turn. Before this, we consider the main methods and specifics of building AA in the space of loads, physic-mechanical and structural parameters of a *specific designed* make.

4. Specifics of constructing the LSF and AA in the framework of TISR

The construction of the LSF and admissible area (AA) are the determining steps in assessing individual structural reliability. When formulating the LSFs for an *already designed* structure according to existing canons, equations and algorithms are used that connect its parametric properties with loads and influences to resist which it was created. At the same time, it is assumed that the design satisfies all the weight, size, cost and functional requirements of the technical specifications (TS) for this project.

According to the LSF formed in this way, the corresponding AA is constructed. To do this, it is necessary to solve the corresponding *inverse problems* of mechanics and those sections of knowledge to which its design functions relate. In the context of structural reliability, such loads and impacts are sought for which certain ultimate conditions arise in the system elements (yield strength, ultimate strength, low-cycle strength, high-cycle fatigue, buckling load, maximum allowable deflections, deformations, etc.). Here it is also necessary to consider such generalized characteristics of the product as maximum allowable rigidity and accuracy of positioning (not only of individual nodes — hinges, rods, reflectors, but also the US as a whole).

In addition to the classical design scheme “*load — resistance*”, in a comprehensive assessment of spacecraft reliability, it is necessary to use generalized versions of this scheme, when the load and resistance are some parameters of the structure itself, which indirectly depend on external or internal loads and influences. Such cases include all tasks associated with clearances in joints. To solve this type of problems, it is necessary to use the multi-criteria stochastic optimization method as applied to multidimensional systems.

Here we note that the issues of rigidity of products directly depend on the manufacturing accuracy of parts and assemblies. This problem was first posed in [6, 7] and solved in relation to the manufacturing technology and assessment of the *assembleability and initial reliability* of steel building structures in [9, 12, 13]. The results of these studies were fully implemented at the Chelyabinsk Plant of Metal Structures in 1978–1979 and were used in compiling the USSR State Standard “Limit deviations of the geometric parameters of steel building structures” in 1986. This approach was also used by SEC of the Ural Branch of the Russian Academy of Sciences in assessing the *assembleability* of nuclear reactor designs.

5. Technology of applying the methodology of individual structural reliability

When applying the TISR methodology, following technology is used.

At the first stage, the designer, guided by the approved TS, and using the entire mandatory arsenal of all levels regulatory documents for the design of US, his personal experience and vision, creates a deterministic version of the object, with all its parameters known.

At the second stage, for the already designed object, the LSFs are built using all the known design limiting states for materials (yield strength, ultimate strength, etc.), as well as for elements, assemblies, aggregates and the system as a whole, taking them from the approved TS for its design, and other affordable sources.

At the third stage, for each LSF its permissible region is built in the space of its parameters that determine performance quality of the element or the system as a whole. Depending on the quality of the initial statistics, the boundaries of the AAs can be deterministic, quantiles, or have their own PDF.

At the fourth stage, the problem is solved of assessing probability of the element or system quality vector exiting from its AA.

The second and third stages of assessing the reliability of the US using *TISR* are the *platform for interaction* between the designer and the individual reliability specialist, since they synergistically complement each other, working with the same materiel, but considering it from different, complementary points of view.

Due to lack of space when demonstrating capabilities of TISR methodology restrict ourselves to analyzing the fulfillment of the *condition for rotation of the rod by a given angle* [3, 4]. The choice of this condition is due, on the one hand, to the nature of failures, that allows full demonstration of the basic principles of obtaining an individual structural reliability assessment. On the other hand, the reasons of failure that characterize nonfulfillment of this condition are universal, independent of the design of the pivoting rod.

1. The "drive failure" type. This type of failure refers to structural reliability. Failure (sudden, unrecoverable) can be caused by a breakdown of the drive during launching the US into orbit, for example, due to mechanical destruction of the opening spring or violation of the electrical contacts of the electromechanical drive (gear motor) caused by vibrations during the active phase of the launch. Typically, drives have a unified modular design and are used in homogeneous environmental conditions. Hence, it is possible to obtain for them an experimental operating time function.

$$R_N = n / N \tag{15}$$

where n is the number of non-failed drives during ground-based experimental testing and flight practice; N is the total number of drives in the sample.

The reliability condition for the drive taking into account (15) is written as

$$R_N > P_{\lim} \tag{16}$$

where $P_{\lim}$ is the probability of failure-free operation of the drive in accordance with the specified design requirement of the reliability indicator for the rod.

In case of non-compliance with condition (16), the required reliability of the drive is ensured by the m-th duplication multiplicity of its critical elements (structural or functional) according to formula

$$R_d = 1 - \left(1 - R_N\right)^{m+1}. \tag{17}$$

2. The "brakes on rod" type of failure. This failure $Q(\tau)$ can occur if the magnitude of the driving moment $M_0(\tau)$ for some reason is less than the moment of resistance forces $M_r(\tau)$

$$Q(\tau) = \left\{\left[M_0(\tau) - M_r(\tau)\right] < 0;\ 0 \le \tau \le t_o\right\}$$

where t_o is the moment of failure.

In engineering practice, it is assumed for the condition $M_0 > M_r$ to be met at every point in the trajectory of the pivoting rod under the condition of zero kinetic energy. The visualization of this process is presented in Fig. 10. In it, the LSF is the OO'B'B plane, AA is the region OABB'A'O' (upper trihedral parallelepiped), where the segment OO' is the estimated time of the opening of the rod. The lower trihedral box represents the failure area.

Curve 1 describes the successful deployment of the rod; curves 2 and 3 — fatal failure (rod deployment did not occur).

The designer's task is to ensure the start moving condition using *almost (practically) absolutely reliable* (repeatedly tested) structural and technological techniques (18)

$$P\left[M_0(\tau) > M_r(\tau), \tau = 0\right] \to 1{,}0 \tag{18}$$

and the full deployment condition (19)

$$\begin{cases} P\left[M_0(\tau) > M_r(\tau), 0 < \tau < t_r\right] \to 1{,}0 \\ P\left[\varphi = \varphi_\kappa \middle| \tau = t_r\right] \to 1{,}0 \end{cases} \tag{19}$$

where t_r is the completion time of the rod turn.

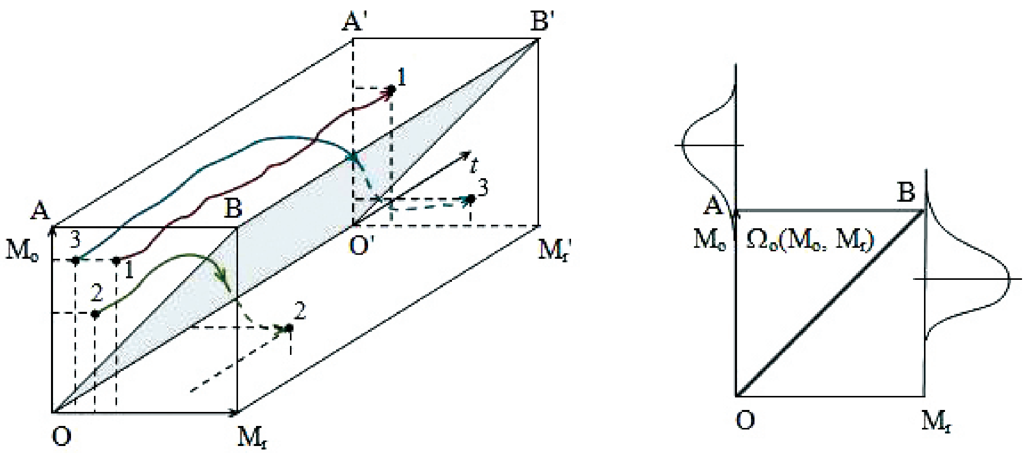

Fig. 10. Visualization: successful turn of the rod, the left figure (curve 1); functional failure of the opening of the rod (curves 2, 3); the right figure shows the PDF of the driving moment (top left) and the moment of resistance forces (right)

The magnitude of the driving moment $M_0(\tau)$ depends on the type of drive and its operating parameters. For mechanical drives (torsion bars, torsion springs, watch springs, tension springs), the driving moment is determined by the following parameters:

- spring dimensions (in the general case, wire and spring diameters, spring length);
- spring materials (strength and stiffness parameters);
- a method of creating a rotating moment ("pure" rotation or by a pair of forces: in the latter case, for example, if a tensile spring is used as a drive, the value of the rotating moment is affected by the action shoulder of the force vector, which generally has a spread due to the distance between the point of force application and the axis of rotation and in itself changes during the movement of the pivoting structure);
- adjustment (installation) of the spring at the initial moment of assembly of the pivoting structure;
- construction opening angle.

All the above factors are determined by technological tolerances.

In general terms, the driving moment for a mechanical drive as a function of time can be expressed by the formula

$$M_0(\varphi,\tau)=f\left\{\vartheta_p(T_{en}),\ \vartheta_c(T_{en}),\ \varphi(\tau),\tau\right\} \quad (20)$$

where ϑ_p is the generalized design parameter of the spring; ϑ_c — generalized structural characteristics of the spring in the assembly of the rotating structure; T_{en} is the ambient temperature; φ is the angle of rotation of the structure to the moment of fixation (contact with the retainer of the final position of the pivoting structure).

The moment of resistance forces in the path of the rod movement is determined by the friction forces in the hinge and the bending (torsion) resistance of the interpanel cable bundle (in the general case: electrical, low-current, coaxial).

In general, the moment of resistance forces $M_r(\tau)$ as a function of time can be expressed by formula

$$M_r(\varphi,\tau)=f\left\{N(\varphi),\mu(T_{en}),r,\ k\left[T_{en},\nu,l,\varphi(\tau),\tau\right]\right\} \quad (21)$$

where *N* is the transverse force acting on the axis, which is determined depending on the method of creating the moving moment; μ — coefficient of sliding friction in the hinge; *r* is the radius of the hinge; *k* is stiffness of the cable bundle (as a rule, to reduce the rigidity, the cable bundles in the interpanel zone are "fluffed", that is, each wire in the cable bundle can be deformed independently); *v* is a parameter depending on the position of the bundle between the fixed attachment points with respect to the hinge axis (usually the tendency is to make the intermediate rotating bundle support coaxial with the axis of hinge rotation); *l* is the length of the bundle between the fixed mounting points on the structure.

The reliability function of the rod rotation depending on the angle, taking into account (20) and (21), is

$$R_0(\tau)=P\left\{\left[M_0(\varphi,\tau)-M_r(\varphi,\tau)\right]>0,\quad 0\le\varphi\le\varphi_\kappa,\quad 0\le\tau\le t_r\right\} \quad (22)$$

Formula (22) uses the "*load — resistance*" reliability model, in which the moment of resistance forces M_r acts as "*load*", and the driving moment M_0 as "*resistance*". The admissible region is the range of values of the driving moments M_0, developed by the drive at the rotation angle of the rod, greater than M_r at all time instants $0\le\tau\le t_r$ (see Fig. 9).

To calculate $R_0(\tau)$, it is necessary to build random functions (RF) M_0 and M_r (or to know their characteristics — expectation, variance, correlation function, spectral density), or construct its PDF if they are presented in the form of random variables (RV). This requires the use of the apparatus of statistical dynamics and the theory of random functions.

The values of the parameters in formulas (20)–(21) can be obtained by measuring the magnitudes of the driving moments and the resistance forces moments during ground-based experimental testing, taking into account simulation of the thermal conditions of outer space [3, 14].

3. The " hinge jamming" type of failure. Failure (sudden, restorable or non-restorable) can be caused by the sudden disappearance of the radial clearance in the hinge due to a change in the thickness of the layer of the solid lubricating coating and temperature deformations (Fig. 13). The condition for operability *as related to radial clearance* is determined by the formula

$$\Delta_0(\tau,T)=\delta(\tau,T)-2\delta_n(\tau,T)-\delta_{pr}(\tau,T)>0;\ 0\le\tau\le t_f \quad (23)$$

where Δ_0 is the radial clearance in the hinge; δ is the minimum design clearance in the interface between the male and female hinge parts without taking into account the lubricant layer between them; $\delta_n(\tau)$ is the maximum thickness of the solid lubricant, taking into account its possible changes during operation from grinding and temperature; δ_{pr} — the maximum value of thermal deformations of the hinge structural elements in the radial clearance during volumetric expansion (compression) of the covered (covering) part; *T* is the temperature in the conjunction of the hinge parts; t_f — time (duration) of operation.

From formula (23) it follows that the rod reliability can be assessed using the "*load — resistance*" reliability model, if under the *load* we mean the time-varying parameters of radial clearance δ_r due to possible changes in the dimensions of the mating parts during operation of the US caused by thermal deformations, $\delta_r = 2\delta_n + \delta_{pr}$, and, under *resistance*, the parameter δ, which opposes the change in load. In this case, the reliability function related to maintaining a nonzero radial clearance in the bearing, taking into account the above expressions δ and δ_r, can be represented by formula

$$R_r(\tau) = P\{[\delta(\tau,T) - \delta_r(\tau,T)] > 0, \quad 0 \le \tau \le t_f\} \tag{24}$$

The admissible area in the quality space in the case of hinge wedging/jamming is the area of change of the initial (design) clearance Δ_0 (see Fig. 11).

It should be noted that the reliability condition (24) implies that during the entire life of the US, its total temperature field should not be able to make the initial (design) gap smaller than the gap $\delta_r(\tau,T)$.

The values of the radial clearance parameters for assessing reliability as a random function of time and temperature can be obtained by calculating dimensional chains (for parameter δ), measuring the thickness of the solid lubricant layer and using structural constraints (for parameter δ_n), as well as calculating temperature deformations (for parameter δ_{pr}) [3].

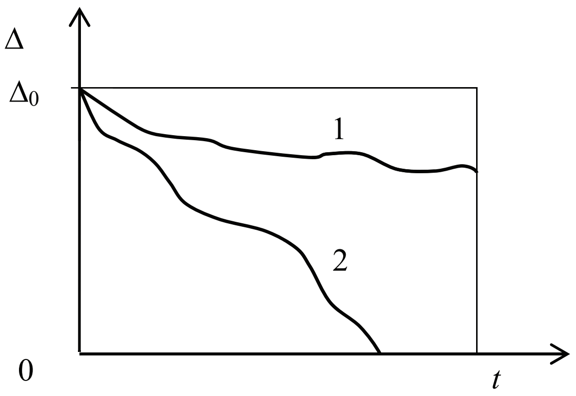

Fig. 11. Changing of the radial clearance Δ:

1 — operable hinge; 2 — failed (wedged/jammed) hinge

4. The "jamming in the hinge assembly" type of failure. This type of failure (sudden, restorable or non-restorable) can be caused by the disappearance of the axial clearance in the hinge assembly due to temperature deformations. The condition for axial clearance is determined by formula

$$\Delta_{sh}(\tau,T) > \Delta l(\tau,T) \tag{25}$$

where Δ_{sh} is the *actual* axial clearance in the hinge assembly, considered as the design (quasi) deterministic quantity, which should always be greater than zero; Δl — thermal deformation as a random function of temperature and time, capable of causing spacer forces in the design of the hinge assembly in the case when $\Delta_{sh} < \Delta l$.

Thermal deformation is defined by formula

$$\Delta l = l \cdot \varepsilon \tag{26}$$

where $\mu = \Delta t(\alpha_1 - \alpha_2)$; l is the distance between the hinges; ε is the elongation between the joints; Δt is the calculated temperature difference between the operating temperature in space and the rod assembly temperature at the plant; α_1, α_2 — coefficients of linear thermal expansion of the material of the rod and body of the US.

As follows from formula (25), the reliability of the rod as related to its axial clearance in the hinge assembly also obeys the "*load — resistance*" model, if by *load* we mean the axial clearance parameters that change due to thermal deformations Δl, and by *resistance* — the parameter Δ_{sh}, that opposes the change in *load*. In this case, the reliability function as related to maintaining the axial clearance taking into account (9) and (10) can be represented as

$$R_{sh}(\tau) = P\{[\Delta_{sh}(\tau,T) - \Delta l(\tau,T)] > 0, \quad 0 \le \tau \le t_f\} \tag{27}$$

The admissible region for the case of jamming in the hinge assembly is the one-dimensional gap space Δ_{sh} in the form of a zero segment on the abscissa axis, which is equal to the design gap in magnitude.

Changes in time of the axial clearance for calculating reliability (27) can be obtained by calculating dimensional chains as a function of temperature (for the Δ_{sh} parameter) and temperature deformations (for the Δl parameter) (26). Here we have the case when the gap Δ_{sh} itself is a quasi-random quantity, depending on the temperature, which should always be greater than Δl.

It should be noted that failures of the type "*wedging of the hinge*" and "*jamming in the hinge assembly*" are the most common failures when deploying unique spacecraft structures. In foreign practice they are combined into the "*loss of gaps*" type of failures. As follows from the Aerospace Corporation report for 2008, analyzes of abnormal incidents with moving mechanical components of spacecraft showed that out of 164 ground and 24 orbital failure cases, most of them (up to 47 % of the total) were associated with "loss of gaps" [15].

5. The "rod engagement" type of failure. Such failure (sudden, unrecoverable) may be caused by the occurrence of unforeseen obstacles in the way of rod movement, caused by unaccounted for conditions of weightlessness, vibration, kinematics of movement or unfortunate layout of adjacent structures, as well as incorrect actions and gross errors of product assembly workers. Failures of this type are always unexpected (belong to the black swan category), and are the result of the lack of an algorithm for checking the product, ready to be sent to the launch pad, for its readiness for deployment in orbit. Nevertheless, practical cosmonautics periodically encounters such failures. For example, on Soyuz 1 spacecraft, one of the wings of the solar battery was hooked onto the screen-vacuum insulation mats; on the automatic US Telstar 14R, getting of the weakened cable harness into the deployment mechanism also led to the incomplete deployment of the solar panel wing [3].

The algorithm for detecting such failures involves construction of a full group of sequences of checks of actions preparing the unique spacecraft for perfect deployment in orbit. Calculation of the rod reliability according to this criterion does not fall under the "*load — resistance*" scheme. This reliability can be assessed by constructing, if possible, a *complete group of* "*events — checks*" sequences with subsequent computer modeling of these chains for assessing the probability of missing out on any check and sizing its consequences. To implement this approach, it is necessary to have reliable statistical data on the probability of human errors of installation/assembly workers.

Often designer is forced to compose the US system in a way that creates narrow three-dimensional zones of unhindered deployment of structures. To ensure reliability of deployment in such cases, it is necessary to use organized movement schemes that allow excluding hooking/catching taking into account random scatter of the movement trajectories. In this case, devices are used to synchronize the movement, but the need to ensure that no engagement will take place still exists. Evaluation of the deployment success can be obtained by multiple computer simulations of these trajectories, taking into account the behavior of interpanel cables that can fall into the deployment mechanism under vibration or the influence of weightlessness.

In the general case, the meaning of all procedures for eliminating a failure of the "rod engagement" type is to assess the probability of fulfilling the condition: $Q_{st} \to 0$, where Q_{st} is the probability of rod engagement.

Accordingly, the reliability of no engagement is determined by the expression

$$R_{st}(t) = 1 - Q_{st} \tag{28}$$

Thus, taking into account (17), (22), (24), (27) and (28), the reliability of fulfilling the condition for *the rotation of the rod* by a given angle when performing the TISR procedures can be calculated using formula (3), and, in case of independence of all the nine type of failures, by multiplying the probabilities:

$$R(t) = R_d \cdot R_0(t) \cdot R_r(t) \cdot R_{sh}(t) \cdot R_{st}(t). \tag{29}$$

To assess the complete reliability of the rod rotation, it is necessary to calculate the reliability of each of the nine conditions of rod rotation, and the overall reliability by the formula (3) or by the structural reliability method.

6. The general algorithm for assessing individual structural reliability of operating unique systems

The problem of assessing the reliability of a unique satellite successfully launched into orbit is a more complicated task than ensuring the functional reliability of its launching and its deployment, since it requires knowledge of stochastic/statistical characteristics of all main degradation processes as functions of time that have occurred during all cycles of US existence (before, during and after the launch of the spacecraft into orbit) in all its structural components.

The accuracy and rigidity of the US cantilever structures in the working position are ensured by the stiffness and dimensional stability of the carbon fiber structural elements of the structures of the US and the stability of their relative position in the hinges. The development and manufacture of one-time-deployment large-size space structures is carried out at enterprises whose technological processes have individual specifics, but when producing similar objects reveal repeating characteristics. This allows using an approach based on the concept and calculations of TISR [6–13; 16, 17].

As part of this approach, following procedures must be completed.

1. Write down the LSF for each structural element and the US as a whole for all possible types of failure.
2. Formulate quantitative conditions of reliability (or failure) for each LSF.
3. Write down the general condition for the functional reliability of the product as a whole.
4. Present all the materials properties used in calculations as deterministic, random values (RV) or functions (RF) of time, using all available information, evaluate the quantitative values of their parameters, and the level of their reliability.
5. Construct quantitative models of all loads and effects on the console structure (in the form of fan processes, regression lines, Markov processes of pure death/birth and diffusion Markov processes, Levy processes, etc.), find quantitative values of its parameters, and evaluate the level of reliability these values.
6. For those parameters of material properties, loads and influences for which the statistical base is currently scarce, use non-traditional methods of probability theory and mathematical statistics (Bayesian approach, bootstrap, re-sampling method, interval estimates, fuzzy logic, neural networks, genetic algorithms, etc.).
7. Find statistical indicators of plant manufacturing accuracy of each element of the US (measurement error statistics), and slipway collectability of each joint and the system as a whole. For this, it is necessary to carry out appropriate multiple measurements after each remake of the initial semi-finished products, elements and assembly of the entire single product.
8. Obtain statistical characteristics of: reproducibility and repeatability of measurements and of the execution of technological operations, which will make it possible to assess the quality of both manufacturing and assembly technology and the quality/reliability of the human factor (the turner, the milling machine operator, the locksmith, the assemblyman, the diagnostician, the managers, etc.).
9. Build permissible areas in the space of loads, impacts and critical system parameters for each element and the system as a whole, taking into

account the possible degradation of the properties and parameters of cantilever structures.

10. Using formulas from [6–13;16–17] find the probabilities of the vector of static, dynamic loads and kinematic effects and functional parameters of the system to be in the admissible area for all critical elements and the system as a whole and for all possible types of its failure.
11. To assess the reliability of various components of mass production that are part of the US, it is possible to use the methods of accelerated reliability tests, similar to how it is done for aircraft engines [18].
12. Assess the reliability level that is actually embedded in the unique design via using existing norms, rules, and the designer's technological techniques.

Compare the results with the specified design requirements in the TS and, in case of non-compliance, change the design and make an iterative recalculation of the system, until the task is unconditionally achieved.

Conclusion

The only way to ensure high reliability of unique USs is to raise the technology of their design, manufacture and debugging to the next level, using the methodology of high-accuracy calculation of individual structural reliability (based on statistics collected in new technological conditions), to analyze and synthesize its reliability.

To avoid as much as possible black swan catastrophes in space or mitigate their consequences if they still happen, it is necessary to provide them with artificial intelligence and security subsystems that would provide on-board diagnostics, monitoring, maintenance and supraresilience.

It seems that *the primary tasks* of the practical TISR of the US are:

- construction of models of loads, effects and physical-mechanical properties of materials and structures of the US as random functions/processes (RF) of time or RV;
- construction of correct and adequate LSFs and AAs for typical failures of the US and its critical components;
- assessment of the initial reliability of the unique system R (0) and its evolution R (t) on all subsequent cycles of the apparatus existence;
- organizational measures for the implementation of this project;
- the identification of the "innate level of reliability", spontaneously embedded into the existing standards during the US design (*to independently confirm the acceptability* of the structural and technological approach to the design of highly reliable USs [3, 4]);
- development of practical orbital diagnostics, monitoring, and resilience oriented robotized maintenance;
- assessment of the US (supra)resilience during their debugging and operation;
- the application of the described above methodology of individual structural reliability above to ensure the accident-free deployment of the US and numerically confirm the necessary high level of reliability during its design.

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