Dependability, vol. 17 no.1 2017 Original article
DOI: 10.21683/1729-2646-2017-17-1-4-10

On the definition of the term “dependability”

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Aim. *Solving the task of ensuring the dependability of flexible space structures requires an unambiguous interpretation of the term “dependability”, as there is an objective need for considering each and every of the many factors that affect the operating performance. In this case, neither the parametric, nor the functional definitions of dependability given in GOST 27.002 are acceptable. The functional definition of dependability does not require a profound knowledge of the physical principles of flexible structures operation, identification and management of the factors that can cause failures, while the parametric definition of dependability does not allow for a complete parametric description of a product, as the explanation of the term “dependability” states and assumes the presence of factors that are “impossible” or “unnecessary” to characterize based on parameters.* **Methods.** *The contradiction between the parametric and functional definitions of dependability can be resolved by means of the hypothesis of confluence of the parametric and functional approaches to dependability that implies that if all the parameters that characterize the ability of a product to perform the required functions continuously maintain their values in time in specified modes and conditions of operation, maintenance, storage and transportation, then the composite dependability indicator of such product also maintains its values in time in specified modes and conditions of operation, maintenance, storage and transportation. Under the hypothesis of confluence of the parametric and functional approaches to dependability omissions in the parametric description of a product in operation are not allowable. As a consequence, the parametric description must take into consideration not only the parameters, but also the indicators that are not technically measurable, but can be evaluated quantitatively. E.g. the probability of an event can be evaluated within the range from 0 to 1.* **Results.** *The parametric description of a flexible structure based on all parameters and indicators that characterize the ability to perform the require functions allows expressing all values of parameters in different units and all abstract numeric values of indicators numerically to enable the “addition” of the parameters and indicator values. For that purpose, the values of each of the parameters and indicators within the specified limits are evaluated subject to the probability of being with the specified limits over the operation time. Thus found probabilities of the parameters and indicators being within the specified ranges can be reduced to a single generalized dependability indicator by using the method of dependability structure diagram that takes into consideration the functional connection between the operation of elements with a certain reliability in a specific sequence.* **Conclusions.** *The article shows the possibility of a uniform understanding of parametric and functional dependability that are connected in terms of meaning, concepts, definition and methodology. In order to solve the flexible structures dependability tasks when every little detail must be taken into consideration, a parametric definition of the term “dependability” can be used with the addition of just two words to the definition given in GOST 27.002. As a result, the definition of the term “dependability” required and sufficient for the purpose of flexible structures dependability can be as follows: “Dependability is the property of an object to maintain in time and within the set limits the values of all parameters and/or indicators that characterize the ability of the system to perform the required functions in specified modes and conditions of operation, maintenance, storage and transportation”.*

Keywords: *term, dependability, parameter, indicator, probability, flexible structure, spacecraft, probability of no-failure.*

For citation: *Pokhabov Yu.P. On the definition of the term “dependability”. Dependability, 2017, vol. 17, no. 1, pp. 4-10. (in Russian) DOI: 10.21683/1729-2646-2017-17-1-4-10*

Introduction

In 2014, Dependability journal published two articles [1, 2] dedicated to the terminology of dependability, in which the authors, as they phrased it, deliberately avoided to give final recommendations as to the definition of the term “dependability”. Meanwhile, solving the task of ensuring the dependability of flexible structures (FS) of spacecraft (SC), that are unique highly vital systems [3], requires an unambiguous interpretation of the term “dependability”, as there is an objective need for considering each and every of the many factors that affect the operating performance [4]. In this case neither the parametric, nor the functional definitions of dependability given in GOST 27.002 are acceptable. The functional definition of dependability does not require a profound knowledge of the physical principles of FS operation, identification and management of the factors that can cause failures, while the parametric definition of dependability does not allow for a complete parametric description of a product, as the explanation of the term “dependability” states and assumes the presence of factors that are “impossible” or “unnecessary” to characterize based on parameters.

Contradictions between the parametric and functional definitions of the term “dependability” in the context of flexible structures

FS operation is defined by a sequence of states over the lifecycle and is characterized by the following time intervals:

t_1 – operation in compact stowage in launch position during storage, ground handling, ground operation, SC flight as part of the launch vehicle and preparation to transformation in near-earth orbit (operation in launch position is allowed within several years);

t_2 – programmed activation of the initiator that releases the structures in launch position at a given time upon a external. In fact, this time interval lasts for a few moments ($t_2 \ll t_1$);

t_3 – operation of the retaining device and release of the stowed structures (assigned change of kinematic state of devices) ($t_3 \approx t_2$);

t_4 – performance of specified functions of spatial reconfiguration of folded structures (transformation) that usually takes from several seconds to several minutes within several hours from insertion into intended orbit ($t_2 \ll t_4 \ll t_1$);

t_5 – performance of intended mission of the structure in open position over the active service life. For today’s SCs this interval is not less than 12-15 years ($t_5 > t_1$).

The term operation should be understood according to the definition given in the now obsolete GOST 22487, i.e. *execution in the facility (system) of a process (processes) according to the specified algorithm and (or) manifestation of specified properties by the facility*.

FS operation in each of the state and transition from state to state is characterized by certain parameters. In the explanations of the term given in GOST 27.002 it is explicitly stated that *the parameters that characterize the ability to perform the specified functions include kinematic and dynamic parameters, structural strength, functional precision, performance, speed and other characteristics.* [5]. At the same time, the parametric definition of dependability reads that dependability is *the property of an object to maintain in time and within the set limits the values of all parameters that characterize the ability to perform the required functions in specified modes and conditions of operation, maintenance, storage and transportation* [5].

Based on the given definition, [6] concludes that dependability is:

1) a generalized property of a technical system’s performance;

2) retention in time of continuous output parameters with the specified limits:

$$X(t) \in [X_l, X_u], \tag{1}$$

where t is the current operation time; X_l and X_u are respectively the lower upper limits of allowable values of the parameter $X(t)$;

3) performance of the required functions in specified modes and conditions of operation (application);

4) observance of operation conditions.

However, during FS operation *«the ability of the system to perform the required functions»* cannot always be characterized by parameters. For instance, during the Soyuz-1 mission in 1967 the left solar array (SA) panel did not deploy which entailed a series of catastrophic failures of onboard systems and ultimately the decision by the State Commission to initiate emergency disorbit of the craft [7]. As it was later found, the design of the spacecraft did not take into consideration the fact that the SA panel rotation function could be disrupted due to the ability of vacuum thermal insulation shields to “inflate” in zero-gravity environment up to the limits of its movement and thus create an obstacle to panel travel which ultimately caused it to catch and fail to deploy. In this case there is no parameter that would characterize the property of ensuring unimpeded movement of the rotating structure along the specified trajectory.

As for this, the explanations of the terms given in GOST 27.002 include an additional functional definition of the term “dependability” as *the property of a facility to retain in time the ability to perform the required functions in specified modes and conditions of application, maintenance, storage and transportation.* This definition *is used when the parametric description is unnecessary (e.g. for the simplest facilities of which the operability is characterized in terms of “yes” or “no”) or impossible (e.g. for “machine-operator” systems, i.e. systems not all functions of which can be characterized quantitatively)* [5].

Thus, there is a conflict of methods, i.e. a parametric description of FS operation as a unique highly vital product must take into consideration literally each and every factor that affects the operability, however in reality that is impossible. The parametric definition of dependability does not allow for an adequate management of the multitude of factors that affect the FS operability, while the functional definition of dependability does not enable that at all.

The above factors that are sometimes not only versatile, but also physically different [4], many of which cannot be characterized by parameters, include:

- strength factors (absence of destruction and intolerable irreversible deformation);
- stiffness factors (required level of minimal partial frequencies of proper oscillations in the folded and working positions);
- stress-related factors (permissibility of displacement of the structure's elements in case of deformations under external mechanical forces and thermal factors);
- stability factors (non-permissibility of bifurcations within the range of operational loads, e.g. due to play in kinematic pairs or unauthorized folding of structures in the working position);
- design factors (design errors, deficiencies in design methods);
- process factors (deficiencies or disruptions in the adopted process, process errors, insufficient adjustment and calibration limits, uncontrollable effects of assembly, etc.);
- geometrical factors (gaps in kinematic pairs, free travel in mechanisms and drive springs, etc.);
- tribological factors (choice of tribicoupling materials, consistency of lubricant properties, assignment of the thickness of lubricant solid films, etc.);
- vibration resistance factors (impermissibility of loosening of screw joints, allowable partial frequencies, allowable vibration displacements, etc.);
- thermophysical factors (allowable heat distortions, compatibility of materials in terms of coefficient of linear expansion, use of thermal isolation in fastening and operation, etc.);
- physical and mechanical factors (drive moment margins, allowable deployment speed, required values of actuator impulse for initial move, etc.);
- precision factors (precision and stability of positioning, lack of play in working condition, etc.);
- organizational factors (used redundancy methods, ensuring specified deployment zones, observance of specified order of restraint of deployed sections, etc.);
- anthropogenic factors (elimination of unauthorized actions and negligence of personnel, management of engineering psychology factors that complicate incorrect assembly or use of structures, foolproofing).

The authors believe that one of the difficulties of practical application of parametric or functional definition of dependability [2] consists in the separation of the *function (task) performed by the system and the function performed by its parts and/or elements,* which in the given example causes the following contradictions:

- a parametric description of SA panels failure is impossible, as the panels themselves do not have intrinsic properties that depend on the state of panel structures at the moment of failure;
- the failure occurs independently of the intrinsic properties of the SA panels as a result of interaction with external structures (SC vacuum thermal insulation shields).

In the given example, we are evidently dealing with a failure to perform the target function, i.e. deployment of SA panel into working position. In the context of the sequence of states in operation the failure to perform the target function is the consequence of a partial function failure that occurs during SA panel state change t_4 in operation.

Hypothesis of confluence of the parametric and functional approaches to dependability

The above noted contradiction between the parametric and functional approaches to dependability can be overcome if the property of ensuring unimpeded movement of the rotating structure of SA panels along the specified trajectory is defined with the probability of events that takes into consideration both the intrinsic properties of the facility and its interaction with external structures and the environment. In this case the occurrence of the event A that conditions the performance of the target function of SA panel rotation into the working position can be characterized by one of the dependability indicators [5, 8], i.e. the probability of no-failure (PNF), while the performance of the intermediate state change t_4 in operation can be defined by the probability as the level of confidence in the occurrence of the event B that conditions the transition from one state into another. The PNF of SA panel rotation into the working position is associated with the probability of performance of the intermediate state change function t_4 through a conditional probability as the probability of occurrence of the event A provided that the event B has already occurred:

$$P(t)=P(A|B). \tag{2}$$

Thus, the factor that ensures the operability and that is *"impossible"* to be characterized by a parameter can be characterized by a probability that completely defines the performance of the intermediate state change function in operation and ultimately the performance of the target function.

As it is known, any property of a facility can be *distinguished qualitatively and defined quantitatively* [9]. In addition, *quantitative information can be changed, while qualitative information cannot be changed, but can be evaluated* [10].

As it follows from the above example, each i^{th} event in the process of operation can be associated with a certain number that is called its probability and representing the measure of this event’s occurrence, while it is impossible to technically measure the probability, but it is possible to evaluate the probability of occurrence of such event within the range between 0 and 1:

$$P_i(t)\in[0,1]. \tag{3}$$

The probability is an indicator that integrates certain data that can be the basis for evaluation of occurrence of an event, manifestation of a property, process or phenomenon.

Thus, the functions of individual parts of a facility not subject to parametric description can be quantitatively evaluated using indicators as probabilities of retention of the properties that characterize the ability to perform the required functions in time according to (3).

For facilities of which the operability is characterized in terms of “yes of no” the i^{th} property to perform the required functions can also be defined by the probability of retaining in time the “yes” and “no” characteristics:

$$P_i(t)\in\{[1,1]\vee[0,0]\}. \tag{4}$$

The probability of *“performing the required functions”* by a product in general at a random moment in time $\tau\in[0,t]$ is described by the formula:

$$P(\tau)+Q(\tau)=1, \tag{5}$$

where $P(\tau)$ is the PNF; $Q(\tau)$ is the probability of failure.

Based on (5), the dependability of a facility over the operation time $0\leq\tau\leq t$ can change within the limits of the unstrict two-sided inequality:

$$1-Q_{\max}\leq P(t)\leq 1, \tag{6}$$

where $Q_{\max}$ is the maximum value of the probability of failure within the time interval $0\leq\tau\leq t$.

Formula (6) can be brought to the form similar to (1):

$$P(t)\in[P_l,1], \tag{7}$$

here $P_l=1-Q_{\max}$.

It is obvious that the parametric and functional definitions of dependability lead to the conclusion of the continuous retention within specified limits in time of the values of not only the output parameters of dependability (1), but also its output indicators (7). Failure to account for some parameters or error in determining their previous values inevitably cause the uncertainty of limit values of output dependability indicators which in turn causes the risk of failures. For instance, failure to account for event B in formula (2) causes the non-fulfilment of condition (7). Therefore, the output dependability indicators can reliably be within the specified limits only in those cases when the parametric description includes *“within the specified limits the values of all parameters that characterize the system’s ability to perform the required functions”*. In this case the parametric and functional approaches to dependability are confluent.

Hypothesis of confluence of the parametric and functional approaches to dependability: ***If all the parameters that characterize the ability of a product to perform the required functions continuously maintain their values in time in specified modes and conditions of operation, maintenance, storage and transportation, then the composite dependability indicator of such product also maintains its values in time in specified modes and conditions of operation, maintenance, storage and transportation.***

Within the hypothesis of confluence of the parametric and functional approaches to dependability the gaps in the parametric description of a product in operation are not tolerable, hence in the above example the performance of the SA panel intermediate state change functions in operation absolutely must be taken into consideration on the parametric description.

The parametric description with regard to (1), (3)–(4) and (7) can be represented with the set of parameters $X_i(t)\in G$ and indicators $P_i(t)=X_i(t)\forall X_i(t)\notin G$ of which the values meet the following condition of $X_i(t)$ being within the range of specified allowable states D (here and elsewhere the functional symbol of time t is omitted):

$$D=\{X_i|X_i\in[X_{min(i)},X_{max(i)}]\}\,\forall i=(\overline{1,n}). \tag{8}$$

If $n\to\infty$ out of (8) follows the proof of the hypothesis of confluence of the parametric and functional approaches to dependability:

$$\because \{X_i\}\subseteq D \therefore P_i = P\left[X_{\min(i)} \leq X_i \leq X_{\max(i)}\right]\Rightarrow$$
$$\Rightarrow P = P\left[X_i \in D\right]. \tag{9}$$

where $P[\cdot]$ is the probability of a random event that is described in the square brackets.

Proof (9) enables parametric descriptions using a set that indifferently consist of parameters or indicators of a product’s elements. In addition, in the limiting case the parametric description may consist of one composite dependability indicator that characterizes the *“ability to perform the required function”* of the product as a whole.

Thus, parametric description of products using parameters and indicators allows harmonizing the parametric and functional approaches to dependability, in which the parametric and functional dependability are parts of a whole.

Differentiation of the notions of parameters and indicators

The use of the hypothesis of confluence of the parametric and functional approaches to dependability requires strict differentiation of the notions of parameters and indicators. Up to this day there is no such differentiation:

– according to GOST 27.002, the ability of a system to perform the required functions is equally characterized by the indicators (*structural strength, operational precision, etc.*) and the parameters (*kinematic and dynamic parameters, speed, etc.*) [5];

– A.S. Pronikov, the founder of parametric dependability, classified as **parametric indicators** mechanical and strength indicators, power, precision of operation, motive force, top speed, performance, efficiency, noise level, pressure, fuel consumption, etc. [11];

– according to the generally accepted practice, the dependability of facilities *is quantified using the indicators that are chosen and defined subject to the facility's distinctive features, modes and conditions of its operation and consequences of failures* [12].

Both the parameters and indicators are physical values that characterize some properties of a facility (dependability, strength, rigidity, geometry, setting, dynamics, etc.). Parameters are understood as values, of which the intensity can be directly measured by technical mans or calculated (length, force, moment, etc.), while indicators are understood as calculated summarized data that can be used to evaluate the state of the considered property or parameter (assurance factor, drive moment margin, PNF, probability, etc.). Parameters are always defined by a numerical value and unit of physical quantity as they serve to measure geometrical and physical values of the world around, while the indicators are only defined by an abstract number that is part of the value [13].

Using indicators for quantitative evaluation of properties allows accounting for:

– properties that can only be distinguished qualitatively in "binary" form: "zero-one", "yes-no" or characterized only by dependability indicators, e.g. PNF;

– statistical characteristics for critical elements of structures, if any (mass-produced elements or those manufactured in numbers sufficient for statistical conclusions);

– confidence level of failure risk elimination in case associated design, engineering and process solutions are used, based on objective supervision facilities and methods.

The importance of joint use of parameters and indicators in preparation of parametric description of facilities consists in the following capabilities:

– dependability evaluation not only based on quantitative information (through parameters), but qualitative information (through indicators) as well;

– universal enumeration of parameters and indicators that affect dependability;

– elimination of selectiveness and subjectivity in selecting the parameters for dependability evaluation.

The use of the notions a parameter and indicator in parametric descriptions of facilities allows choosing the properties of values that are convenient for characterization. For example, the following can be used for defining the properties of strength:

– values of actual loads (parameters) if they allow clearly evaluating the stress-strain state (tension, compression, shift, bend, twist, stability);

– values of actual load (parameters) if it is required to distinguish ultimate limit states (general strength, fatigue, longevity, temperature strength, creep flow, etc.);

– margins of safety (indicators) if a combined stress state is under consideration subject to the chosen strength criterion (limit strain-stress state);

– PNF (indicators) if the strength property is considered as a stochastic value.

Results of application of the hypothesis of confluence of the parametric and functional approaches to dependability

It must be noted that the upper and lower allowable limits of values may have different physical meaning. For instance, the margin of safety of the drive moment with respect to the resistive moment expresses the *property of the actuator to be sufficiently powerful to rotate the structure* and defines the lower limit of the value (in case of low drive moment margin the rotating structure may fail to deploy). The upper limit of this value is defined by *the strength of the rotating structure when fixed in the working position caused by the conversion of the kinetic energy of rotation into potential energy of deformation at the moment of sudden stop (in case of large drive moment margins the structure may be destroyed). That means that the indicators quantify the properties of products in discordant dimensionless form, which does not allow converting the multi-parametric description into a single generalized dependability indicator, not to mention that the parameters themselves have different units of measurement.*

The absence of a method for accounting and conversion of multi-parametric models into a generalized dependability indicator is reflected in the basic concepts of parametric dependability *that deals not with product failure, but changes in its output parameters. In practice, in parametric dependability a product's operability is identified by the governing parameter*. The state is considered operable if the value of the governing parameter of element *X* that defines the quality of such element in operation does not go beyond the specified *working area* or *tolerance range* [14]:

$$X_{\min}\le X\le X_{\max}. \qquad (10)$$

In order to obtain the generalized FS dependability indicator it is required to convert the values of all parameters and indicators that constitute the parametric description to the concordant dimensionless form, i.e. expressing all values of parameters in different units and all abstract numeric values of indicators numerically to enable the “addition” of the parameters and indicators values.

This becomes possible if condition (10) is expressed by the probability of a parameter or indicator being within the allowable range within the time period $\tau\in[0,t]$:

$$P_i(t)=P\left[X_{\min(i)}\le X_i(\tau)\le X_{\max(i)};\ 0\le\tau\le t\right]. \qquad (11)$$

In this case the generalized dependability indicator subject to the parametric description of a product (8) can be obtained using the method of dependability structure diagram that takes into consideration the functional connection between the operation of elements with a certain reliability (11) in a specific sequence. For instance, for products in which all the structural elements are single points of failure, which is typical to FSs, the PNF subject to (11) is found using the formula:

$$P(t)=\prod_{i=1}^{n}P_i(t). \qquad (12)$$

Under the hypothesis of confluence of the parametric and functional approaches to dependability formula (11) with regard to (8) and (11) is equivalent to the following:

$$P(t)=P\left\{X_i(\tau)\in D,\tau\in[0,t]\right\}. \qquad (13)$$

Formula (13) is nothing short of the dependability function in V.V. Bolotin’s general theory of mechanical systems dependability [15].

Conclusion

The article shows the possibility of a uniform understanding of parametric and functional dependability that are connected in terms of meaning, concepts, definition and methodology.

In order to solve the FS dependability tasks when every little detail must be taken into consideration, a parametric definition of the term “dependability” can be used with the addition of just two words to the definition given in GOST 27.002. As the result, the definition of “dependability” sufficiently required for the purpose of FS dependability can be as follows: *“Dependability is the property of an object to maintain in time and within the set limits the values of all parameters* ***and/or indicators*** *that characterize the ability of the system to perform the required functions in specified modes and conditions of operation, maintenance, storage and transportation”.*

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Received on 17.08.2016