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Reliability Standards of Complex Engineering Systems

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Abstract. Production and manufacture play an important role in today's modern society. Industrial production is nowadays characterized by increased and complex communications between its parts. The problem of preventing accidents in a large industrial enterprise becomes especially relevant. In these circumstances, the reliability of enterprise functioning is of particular importance. Potential damage caused by an accident at such enterprise may lead to substantial material losses and, in some cases, can even cause a loss of human lives. That is why industrial enterprise functioning reliability is immensely important. In terms of their reliability, industrial facilities (objects) are divided into simple and complex. Simple objects are characterized by only two conditions: operable and non-operable. A complex object exists in more than two conditions. The main characteristic here is the stability of its operation. This paper develops the reliability indicator combining the set theory methodology and a state space method. Both are widely used to analyze dynamically developing probability processes. The research also introduces a set of reliability indicators for complex technical systems.

1. Introduction

Reliability theory and its methodology changes and evolves according to production needs [1-5]. about a generation ago (that is 30 to 35 years), it was believed that an object or a product might be either in an operable or in a non-operable condition. It was also assumed that being operable the object was fully performing its functions (a functional object). This description of the process of operation is characteristic of relatively simple objects. However, for a number of objects this conception of reliability simplified a complex process of their operation. Specifying complex technical systems as a special class of objects [6] and developing indicators of their work [7] are considered to be notable achievements in the development of reliability theory.

2. Relevance

A complex object consists of simple objects (elements) that are connected together in a specific way [8-20]. These objects usually interact within a compex system. Failure of a simple object makes it nonfunctional, otherwise this object is functional. A complex object can be in more than two conditions. Failure of its constituent elements may affect the quality of its operations, with the object itself being still fictional. Thus, in a complex object, reliability is not a question of its operable condition, but stability of its output parameters values and efficiency of its work. This is a fundamental difference between a complex and a simple object.

3. Research Theory

It is assumed that efficiency refers to the achievement of the desired results with the minimum of effort, the so-called work productivity. For example, the efficiency of water supply is assessed by the level of water supply to consumers in the necessary quantities and under the required pressure at minimal cost. Quality performance of a complex system can be described as work productivity fro some complex systems, and probability of work success at a time for the others. Quality performance is an instant or spot assessment of the system reliability. It shows how its performance has deteriorated (or improved) at this time.

Another group of performance indicators for a complex system is assessed by its output effect. The output effect can be determined by produced quantity or probability of performing the task in a given time interval successfully, that is, the output effect here is an interval indicator. The quality and efficiency of performance characterize the work of complex systems from different perspectives making its assessment more complete. In some cases the efficiency of functioning at a certain time interval satisfies consumers or meets some regulatory requirements. For example, a 24-hour reduction in the daily flow of water will not exceed 30%, which is acceptable under the existing regulations. At the same time, there may be moments during this period when the reduction exceeds 30% of regular feed, i.e. the quality of operation is lower than acceptable. Paper 7 [7] contains recommended indicators for the reliability of complex technical systems (CTS), some of which are shown in Table 1 as examples.

4. Research

Paper 8 introduces a model capable of comprehending all situations connected with theoretical and applied issues of reliability of industrial objects and with calculations of their reliability [8]. This model is based on the set theory involving the use of a state-space device. Each point of this device identifies the state of the system and is characterized by a set of parameters, including reliability. Such models are widely used in various fields of science and technology [10,11]. This article assumes that reliability is determined by operable or non-operable condition of an industrial object in case this condition affects the performance of the oblect. Thus, splitting all possible conditions of the object under investigation into subsets of conditions with a different number of simultaneous failures.

Table 1. Recommended reliability indicators for complex technical systems.

Term	Definition	Notes
Output effect	Useful result obtained during operating the system in a given time interval	
Quality of performance indicator	Mathematical expectation of the quality of the system performance at a of time	
Probability of an alpha-percent operation	Probability that quality performance of the system is not less thanα% at a specified time interval	This is the equivalent of probability of no-failure operation
Average time of alpha percent operation	Average operating time of the system at a specified time interval with quality levels not less than α%	This is the equivalent of average work till the first failure

In particular, in an object consisting of n identical blocks (for example, repair sections of a plumbing or sewage network, pumps at a pumping station, etc.), subsets may differ in the number of non-functional units at a time. In such a case, there is a subset of operable conditions – S_0. The rest of the set presents non-operable conditions, which can be represented as subsets with a single failure (S_1), with two failures at a time (S_2), and so on. Obviously, S_0 subset contains one unit, S_1 subset includes as many units as there is in the block of object that are switched off during repair. A block can consist of a number of units that are in connected a certain way and interoperable. The failure of at least one unit in the block requires switching off the entire block to repair it. An example of such a block is a repair section of a water-supply system, in which a pipe failure, or a failure in connection between them requires to switch off the entire section to repaire one unit. S_2 subset will contain as many elements as can be combined into pair of n blocks, i.e. C_n^2. In general, in S_k containing n blocks by k, the number of combinations will be

$$C_n^k = \frac{n!}{k!(n-k)!} \tag{1}$$

Each condition of a set of multiple (or subsets) is obviously characterized by a certain level of reliability, which is evaluated by specific parameter values. In this set of multitude, H subset can be extracted as it covers all conditions providing a normal level of performance for the object. After H subset has been extracted, we see that the remaining X subset covers conditions with a lower level of reliability compared to normal. The degree of reliability level decrease compared to the normal level for each condition of X subset will be different. For some reason, there is also A subset in X space, which is considered to be invalid, and each time the technical system falls into any of the conditions belonging to A, the system is considered to be in failure condition. It is clear that the choice of A subset is extremely conventional and is determined by purposes for which the engineering system is intended. Therefore, it can happen that A subsets (for failure conditions) are not the same for one and the same system in different contexts. The choice of A subset depends mostly on the tasks assigned to the system.

Let us take water supply and distribution system (WSDS) as an example. Water supply for a livestock farm or a small residential village is allowed to break for several hours. A several hours break in water supply for cooling open-hearth furnace will cause a failure with great material damage. In the first case we can select a relatively small subset as A subset. In the second case it will be a very large subset. After A subset is extracted from X subset, the remaining C subset contains conditions with reliability which is lower than normal, but these conditions are not failures. These conditions, with reliability reduced to a certain limit, are considered to be valid when the object is in operation during some definite predetermined time. In other words, all state space is divided into three areas.

Area H focuses on all conditions where the reliability is not below the established level, area C, which contains low-reliability conditions as compared to an established limit, and area A, in which conditions of failure with reliability below the minimum limit. Under the influence of changes in the external and internal conditions of an object, which are usually probabilistic or stochastic, the object can randomly move from one state to another, that is, move between individual units of multiple conditions. These individual units are separate points of its path of motion. During the operation process, the path of an object's motion in the state space at a certain period of time, such as a year, will generally run through areas H, C and A. Clearly, the system will stay in each of these areas for a part of time proportional to the location of the corresponding part of the mothion in this area. This makes possible to determine, for example, how long the system operates normally (T_n), how long the system operates within the lowest permissible level of quality (decreased quality - d) (T_d), and how long the system is failure condition. This assessment of the reliability of the system operation is sufficiently complete to solve the problem of stability of its work at a time, which is vital to its practical use. Thus, the condition of the system in the state space at a time follows a path of motion that gives a complete picture of changes in its properties over time.

The assessment of the path of motion can be done in connection with two types of indicators: dot graph or instantaneous, assessing separate conditions or path points; interval or temporal, which characterize the behavior of the path at a specific time interval.

It means that the reliability of an object cannot be determined by one indicator. To characterize reliability properties of an object fully, it is necessary to use a set of indicators covering all the major phases of its work. The main indicators that make up this set should make it possible to identify and determine all reliability characteristics of the object, and at the same time provide instantaneous assessment of its reliable performance.

Instantaneous indicators offer assessment of separate conditions, determine the degree up to which the system is able to perform its functions in that condition, and set the level of quality for the operation of the object in this condition. With the help of instantaneous indicators, the set of the object conditions is divided into H subset with a normal level of performance, C subset evolving conditions with reduced to a certain level quality of operation, and A subset evolving conditions with performance below the established minimum limit, that is, failure conditions.

Interval indicators allow to estimate the time period with the system staying in this or that subset, or the duration of the object's work until it is first enters C or A areas. An important interval indicator is the output effect [7] The output effect is a useful effect obtained from the operation of the system at a given time interval. For complex engineering systems (CES), the probability of no-failure operation analogy is the probability of an alpha percent operation [7], i.e. the probability that the system will work at a given time at a level of performance quality not less than α%. Another analogy here is the average time of alpha percent operation [7]. It is the average operating time of the system for a given time interval at a level of performance quality of at least α%.

As we have already mentioned, two types of indicators can be used to describe the path of motion. They are instantaneous and integral indicators. Instantaneous indicators can be presented as follows: R^0 – rate parameter values at normal performance quality level; R^0_{min}– rate minimum-permitted values of parameters when compared to normal operating quality; R – current calculated values of rate operation parameters. The values of R^0 and R^0_{min} parameters should be universally recognized. It is also required to determine these values in regulataory and reference guide literature while designing CES. With the use of instantaneous or dot graph indicators, all CES conditions can be divided into three subsets: if $R \geq R^0$, this condition is referred to H area; if $R^0 > R \geq R^0_{min}$ this condition is referred to C area; if $R < R^0_{min}$ this condition is referred toA set. Then, it is necessary to determine the time when the object stays in H area (time of stay T_H), C area (time of stay T_C) and A area (time of stay T_A). T_H, T_C and T_A values are considered to be CES reliability indicators. The physical meaning of such indicators is obvious and understandable to everyone without special training and education. Conditions with $R^0 \geq R \geq R^0_{min}$ are characterized by a reduced level of performance quality which does not exceed a certain limit. The decrease in the quality of operation is measured by relative or absolute values.

When comparing options in T_C period with other parameters being equal, it is preferable to choose the one in which the decrease in performance quality is lowest. To do this, we have to introduce an output effect as another indicator. According to Paper 7 [7], the output effect is a useful result obtained from the operation of the system over a given time interval. In all cases, with other parameters being equal, the best option would have a stronger output effect. Obviously, the output effect can be calculated not only for the object as a whole, but also for its separate units.

The time the failure before it is localized or the emergency element is disabled is the period of transition mode of the first type or the emergency state of the object. The second type of transition mode is a period during which the previously repaired unit of the object is introduced into its work. The first type of transition is of a sudden, random character. This transition often decreases reliability of the object operation. The second type of transition may occur routinely and does not decrease reliability of the object.

In terms of performance evaluation during the transitional regime, comp[lex systems are divided into systems of long-lasting action and of instant-action. In systems of long-lasting action we estimate efficiency of the performance during a transitional mode in $[t, t + \Delta t]$ interval. In instant-action systems, the performance during a transition period is not significant because the interval is small, as the system goes from from one state to another quickly enough.

During $[t, t + \Delta t]$ interval it is possible to determine the fact that the system is malfunctioning, to location failed elements, to contain the accident by disabling the failed element. Thus, the set of indicators for determining the reliability of a complex engineering system should include the following parameters: R^0 – rate parameter values at normal performance level; R^0_{min}– normalized minimum-permitted values of parameters with reduced quality of operation; T_H – average time of operation with normal quality (during the year the operation of the facility); T_C– average time of operation with quality reduced to a certain limit (during the year the operation of the facility); t_n – time of transition; B – output effect.

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Besides, important indicators of CES reliability are those of failure-free performance and maintainability. Paper 12 states that "random process theory provides the basis for analytical methods for calculating reliability indicators ... and homogeneous Markovian processes with finite number of states and continuous time serve as the primary mathematical apparatus for research into the reliability of complex systems with renewal. This is these processes allow analytical expressions or design computational diagrams to be used to calculate different reliability indicators [12]". $T_{н}$ and T_{c} indicators are calculated while using a failure rateλ [1km/per year] (9, p. 6.13) and an average recovery time μ [1/year] (9, p. 6.91) using the Markov model with continuous time and discrete conditions.

5. Conclusions

On the basis of the mathematical model developed in Paper 8 [8], this paper has introduced a set of reliability indicators for such complex technical systems as water and sewage city facilities, industrial enterprises and the like [13].

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