UDC 623.418.2
DOI: 10.15587/1729-4061.2021.225484

DEVELOPMENT OF THE COMBINED METHOD FOR EVALUATING AND CONTROLLING THE RELIABILITY INDICATOR "PROBABILITY OF FAILURE-FREE SWITCHING" OF A RADIO TECHNICAL COMPLEX

V. Lukianchuk
Doctor of Technical Sciences, Senior Researcher, Head of Department*
B. Lanetskii
Doctor of Technical Sciences, Professor, Leading Researcher*
H. Khudov
Doctor of Technical Sciences, Professor, Head of Department
Department of Radar Troops Tactic**
E-mail: 2345kh_hg@ukr.net
O. Zvieriev
PhD, Associate Professor, Researcher
Research Laboratory of Automation of Scientific Researches
Central Scientific Research Institute of Armament and Military Equipment of the Armed Forces of Ukraine
Povitroflotsky ave., 28b, Kyiv, Ukraine, 03049
I. Terebuha
PhD
Combat unit A0800
Italiysky blvd., 3a, Odessa, Ukraine, 65012
V. Kuprii
PhD, Associate Professor, Deputy Head of Department
Department of Training Command
Combat unit A0105
Dehtiarivska str., 19, Kyiv, Ukraine, 04119
K. Borisenko
Senior Lecturer
Department of Air Defense Weapons Land Forces**
A. Artemenko
Senior Research
Department of Radio-Technical and Special Troops***
O. Aristarkhov
Adjunct
Department of Technical Support***
Y. Kondratenko
Adjunct
The Center for Military and Strategic Studies***
*Research Department for the Development of the WME system of the Air Force Air Defense Forces of the Air Force Science Center**
**Ivan Kozhedub Kharkiv National Air Force University
Sumska str., 77/79, Kharkiv, Ukraine, 61023
***Ivan Chernyakhovsky National Defense University of Ukraine
Povitroflotskyi ave., 28, Kyiv, Ukraine, 03049

The operation of a radio-technical complex based on a technical condition is represented by cycles. Each cycle implies control over a limiting state in order to make timely and informed decisions on managing the operation of a radio-technical complex. That should resolve the task of assessing and monitoring the indicators of fault-free operation with the required accuracy and reliability based on operational observations and, if necessary, special tests that could minimize the cost of special tests.

Given the introduction for a radio-technical complex of the repeated application of a new indicator of fault-free operation "the probability of trouble-free switching", a combined method of its evaluation and control has been developed. This method is a set of known and developed criteria, models, methods, and schemes that determines the sequence of their application for joint evaluation and control of this indicator.

The criteria for verifying the uniformity of data on the operational observations and special tests for the fault-free operation of a radio-technical complex have been defined, as well as the corresponding models for assessing the one-sided lower confidence boundaries of the indicator under consideration, and the methods to control it.

The devised method makes it possible to derive estimates of the probability of trouble-free switching, as well as the magnitudes of the observed risks of decisions being made with acceptable accuracy and reliability.

The results of modeling the devised combined method helped obtain the accuracy and reliability of its estimates and the observed risks of controls carried out. Recommendations have been compiled for applying the method to address the challenges of joint assessment and control of the probability of trouble-free switching of the considered complexes

Keywords: assessment and control of fault-free operation, operation based on technical condition, radio-technical complex

Received date 16.12.2020
Accepted date 21.01.2021
Published date 26.02.2021

Copyright © 2021, V. Lukianchuk, B. Lanetskii, H. Khudov, O. Zvieriev, I. Terebuha, V. Kuprii, K. Borisenko, A. Artemenko, O. Aristarkhov, Y. Kondratenko
This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0)

1. Introduction

It is possible to reduce the cost of operating modern radio-technical complexes (RTC) at the predefined effectiveness of their operation by using resource-saving technologies, and, in particular, methods of operation and repair based on the technical condition [1]. In order to implement these methods, it is necessary to control the limiting state of a particular RTC over a regular period or a period adapted to the level of fault-free operation. Based on the results of controlling an RTC's limiting state, timely and informed decisions on operational management should be made, including the need to repair, decommission, and dispose of. At the same time, the operation of a specific RTC is carried out in cycles; during each, the task must be resolved of assessing and monitoring the indicators of fault-free operation (IFO) at the required accuracy and reliability; their results must be used to manage the operation and repairs. These IFO include such reliability indicators as «average failure rate» and «probability of trouble-free switching», as well as indicators of residual durability «average residual life (resource) performance» and «gamma-percentage residual service life (resource)». The need to introduce a new indicator of fault-free operation «the probability of trouble-free switching» in the range of the rated RTC IFO, which is a product for repeated operations, is justified in [1, 2].

The task of assessing and monitoring reliability indicators should be solved on the basis of operational observations and, if necessary, the results of special tests for fault-free operation, which must be carried out when controlling the limiting state. Special tests are defined as reliability tests, organized specifically to determine (control) their indicators [1, 3]. At the same time, quantitative assessments of these indicators are used to estimate the indicators of RTC residual durability and to decide on its maximum (non-limiting) state, as well as to plan activities to manage its operation and repair.

The main requirements for the quality of the results of the experimental evaluation and control of IFO are [3] the accuracy and reliability of the results of the assessment and control, the cost-effectiveness of tests (minimization of the duration of tests), etc.

The application of known methods to these tasks is not effective as they usually involve a separate solution to the tasks of assessing and monitoring the indicators of fault-free operation for a group of homogeneous articles. In addition, they imply separate tests of RTC for reliability and durability, and, accordingly, separate assessment and control of their indicators. Such tests require significant financial, temporal, and other resources, the need to isolate a group of homogeneous articles, which is not acceptable during the operation of RTC based on technical condition.

In order to implement the operation and repair of RTC based on the technical condition, it is necessary to devise methods of joint assessment and control of their reliability indicators (RI) at the required accuracy and reliability while minimizing the cost of special tests. Of these tasks, the priority is to assess and monitor such an indicator of fault-free operation as «the probability of trouble-free switching», which is new for RTC.

In this regard, it is relevant to develop methods of joint assessment and monitoring of the fault-free operation indicator «the probability of trouble-free switching» for a radio-technical complex that could minimize the volume of special tests.

2. Literature review and problem statement

The radio-technical complex is a controlled, restored, and serviced article of repeated use [2, 4–6]. RTC is characterized, as an object of operational testing for reliability, by high reliability, the means of technical condition control and registration of its components, measured in hours, the number of switching, which are recorded in operational documentation. To assess such RI as «the probability of trouble-free switching», it is possible to use data from operational observations in the form of the number of RTC switching over a certain interval of operation and their results. At the same time, this data can be considered as the results of operational tests of RTC based on the indicator of «the probability of trouble-free switching» under the binomial scheme [1, 2].

The literature reports methods to derive separate solutions to the tasks of assessing RI of the type «probability» and to the tasks on their control [3, 7, 8], to a lesser extent – methods of their joint solution, for example, the method of control involving confidence boundaries [7]. To solve the tasks related to control RI of the type «probability», the typical methods used include checking statistical hypotheses without taking into consideration a priori information [7]. Regulatory documents recommend the use of the most developed methods to control IFO (single-stage, two-stage, sequential, sequential truncated, using confidence boundaries) and their modification on two levels. The above methods of consistent reliability control are aimed at reducing the required test volumes [9]. Analysis of these methods shows that their use in binomial tests of highly reliable objects does not give a significant effect. In addition, the known methods of reliability control do not provide for the possibility of planning the rational determining or controlling tests. A rational plan for a reasonable reliability test [10] is understood as the one that, at the predefined test duration, ensures the highest accuracy of indicators' assessment. A rational control test plan [3] is understood to be one that, at the assigned cost of control, is characterized by the lowest area under its operational characteristic. The known two-tier methods of reliability control can be arranged, in the order of improving their level of rationality, as follows: single-stage, multistage, sequential, sequential, optimal generalized sequential, combined [3, 10]. Among single-level control methods, two-stage control is more rational than single-stage control [10]. All these methods, except for the method of control based on confidence boundaries, do not provide for joint evaluation and control of RI.

It is possible for RTC operated on the basis of technical condition, along with control methods based on the theory of statistical hypothesis verification, to use control methods using confidence boundaries [7]. At the same time, it is necessary to adhere to the well-known position of this theory about the mutually unambiguous correspondence between the regions of decision-making and the system of unilateral confidence intervals. Control by confidence boundaries implies assessing the failure rate, making a decision on acceptance or refusal determining the observed risk of supplier α or consumer (operator) β [7]. In this case, a control option is possible without planning the scope of tests (operational observations) or with their preliminary planning. In the course of monitoring without planning, it is possible to make a decision based on the data from operational observations accumulated from the results of control of RTC operation, as well as other activities over a certain interval of its operation. Hence, the feasibility of using this method in the operation of RTC based on technical condition [1]. In addition, when implementing the control of fault-free operation based on confidence boundaries, it is possible to take into consideration a priori information, which makes it possible to reduce the volume of special tests of RTC.

A known method of control using confidence boundaries [7, 9] does not involve the use of a priori information, which reduces the effectiveness of its application for the operation based on technical condition.

Papers [11–13] address the development of IFO assessment methods, such as readiness ratio, complex systems with temporal redundancy during development. The issue of assessing the reliability of technical systems during the operational phase with the development of diagnostic systems is considered in [14]. A method of assessing the stationary readiness factor of the mechatronic system has been developed in [15]. The authors of [16] considered a method of assessing the reliability of a complex technical system with cold reservation taking into consideration the priorities of its devices for use as intended and for restoring. However, the methods reported in [11–16] solve only the task of assessing reliability indicators at the normal operational stage. This is due to the regulated method of the operation of objects under consideration, under which their operation during the «aging» phase is not implied, and ceases.

Study [17] proposes an analytical method for assessing the reliability of modular multi-level devices in different reservation schemes, making it possible to justify their structure based on calculating the reliability of different build options. The approach used in [17] is only applicable to non-recoverable systems of continuous long-term use with a simple mode of operation.

The authors of [18] consider a method of predicting the reliability of general-purpose technical articles, based on the continuous process of Markovian degradation, which makes it possible to assess the reliability of such objects during design. The method proposed in [18] is only applicable to non-recoverable objects of continuous long-term use.

A method of monitoring the reliability of a complex continuous long-acting technical system, which includes space-distributed components, is presented in [19]. The method makes it possible to solve the problem only by controlling the reliability of the system taking into consideration the emergency states. However, the method reported in [19] does not provide quantitative estimates of the reliability of such systems.

The authors of [20] devised a method of monitoring the reliability of the recoverable technical system taking into consideration the hardware failures and failures caused by operator errors. The method from [20] is used to monitor the reliability of systems based on experimental data and can be applied to monitor the reliability of the operator or equipment at the predefined requirements for the system in general. At the same time, the issues of joint evaluation and monitoring of the system's reliability indicators were not considered.

There is a growing body of research on the evaluation of complex technical systems' IFO, taking into consideration the a priori information [21, 22]; this task, however, has no final solution. Thus, to minimize the volume of tests, it is possible to use methods of linear combining of non-displaced assessments of such articles' IFO, evaluation on the basis of two samples, Bayesian approach [22], etc. The use of the above techniques (except for the latter) requires that by the time the test is planned, the so-called «information transfer model» should be known, to determine the relationship between the parameters of such articles.

Thus, the known methods of evaluation and control of RTC are not used for the «probability of trouble-free switching» fault-free operation indicator and are focused on the separate solutions to tasks of assessing and monitoring reliability indicators without taking into consideration a priori information.

It follows from the above that there is a need to devise a combined method of assessing and monitoring such an indicator of fault-free operation as «the probability of trouble-free switching» for RTC operation based on technical condition involving interconnected solutions to these tasks.

3. The aim and objectives of the study

The aim of this study is to develop a combined method for assessing and monitoring the probability of RTC failure-free switching that could ensure the accuracy and reliability required to operate it on the basis of its technical condition.

To accomplish the aim, the following tasks have been set:

– to devise general provisions for joint assessment and control of the probability of RTC failure-free switching;

– to develop criteria to verify the homogeneity of observational and test data and models for the evaluation of failure-free turning on probability (FFTP);

– to build a scheme of the joint assessment and control of the probability of RTC failure-free switching;

– to investigate characteristics of the combined method for assessing and controlling the probability of RTC failure-free switching.

4. Devising general provisions for the joint assessment and control of the probability of RTC failure-free switching

Each cycle of RTC operation based on its technical condition (Fig. 1) is split into intervals of fixed duration ΔT, in which the data from operational observations are registered [1]. These data are treated as results of reliability tests and are used to evaluate and control RTC FFTP.

The operation cycle of RTC based on a technical condition is understood to be the least repetitive time interval during which all defined types of technical control and maintenance operations (MO) controls are executed in a certain sequence. The types of control over the technical conditions of RTC include periodic control of functioning, control of performance and operability during MO at different periodicities, as well as control of the limiting state. At the same time, the period of control of the limiting state can be adapted to the level of failure-free operation, or fixed, and equal, for example, the MO period of maximum frequency for RTC of a certain type [1]. The timeliness of the decision on managing the RTC operation is determined by the time of the response of the RTC limiting state control system to a change in the level of its failure-free operation. At the same time, a significant change in the level of RTC failure-free operation is established within several intervals ΔT within the same cycle of operation.

The duration of intervals ΔT of the operating cycle based on technical condition should be sufficient to accumulate an acceptable (for the assessment of RI) number of switching, and consistent with the periodicity of RTC MO. In addition, the RTC failure-free operation over duration ΔT should not change significantly.

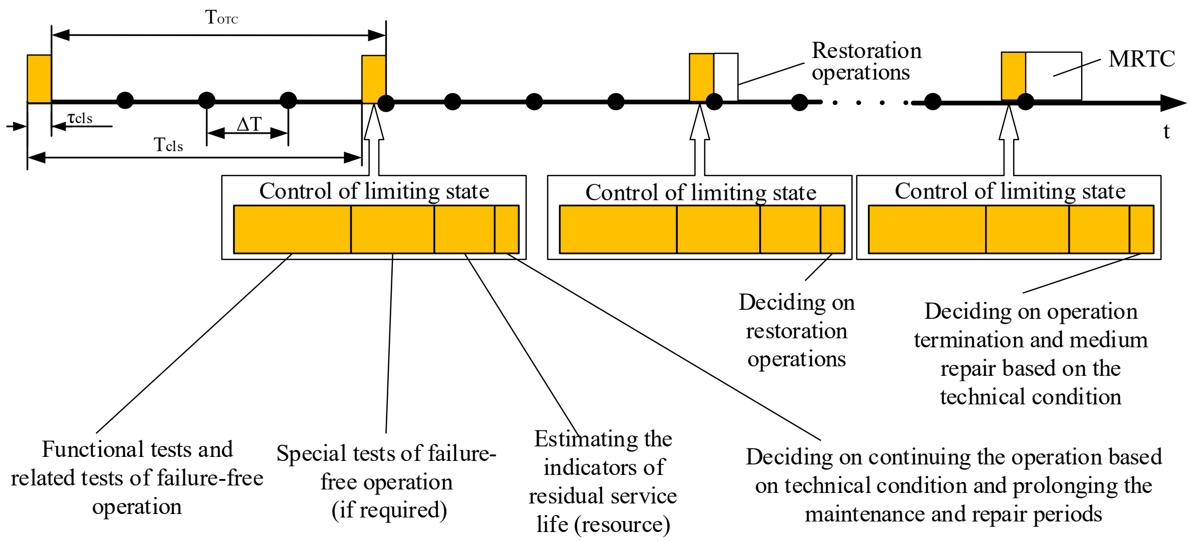

Fig. 1. Graphic representation of the possible variant of implementing the operation of RTC based on technical condition: T_{OTC} – cycle of operation; T_{cls}, τ_{cls} – the frequency and duration of control of the limiting state, respectively; ΔT – duration of the operational cycle interval; MRTC – medium repair based on the technical condition

Control over the limiting state of RTC involves functional tests, which are considered as combined tests for failure-free operation. If there are no enough operational observations and functional tests of RTC over the final interval ΔT (Fig. 1), it is necessary, to solve the task of the assessment and control of failure-free operation, to provide special tests on the failure-free operation. The results of the evaluation and control of RTC FFTP are then used to estimate the values of the residual resource (lifetime) indicators [1].

The characteristics of the evaluation and control of RTC FFTP RI, operated based on technical condition, are:

– assessment and control is carried out, as a rule, sequentially over various adjacent intervals ΔT of operating cycles towards prolonging the duration of operation (Fig. 1);

– in the process of operation, technical maintenance and ongoing repairs do not lead to an increase in the value of RI;

– the conditions for special testing and operation over intervals ΔT correspond to the RTC routine operating regimes.

The following assumptions have been adopted when devising the method:

– changes in the value of the controlled (estimated) indicator over the duration of operating interval ΔT, including special reliability tests, can be neglected;

– over a cycle of operation and longer the value of the controlled (estimated) indicator of failure-free operation can change significantly and is characterized by a monotonously non-ascending dependence;

– the requirements for the accuracy and reliability of RI assessment and control are set;

– there are known formulae or tables of plans for a single-stage control of RI the type of «probability» or a technique to calculate confidence boundaries.

For the evaluation and control of FFTP, cyclical tests of RTC are carried out, consisting of a series of n consecutive «on-off» cycles. Each cycle is a single experience and consists of:

– disabling RTC in an operating state, established by the results of the control of the operation conducted before the shutdown;

– expectation when off for at least the duration of transitional thermal processes in RTC equipment;

– enabling RTC and monitoring the operation to obtain the result «RTC is operational» or «RTC is inoperable».

The results from each individual «on-off» cycle can be seen as independent random events. At the same time, the number of unsuccessful cycles observed as a result of the tests «on and off» over interval ΔT is subject to a binomial distribution with a constant probability of failure in every single experience.

A certain number of these switching cycles are implemented over an interval ΔT, the results of which are used to evaluate and control the RTC FFTP. At the final interval, various operational observation plans and special tests of RTC are possible, due to a different number of switching cycles, the criteria for their completion, etc. In this regard, in order to ensure the predefined accuracy and reliability of the assessment and control of FFTP at the final interval, it is advisable to provide for the processing of observational and testing data taking into consideration their possible heterogeneity. At the same time, special tests should be carried out in a planned volume taking into consideration the volume of operational observations realized at this interval ΔT.

In terms of the specificity of the baseline data obtained during the implementation of RTC operation based on technical condition (Fig. 1), two cases should be identified. In the first case, which is typical of all intervals ΔT of a cycle, except the final one, the results of only operational observations over ΔT are used. In the second case, which is typical of the final interval ΔT in a cycle, the results of operational observations and special reliability tests are used.

In the first case, it is proposed to use the method of control through confidence boundaries without prior planning for the evaluation and control of RTC FFTP. It makes it possible to obtain FFTP assessments and to solve the control problem with an assessment of the observed risk by the data from operational observations over the interval ΔT [7].

In the second case, the evaluation and control of RTC FFTP may be executed by using a control method assuming confidence boundaries with pre-planning. In this case, the task of determining one-way confidence boundaries of the predefined level should be resolved on the basis of data accumulated during operational observations and tests taking into consideration their possible heterogeneity. At the same time, there are three options for processing this data with the development of appropriate models for the evaluation of RTC FFTP. The first option assumes their belonging to one general population, the second and third, respectively, their homogeneity or heterogeneity at the predefined level of significance. Appropriate criteria for verifying their homogeneity are used to select a specific option for processing operational observations and special test results.

It is proposed to tackle the set of these tasks through the development of a combined method of assessment and control of RTC FFTP. It should represent a totality of known and devised criteria, models, methods, and schemes that determine the sequence of their application for the joint evaluation and control of «FFTP» in the operation of RTC based on technical condition.

5. Developing the criteria to verify the homogeneity of observational and test data and the models of FFTP assessment

In accordance with the theory of statistical solutions, different criteria for verifying the homogeneity of samples are possible. In order to implement the operation of RTC based on technical condition, the most appropriate are the criteria that do not require a significant expenditure of the technical resource of the complex, large time, financial, and other costs, and that provides for acceptable risks. These include a criterion based on the principle of maximum plausibility (first) and a criterion based on the use of a confidence interval (second).

In accordance with the first criterion, the decision on the uniformity of the results of operational observations and special tests is taken if the test of RTC with FFTP $\widehat{P}_1$ in the volume n produces the most likely number of failures $\boldsymbol{d}$. The $\widehat{P}_1$ means a point estimate of the maximum plausibility of this probability, derived from the results of operational observations.

With a positive decision on this criterion, the data of operational observations and special tests are combined, which makes it possible to obtain estimates of FFTP with the predefined accuracy and reliability.

In accordance with the second criterion, the decision to jointly process data from operational observations and special tests is made if the hypothesis of their homogeneity is confirmed at the predefined level of significance. These data are processed on the basis of their possible heterogeneity that allows for the assessments of FFTP of acceptable accuracy and reliability.

If in accordance with the second criterion, a decision is made on the non-conformity of data from operational observations and special tests at the predefined level of significance, only special tests are used to evaluate FFTP. This employs known ratios for point and interval assessments of V FFTP, obtained according to special tests.

The first criterion. According to the principle of maximum plausibility, it can be considered that in binomial tests in the volume of n the most likely number of failures d occurred. The number of failures would be most likely if the following conditions are met:

$$P_n(d) \geq P_n(d+1), \tag{1}$$

$$P_n(d) \geq P_n(d-1), \tag{2}$$

where

$$P_n(d) = C_n^d \cdot P^{n-d}(1-P)^d,$$

P is the actual value of an article's FFTP.

By transforming expressions (1), (2), we obtain:

$$\frac{n-d}{n+1} \leq P \leq \frac{n-d+1}{n+1}. \tag{3}$$

Then, if inequality (3) holds, the data on operational observations and special tests for failure-free operation based on the FFTP indicator are considered as homogeneous implementations. At the same time, d is the most likely number of failures of RTC in tests in the volume of n, and, the actual level of failure-free operation used is its assessment $\widehat{P}_1$ based on operational observations over this interval.

Inequality (3), where $P = \widehat{P}_1$, is to be considered as a check rule on the uniformity of data from operational observations and special tests at the end interval of the cycle of operation based on technical condition. At the same time, the volume of special tests should be planned taking into consideration the realized volume of operational observations, based on the set requirements for the quality of FFTP assessment. Assessment of FFTP by combined data would make it possible to obtain estimates for this indicator with the required accuracy and reliability for subsequent control involving confidence boundaries. That would ensure that the RTC's non-limiting (or limiting) state is decided on with risks not exceeding those set. In addition, these results are used to assess controlling influence over the subsequent RTC operating cycles based on technical condition.

The first model of evaluation. Combining the results of operational observations and tests, considered as homogeneous implementations, using the Bayesian method. Then, for the results of operational observations and special tests, represented in the form of (n_1, d_1) and (n_2, d_2), respectively, the point estimate of FFTP is derived from the following ratio:

$$\widehat{P}_{1,2} = 1 - \frac{d_1 + d_2}{n_1 + n_2}. \tag{4}$$

At the same time, one-sided lower and upper confidence boundaries $\underline{P}$ and $\overline{P}$ at confidence probability γ are found as a result of solving the Clopper-Pearson equations [3, 7].

$$\sum_{r=0}^{d_1+d_2} \frac{(n_1+n_2)!}{r!(n_1+n_2-r)!} \underline{P}^{n_1+n_2-r} (1-\underline{P})^r = 1-\gamma, \tag{5}$$

$$\sum_{r=0}^{d_1+d_2-1} \frac{(n_1+n_2)!}{r!(n_1+n_2-r)!} \overline{P}^{n_1+n_2-r} (1-\overline{P})^r = \gamma. \tag{6}$$

These roots are denoted via $\underline{P} = f_2(n_1+n_2, \widehat{P}_{1,2}, \gamma)$ and $\overline{P} = f_1(n_1+n_2, \widehat{P}_{1,2}, \gamma)$. Tables for f_1 and f_2 are given in [8].

The second criterion. Suppose that the data from operational observations produced a priori FFTP assessment of $\widehat{P}_1$, while the results of special tests in the control of the limiting state – an assessment of $\widehat{P}_2$. Since the estimates $\widehat{P}_1$ and $\widehat{P}_2$ characterize one actual quantity P, their difference ΔT can be considered a random quantity with zero mathematical expectation.

Then the original hypothesis to determine the possibility of evaluating FFTP taking into consideration the a priori confidence interval is the hypothesis $H_0: \hat{P}_1 = \hat{P}_2 = P$. If the H_0 hypothesis is rejected, then one of the two competing hypotheses is accepted: $H_1: \hat{P}_1 < \hat{P}_2$ or $H_2: \hat{P}_1 > \hat{P}_2$.

The set of all possible outcomes, determined by the number of fail-free RTC switching in n tests, consists of discrete points $\{0,1,...,n\}$. Split this set by points r_l and r_u into the regions of the lower critical values $\{0,1,2,...,r_l\}$, permissible values $\{r_l+1, r_l+2,...,r_u-1\}$, and upper critical values $\{r_u, r_u+1,..., n\}$.

For the significance level $\alpha=\alpha_l+\alpha_u$ and the results of tests if the H_0 hypothesis holds it is possible to determine the boundaries of the lower critical region according to the predefined level of significance α_l provided:

$$P\{r \le r_l | H_0\} \le \alpha_l, \quad (7)$$

and the upper critical region of level α_u provided:

$$P\{r \ge r_u | H_0\} \le \alpha_u. \quad (8)$$

The fact that the H_0 hypothesis holds and these inequalities are satisfied warrants that the test outcomes fit one of the critical regions with a probability not exceeding α. Then one can find the unknowns r_l and r_u based on the binomial law of distribution at $\hat{P}_1 = \hat{P}_2 = P$:

$$\sum_{i=0}^{r_u} C_{n_2}^{i} P^i (1-P)^{n_2-i} \le \alpha_l, \quad (9)$$

$$\sum_{i=r_u}^{n_2} C_{n_2}^{i} P^i (1-P)^{n_2-i} \le \alpha_u. \quad (10)$$

This problem can be solved by using the appropriate tables to calculate the confidence intervals [8]. Based on the found values r_l and r_u one can determine the boundaries of the $\underline{P} = r_l/n_2$ and $\overline{P} = r_u/n_2$, interval, which should host the a priori value of FFTP $\hat{P}_1 = P$ at the predefined α. Then with the probability of $1-\alpha$ one can argue about the homogeneity of data from observations and tests if the following inequality holds:

$$\frac{r_l}{n_2} \le \hat{P}_1 \le \frac{r_u}{n_2}. \quad (11)$$

At the same time, the level of significance α can be selected within 0.2–0.05 at $\alpha_l=\alpha_u=\alpha/2$.

Inequality (11) is being considered as a rule of check of the uniformity of data from operational observations and special tests with a confidence probability $\gamma=1-\alpha$ over the final interval of the cycle of operation. At the same time, the FFTP assessments are to be obtained with acceptable accuracy and reliability for the decision-making about the limiting (non-limiting) state of RTC with the clarification of the moment to execute control over the limiting state.

The second model of evaluation. The processing of data from operational observations and special tests, considered as possible heterogeneous implementations, for the evaluation of FFTP using a priori confidence boundaries.

Resolving the task of assessing FFTP by a Bayesian method at known a priori confidence interval is a laborious task of non-linear programming, which necessitates approximate calculations [22].

The classic approach prescribes the use of estimate $\hat{P}_{1,2}$, if a hypothesis on data homogeneity is accepted, and estimate $\hat{P}_2$, if an alternative hypothesis is accepted. As it is proposed in [23], rather than work with a fixed level of significance and agree to the adoption (refusal) of the hypothesis about data homogeneity, the probability R be found to accept this hypothesis based on available statistics. At the same time, the choice between the two options of assessments $\hat{P}_{1,2}$ and $\hat{P}_2$ is proposed to be carried out by averaging them with appropriate weight ratios, which make sense of the probability of selecting each of the cases:

$$\hat{P}^* = R\hat{P}_{1,2} + (1-R)\hat{P}_2. \quad (12)$$

Then the one-way confidence intervals of FFTP are found on the basis of a point assessment $\hat{P}^*$ and the heuristic rule of converting the volume of operational observations and special tests into some equivalent number of homogeneous tests.

In the devised method for assessing FFTP, we suggest using the Bayesian method with a priori fiducial distribution of this probability (Fig. 2).

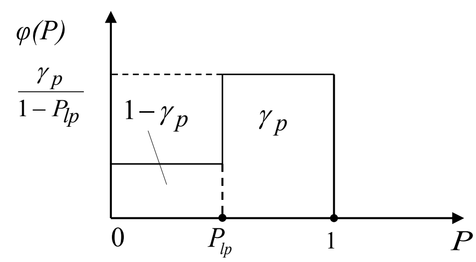

Fig. 2. Stepped fiducial distribution of FFTP P

The one-side lower confidence boundary of FFTP P_{lp} of level γ_p, as a parameter of this distribution, is found from the data on operational observations (n_1, d_1) from the following ratio:

$$P_{lp} = f_2(n_1, \hat{P}_1, \gamma_p). \quad (13)$$

At the same time, it is assumed that the true value of FFTP is derived in the interval $[P_{lp}, 1]$ with probability γ_p. This assumption corresponds to setting the density of the FFTP distribution $\phi(P)$ in the form of a stepped fiducial distribution (Fig. 2):

$$\varphi(P) = \begin{cases} \dfrac{1-\gamma_p}{P_{lp}}, & 0 \le P < P_{lp}, \\ \dfrac{\gamma_p}{1-P_{lp}}, & P_{lp} \le P \le 1. \end{cases} \quad (14)$$

Such an a priori distribution can be attributed to the «least favorable» providing maximum entropy.

Assume that the result of special tests of RTC in n_2 cycles of switching produced d_2 failures. The credibility function for the test scheme under consideration takes the following form:

$$L(P, n_2, d_2) = C_{n_2}^{d_2} P^{n_2-d_2} (1-P)^{d_2}.$$

Then, in accordance with the Bayesian formula, the a posteriori density of the FFTP distribution taking into consideration the data from special tests (n_2, d_2) is found from the following ratio:

$$f\left(P\middle|n_2,d_2\right)=\frac{\varphi(P)P^{n_2-d_2}\left(1-P\right)^{d_2}}{\int_0^1\varphi(P)P^{n_2-d_2}\left(1-P\right)^{d_2}\,\mathrm{d}P}. \qquad (15)$$

Ratio (15) at a priori density (14) takes the following form:

$$f\left(P\middle|n_2,d_2\right)=\begin{cases}\dfrac{1-\gamma_p}{P_{lp}J_0}P^{n_2-d_2}\left(1-P\right)^{d_2},\ 0\le P\le P_{lp},\\ \dfrac{\gamma_p}{\left(1-P_{lp}\right)J_0}P^{n_2-d_2}\left(1-P\right)^{d_2},\ P_{lp}\le P\le 1,\end{cases} \qquad (16)$$

where

$$J_0=\int_0^1\varphi(P)P^{n_2-d_2}\left(1-P\right)^{d_2}\,\mathrm{d}P.$$

Then the Bayesian one-sided confidence boundaries $\underline{P}$ and $\overline{P}$ at γ level are derived from the equations given in [24, 25].

$$\int_{\underline{P}}^1 f\left(P\middle|n_2,d_2\right)\mathrm{d}P=\gamma, \qquad (17)$$

$$\int_0^{\overline{P}} f\left(P\middle|n_2,d_2\right)\mathrm{d}P=\gamma. \qquad (18)$$

Consider solving them using an example of the one-sided lower confidence boundary $\underline{P}$. We suggest the following order of its derivation:

1. Check that the following inequality holds:

$$\int_{P_{lp}}^1 f\left(P\middle|n_2,d_2\right)\mathrm{d}P\ge\gamma. \qquad (19)$$

2. If inequality (19) is satisfied, $\underline{P}$ is found by solving the following equation:

$$\frac{\gamma_p}{\left(1-P_{lp}\right)J_0}\int_{\underline{P}}^1 P^{n_2-d_2}\left(1-P\right)^{d_2}\,\mathrm{d}P=\gamma. \qquad (20)$$

3. If inequality (19) is not satisfied, $\underline{P}$ is derived by solving the following equation:

$$\frac{1-\gamma_p}{P_{lp}J_0}\int_{\underline{P}}^{P_{lp}} P^{n_2-d_2}\left(1-P\right)^{d_2}\,\mathrm{d}P=\Delta\gamma, \qquad (21)$$

$$\Delta\gamma=\gamma-\frac{\gamma_p}{\left(1-P_{lp}\right)J_0}\int_{P_{lp}}^1 P^{n_2-d_2}\left(1-P\right)^{d_2}\,\mathrm{d}P.$$

Thus, when inequality (19) holds equation (20) to find the one-sided lower confidence boundary $\underline{P}$ at γ level takes the following form:

$$\frac{\gamma_p}{\left(1-P_{lp}\right)J_0}\left[\sum_{i=0}^{d_2}\frac{(-1)^i C_{d_2}^i}{n_2-d_2+i+1}-\sum_{i=0}^{d_2}\frac{(-1)^i C_{d_2}^i\underline{P}^{n_2-d_2+i+1}}{n_2-d_2+i+1}\right]=\gamma, \qquad (22)$$

$$J_0=\frac{1-\gamma_p}{P_{lp}}J_1+\frac{\gamma_p}{\left(1-P_{lp}\right)}J_2, \qquad (23)$$

$$J_1=\int_0^{P_{lp}}P^{n_2-d_2}\left(1-P\right)^{d_2}\,\mathrm{d}P=\sum_{i=0}^{d_2}\frac{(-1)^i C_{d_2}^i P_{lp}^{n_2-d_2+i+1}}{n_2-d_2+i+1}, \qquad (24)$$

$$J_2=\int_{P_{lp}}^1 P^{n_2-d_2}\left(1-P\right)^{d_2}\,\mathrm{d}P=\sum_{i=0}^{d_2}\frac{(-1)^i C_{d_2}^i\left(1-P_{lp}^{n_2-d_2+i+1}\right)}{n_2-d_2+i+1}. \qquad (25)$$

In the case of fail-safe tests (d_2=0) if there is a priori information (γ_p=1, P_{lp}=0) or if it is absent ratio (22) takes the known form $\underline{P}^{n_2}=1-\gamma$, that is $\underline{P}=\sqrt[n_2]{1-\gamma}$ [3].

Similar ratios were obtained for the case where inequality (19) is not satisfied, and for finding a one-sided upper confidence boundary of FFTP.

6. Devising a scheme to assess and control the probability of failure-free switching of a radio-technical complex

Based on the above general provisions, criteria, assessment models, control methods, we have devised a scheme to jointly evaluate and control FFTP when operating RTC based on technical condition (Fig. 3). It defines the following procedure for evaluating and controlling FFTP, including transition conditions (criteria) (units 5, 8) between the assessment models used.

Step 1. Process data from operational observations, registered over interval ΔT; based on their results, obtain an assessment of the one-side confidence boundaries of FFTP at the predefined level. Control FFTP using confidence boundaries thereby determining the observed risk $\hat{\alpha}$ or $\hat{\beta}$ (unit 1).

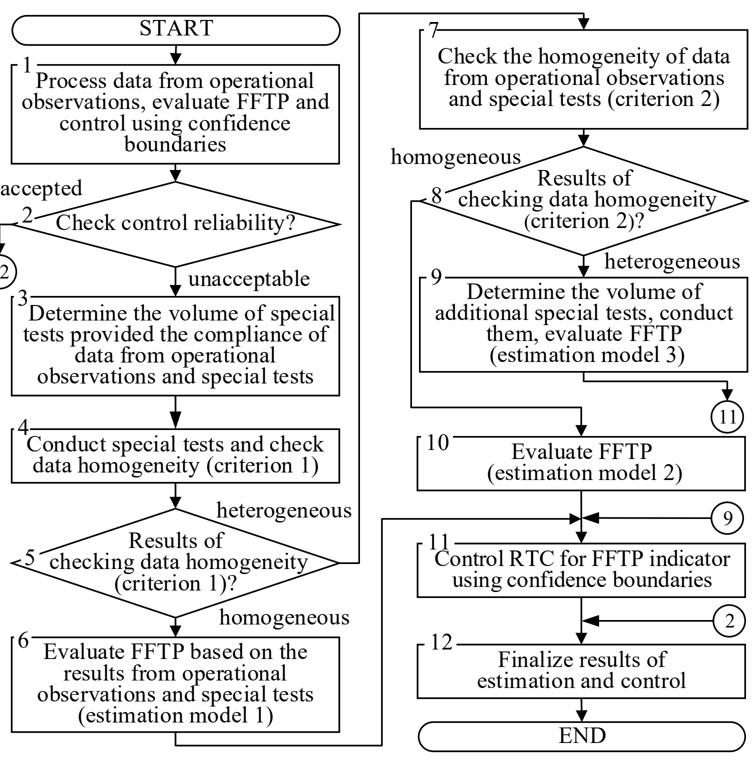

Fig. 3. The scheme of joint assessment and control of an indicator related to the probability of RTC failure-free switching

Step 2. Check the validity of FFTP control, that is, the acceptability of magnitude $\hat{\alpha}$ or $\hat{\beta}$ (unit 2). If the magnitude of the observed risk is acceptable, the evaluation and control procedure is completed (unit 12). Otherwise, proceed to step 3 (unit 3).

Step 3. Determine the volume of special tests of RTC on FFTP in accordance with the method of single-stage control taking into consideration the data from operational observations and their homogeneity (unit 3).

Step 4. Conduct special tests in the volume defined in unit 3, check the compliance of operational observations and special tests for criterion 1 (unit 4).

Step 5. If the results of the test of the uniformity of data from operational observations and special tests (meeting the first criterion, unit 5) are positive, evaluate the FFTP indicator for the first assessment model (unit 6).

Step 6. If the test results are negative (unit 5), check the homogeneity of the data for the second criterion (unit 7).

Step 7. If the data homogeneity check result is positive (the second criterion is met, unit 8) the FFTP RIB is assessed for the second estimation model (unit 10); control is executed using confidence boundaries (unit 11).

Step 8. If the check results are negative (failure to meet the second criterion, unit 8), the operational observation data are discarded and the required volume of additional tests is determined. Additional special tests are carried out, the evaluation of FFTP for the third model (unit 9) using all data from special tests (units 4, 9) and control of FFTP using confidence boundaries (unit 11).

7. Investigating the characteristics of the combined method for assessing and controlling the probability of trouble-free switching of a radio-technical complex

When investigating the characteristics of the developed method, we determined the accuracy and reliability of assessing and controlling the FFTP indicator to ensure the operation of the RTC based on technical condition. These characteristics of the combined method are defined by the criteria for verifying the uniformity of data from operational observations and special tests, by the methods of FFTP assessment according to these data, and the methods of control in accordance with the scheme shown in Fig. 3.

Our study was conducted employing a computer algebra system from the Mathcad 15.0 M05 automated design system. The following restrictions and assumptions were adopted:

– as a reusable RTC, we consider the S-300-type surface-to-air missile system (the range is up to 75 km) RTC;

– reusable RTC is considered to be a controlled, recoverable, serviced, and repairable object;

– two phases of RTC operation are considered: «normal» (10 years) and «aging» (over 10 years);

– operating conditions are supposed to be standard;

– in the first phase, we accepted a monotonous reduction in the level of FFTP under a linear law with a tilt ratio of 0.009 per year of operation; in the second phase – 0.05 per year;

– other modeling parameters are given below in the forms of dependence charts and tables;

– the adopted initial level of RTC FFTP accepts a value of 0.99.

When analyzing the data homogeneity check criteria used in the method, we built the regions of possible decisions about data homogeneity (region 1), data homogeneity (region 2), or data heterogeneity (region 3) at the predefined probability. Fig. 4, 5 show these regions at d_2=0 and d_2=n_2, built by using ratio (3) for region 1 and ratio (11) for region 2 at γ=0.8; 0.9; 0.95.

The analysis of these regions shows that the first criterion imposes more stringent requirements for the uniformity of data from operational observations and special tests than the requirements of the second criterion.

We shall analyze the accuracy and reliability of the assessment and control of a fault-free indicator of the probability of failure-free switching using the combined method. If the observation and testing data are categorized as homogeneous by the first criterion (region 1), the accuracy and reliability of FFTP assessment (first model) are consistent with predefined ones as their total volume corresponds to the planned one. If the observation and test data are heterogeneous by the second criterion (region 3), the accuracy and reliability of FFTP assessment (third model) are consistent with predefined one as the volume of special tests corresponds to the planned one. In this regard, we studied the second model of FFTP assessment in order to obtain the characteristics of the accuracy and reliability of the developed method.

The baseline data used for the simulation were the magnitude of the one-sided lower confidence boundary P_{lp} at level γ_p of the a priori confidence interval, the data from special tests (n_2, d_2), and the predefined value of a posteriori confidence of probability γ. The results of assessing the one-sided lower confidence boundary of FFTP at level γ using the second model are given in Table 1.

Table 1 demonstrates that with an increase in the value P_{lp} at a fixed γ_p and the predefined probability γ the value of the one-sided lower confidence boundary of FFTP behaves non-linearly. It rises to a certain magnitude and has an extremum, characterized by the ratio of a posteriori confidence probability γ and the probability of the event «a posteriori evaluation of FFTP belongs to a priori confidence interval [P_{lp}, 1]».

We have compared the accuracy and reliability of FFTP assessments reported in [19, 20] and derived by using the developed method. The comparison results show that the known method gives an inflated accuracy and reliability of estimates compared to the devised method.

The results of our modeling show that estimates of the one-sided lower confidence boundary of FFTP obtained by using the developed method make it possible to execute control over RTC for FFTP with the help of confidence boundaries at the predefined reliability (γ=0.8–095). This, in turn, ensures that informed decisions are made to manage the operation of RTC based on technical condition.

The combined method of controlling FFTP using confidence boundaries, in contrast to others, makes it possible to assess the observed risk of the decision to be taken and confirm the predetermined validity of the control. At the same time, the implemented accuracy of the control is defined by the width of the uncertainty interval, characterized by the predefined acceptance and defect levels of FFTP.

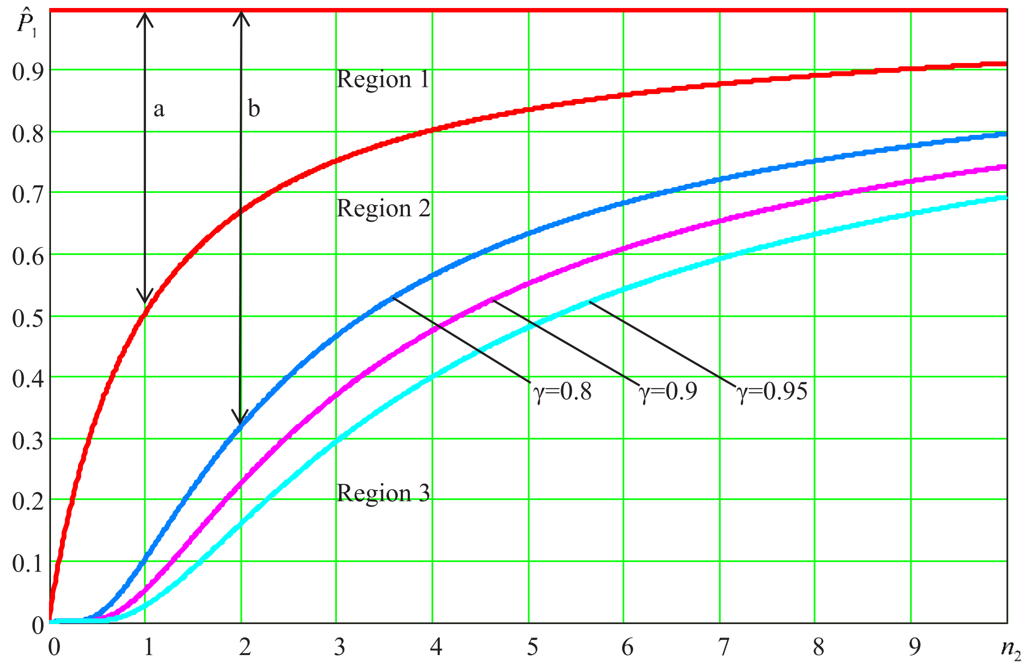

Fig. 4. Regions of possible decisions on the homogeneity of data from operational observations and special tests at d_2=0 based on: *a* – criterion 1 (region 1); *b* – criterion 2 at the predefined γ=0.8; 0.9; 0.95 (regions 2, 3)

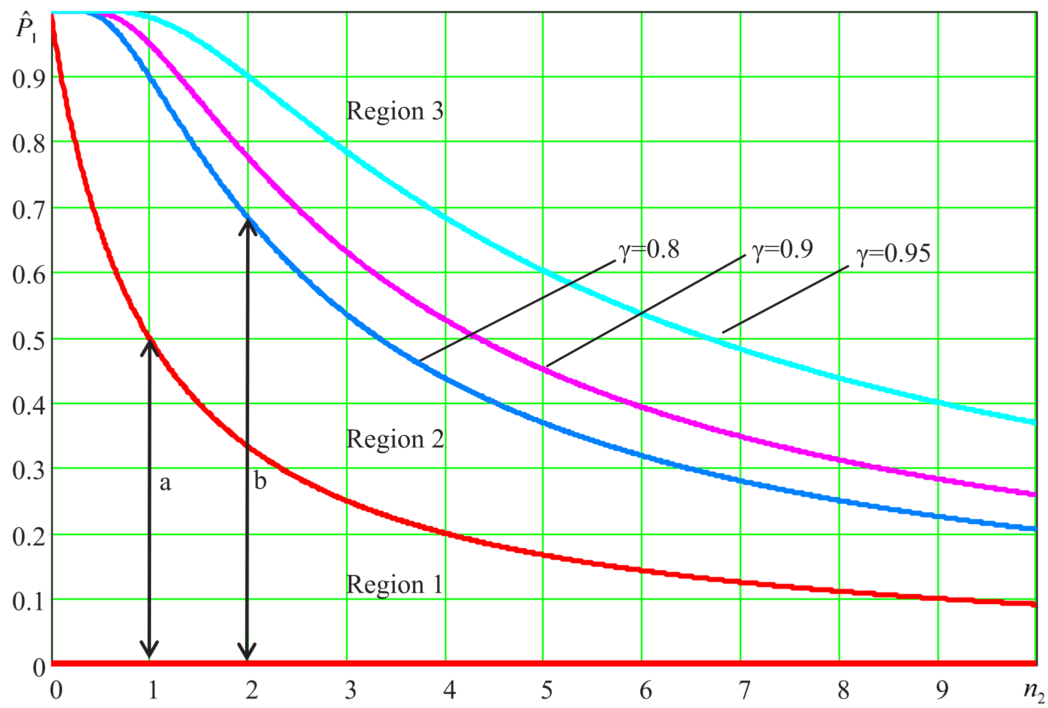

Fig. 5. Regions of possible decisions on the homogeneity of data from operational observations and special tests at $d_2 = n_2$ based on: *a* – criterion 1 (region 1); *b* – criterion 2 at the predefined γ=0.8; 0.9; 0.95 (regions 2, 3)

The results of the simulation of the processes of changing an RTC's failure-free operation and its evaluation according to the combined method developed show the following for the RTC that is operated based on the technical condition at the stage of normal operation:

– a high probability (≈0.8) characterizes the assessment and control without special tests for failure-free operation;

– a low probability (≈0.1) characterizes the assessment for the first model, followed by control with the help of confidence boundaries;

– a probability of (≈0.09) characterizes the assessment for the second model, followed by control with the help of confidence boundaries;

– a probability of (≈0.01) characterizes the assessment for the third model, followed by control with the help of confidence boundaries.

During the aging phase, these events are characterized by the probabilities of 0.5, 0.3, 0.16, and 0.04, respectively.

At the same time, the share of special tests relative to their total volume was 0.47 at the «normal» stage of operation, and at the «aging» stage – 0.56.

Table 1

Bayesian lower confidence boundaries of FFTP at level γ at the predefined confidence interval $[P_{lp}, 1]$ at level γ_p and data from special tests (n_2, d_2)

n_2, d_2	γ	γ_p	P_{lp}				
			0,5	0,6	0,7	0,8	0,9
5, 1	0.9	0.5	0.42	0.46	0.49	0.5	0.48
		0.6	0.47	0.51	0.54	0.54	0.53
		0.7	0.51	0.56	0.60	0.60	0.57
		0.8	0.54	0.63	0.71	0.71	0.64
		0.9	0.56	0.65	0.73	0.83	0.83
	0.95	0.5	0.35	0.37	0.40	0.41	0.40
		0.6	0.38	0.41	0.43	0.44	0.43
		0.7	0.43	0.46	0.49	0.49	0.45
		0.8	0.50	0.53	0.56	0.56	0.51
		0.9	0.53	0.63	0.72	0.71	0.63
10, 2	0.9	0.5	0.55	0.59	0.61	0.62	0.60
		0.6	0.57	0.62	0.65	0.66	0.61
		0.7	0.58	0.63	0.7	0.71	0.65
		0.8	0.58	0.64	0.72	0.78	0.69
		0.9	0.59	0.65	0.73	0.82	0.81
	0.95	0.5	0.49	0.52	0.54	0.55	0.53
		0.6	0.52	0.55	0.57	0.58	0.54
		0.7	0.53	0.59	0.61	0.61	0.57
		0.8	0.54	0.61	0.67	0.66	0.61
		0.9	0.55	0.62	0.7	0.78	0.68

8. Discussion of results of investigating the characteristics of the devised combined method of evaluation and control

The operation of reusable RTC based on technical condition (Fig. 1) requires resolving the tasks of assessing and controlling FFTP at the predefined accuracy and reliability, for example, the relative accuracy is 0.1–0.15; the reliability is at least 0.9. At the same time, in order to effectively operate the RTC based on technical condition, it is necessary, at each cycle, to minimize the volume of special tests for failure-free operation.

The combined method developed here makes it possible to ensure the required accuracy and reliability in the assessment and control of FFTP acceptable for the RTC operation based on technical condition while minimizing the cost of special tests. This is achieved by using data from the operational observations and special tests taking into consideration their possible heterogeneity. At the same time, if their homogeneity is established according to the first criterion – expressions (1), (2) – to assess and control FFTP the data are used in full, and the scope of tests is planned taking into consideration the realized volume of observations.

If their homogeneity is established under the second criterion – expressions (7), (8) – the data from observational and special tests are used to assess and control FFTP taking into consideration their possible heterogeneity. In this case, the accuracy and reliability of the assessment and control of FFTP would be acceptable for the tasks of managing the operation of RTC based on technical condition (11).

The devised combined method of the assessment and control of RTC «FFTP» RI for the operation based on technical condition, based on the results from operational observations and tests, is based on the following:

– solving the task of assessing FFTP on the data of operational observations over individual intervals of the cycle of operation using the methods of point and interval assessment in binomial tests and, if necessary, the results of special tests – expressions (19), (20). We employ the known and proposed methods of combining the results from operational observations and special tests depending on the results of the verification of their homogeneity;

– solving the task of controlling RTC FFTP by using the established one-sided confidence boundaries thereby identifying the observed risk as a measure of error of a decision to be made (23) to (25).

The derived estimates of the probabilities of implementing the process of assessing and control of an RTC indicator of failure-free operation and the proportion of volumes of special tests in terms of their total volume during the «normal» operation and «aging» phases reveal the average cost of conducting special tests for failure-free operation. These costs represent up to 10 % of the total cost of special RTC tests for reliability at the «normal» stage, and up to 30 % at the «aging» stage (Fig. 4, 5, Table 1).

The combined method developed is an improvement of the well-known method of controlling RI of the type «probability» through confidence boundaries and methods of their evaluation. It takes into consideration the specificity of the baseline data obtained during the operation of RTC based on technical condition, and provides a solution to the task of joint evaluation and control of FFTP.

The reliability of the devised method has been confirmed by the fact that in a particular case (failure tests and the presence of trivial a priori information) the result of the assessment of FFTP takes the form known from [3] (22). In addition, the joint assessment and control scheme of RTC FFTP (Fig. 3) implies the verification of the validity of controlling this indicator through an assessment of the observed risk, which does not exceed a predefined one. The adequacy of the constructed models for the evaluation of FFTP indicator has been confirmed by the results of the simulation and their convergence, in particular cases, with the results known from [3] (Table 1).

This method is useful to evaluate and control the failure-free operation of different types of reusable RTC operated based on technical condition. For example, an anti-aircraft missile system, a radar system, a radar landing support station.

It should be noted that the developed method takes into consideration the peculiarities of RTC operation based on technical condition and, to a lesser extent, accounts for the features of other methods of operation and other stages of the life cycle. Thus, part of the ratios within the method (19) to (21) are obtained under the assumption that the operation is carried out on the technical condition, a change in the level of failure-free operation is characterized by a monotonous non-ascending dependence, etc. This imposes certain restrictions on the scope of the application of this method, which can be attributed to its shortcomings. Further research related to their elimination should aim to improve the combined method for the development phase on the reliability of the RTC being developed, as well as the possibility of its implementation for other operating methods. Such a method would have a broader scope of application for the tasks of the joint evaluation and control of RTC RI at all stages of the life cycle and under different operating modes.

9. Conclusions

1. The operation of RTC based on its technical condition is represented by cycles, the period of which is determined by the period of control over the limiting state. Each cycle is divided into fixed-length intervals where operational observations are registered, considered as failure-free operation test results, and used to evaluate and control RTC FFTP. In the final interval of the cycle, the RTC's limiting state is additionally monitored, with special failure-free operation tests, if necessary. Two possible cases of the joint evaluation and control of FFTP have been highlighted. The first case, characteristic of all intervals of the cycle except the final one, involves the use of the results from operational observations only, and the second, characteristic of the final interval, the results from operational observations and special tests for failure-free operation. For each situation, the tasks of the joint evaluation and control of FFTP have been stated taking into consideration the possible heterogeneity of the raw data.

2. Two criteria for verifying the homogeneity of data from operational observations and tests have been developed, as well as three models of FFTP assessment. The first criterion, based on the principle of maximum plausibility, makes it possible to use the first model to evaluate the data received as a homogeneous implementation. The second criterion, based on the application of a confidence interval, makes it possible to employ the second model to evaluate the data received as possible heterogeneous implementations. Failure to meet these criteria makes it possible to use the third assessment model based on data from special tests only.

3. Based on the formulated general provisions, criteria, evaluation models, control methods, a scheme of the joint evaluation and control of FFTP in the operation of RTC based on the technical condition has been built. It defines how these tasks are addressed taking into consideration the observed risks of decision-making and the results of verifying the homogeneity of data from operational observations and special tests.

4. Compared to known methods of assessment, the devised method produces a «guaranteed» assessment of the probability of RTC failure-free switching, that is, the predefined probability (γ=0.8–0.95) defines the one-sided confidence boundaries of this failure-free operation indicator. This assessment makes it possible to make informed decisions with observed risks not exceeding 0.1–0.2, which is acceptable in the operation of RTC based on technical condition. In addition, the implementation of our method makes it possible to reduce the cost of conducting special tests of RTC for failure-free operation at the stage of «normal» operation to 90 % of their total cost, and at the stage of «aging» – up to 70 %. It is recommended that the operation of radio-technical complexes based on technical condition should be implemented in cycles with a period of control of the limiting state adapted to the level of failure-free operation. At the same time, the assessment and control of the probability of RTC failure-free switching should be carried out in accordance with the constructed scheme of the combined method.

References

1. Lanetskiy, B. M., Lukjanchuk, V. V., Artemenko, A. A. (2016). Complex evaluation of faultness and residual durability characteristics of the difficult technical systems that are exploites on the technical state. Generalities. Systemy obrobky informatsiyi, 2 (139), 40–43.
2. Lanetskii, B., Lukyanchuk, V., Khudov, H., Fisun, M., Zvieriev, O., Terebuha, I. (2020). Developing the model of reliability of a complex technical system of repeated use with a complex operating mode. Eastern-European Journal of Enterprise Technologies, 5 (4 (107)), 55–65. doi: https://doi.org/10.15587/1729-4061.2020.214995
3. Gnedenko, B. V., Belyaev, Yu. K., Solov'ev, A. D. (2017). Matematicheskie metody v teorii nadezhnosti. Osnovnye harakteristiki nadezhnosti i ih statisticheskiy analiz. Moscow: KD Librokom, 582.
4. Ruban, I., Khudov, H., Lishchenko, V., Zvonko, A., Glukhov, S., Khizhnyak, I. et. al. (2020). The Calculating Effectiveness Increasing of Detecting Air Objects by Combining Surveillance Radars into The Coherent System. International Journal of Emerging Trends in Engineering Research, 8 (4), 1295–1301. doi: https://doi.org/10.30534/ijeter/2020/58842020
5. Barabash, O. V., Dakhno, N. B., Shevchenko, H. V., Majsak, T. V. (2017). Dynamic models of decision support systems for controlling UAV by two-step variational-gradient method. 2017 IEEE 4th International Conference Actual Problems of Unmanned Aerial Vehicles Developments (APUAVD). doi: https://doi.org/10.1109/apuavd.2017.8308787
6. Khudov, H., Zvonko, A., Khizhnyak, I., Shulezko, V., Khlopiachyi, V., Chepurnyi, V., Yuzova, I. (2020). The Synthesis of the Optimal Decision Rule for Detecting an Object in a Joint Search and Detection of Objects by the Criterion of Maximum Likelihood. International Journal of Emerging Trends in Engineering Research, 8 (2), 520–524. doi: https://doi.org/10.30534/ijeter/2020/40822020
7. Belyaev, Yu. K. et. al.; Ushakov, I. A. (Ed.) (1985). Nadezhnost' tehnicheskih sistem. Moscow: Radio i svyaz', 608.
8. Sudakov, R. S., Teskin, O. I. (Eds.) (1989). Nadezhnost' i effektivnost' v tehnike. Vol. 6: Eksperimental'naya otrabotka i ispytaniya. Moscow: Mashinostroenie, 376.
9. DSTU 2864-94. Industrial product dependability reliability. Experimental determinating and complinating. Basic principles.
10. Grodzenskiy, S. Ya. (1981). Ratsional'nye plany ispytaniy promyshlennyh izdeliy na nadezhnost'. Moscow: Znanie, 57.
11. Viktorova, V. S., Stepanyants, A. S. (2016). Modeli i metody rascheta nadezhnosti tehnicheskih sistem. Moscow: LENAND, 256.

12. Kredentser, B. P. (2019). Raschet pokazateley nadezhnosti tehnicheskih sistem s izbytochnost'yu. Kyiv: Feniks, 520.
13. Tobias, P. A., Trindade, D. (2012). Applied Reliability. Chapman and Hall/CRC, 600. doi: https://doi.org/10.1201/b11787
14. Kuzavkov, V., Khusainov, P., Vavrichen, O. (2017). Evaluation of the same type firmware network technical condition. Zbirnyk naukovykh prats Natsionalnoi akademiyi Derzhavnoi prykordonnoi sluzhby Ukrainy. Ser.: Viyskovi ta tekhnichni nauky, 3, 314–323.
15. Zhang, W., Zhang, G., Ran, Y., Shao, Y. (2018). The full-state reliability model and evaluation technology of mechatronic product based on meta-action unit. Advances in Mechanical Engineering, 10 (5), 168781401877419. doi: https://doi.org/10.1177/1687814018774191
16. Peng, D., Zichun, N., Bin, H. (2018). A New Analytic Method of Cold Standby System Reliability Model with Priority. MATEC Web of Conferences, 175, 03060. doi: https://doi.org/10.1051/matecconf/201817503060
17. Guo, J., Wang, X., Liang, J., Pang, H., Goncalves, J. (2018). Reliability Modeling and Evaluation of MMCs Under Different Redundancy Schemes. IEEE Transactions on Power Delivery, 33 (5), 2087–2096. doi: https://doi.org/10.1109/tpwrd.2017.2715664
18. Ding, F., Sheng, L., Ao, Z. et. al. (2017). Research on reliability prediction method for traction power supply equipment based on continuous time Markov degradation process. Proc CSEE, 37, 1937–1945.
19. Hou, K., Jia, H., Li, X., Xu, X., Mu, Y., Jiang, T., Yu, X. (2018). Impact-increment based decoupled reliability assessment approach for composite generation and transmission systems. IET Generation, Transmission & Distribution, 12 (3), 586–595. doi: https://doi.org/10.1049/iet-gtd.2017.0745
20. Peng, W., Shen, L., Shen, Y., Sun, Q. (2018). Reliability analysis of repairable systems with recurrent misuse-induced failures and normal-operation failures. Reliability Engineering & System Safety, 171, 87–98. doi: https://doi.org/10.1016/j.ress.2017.11.016
21. Polovko, A. M., Gurov, S. V. (2006). Osnovy teorii nadezhnosti. Sankt-Peterburg: BHV-Peterburg, 702.
22. Savchuk, V. P. (1989). Bayesovskie metody statisticheskogo otsenivaniya: Nadezhnost' tehnicheskih obektov. Moscow: Nauka. Gl. red. fiz.-mat. lit., 328.
23. Teskin, O. I. (1981). Otsenka nadezhnosti sistem na etape eksperimental'noy otrabotki. Sbornik: Obrabotka rezul'tatov ispytaniy na nadezhnost'. Moscow: Znanie, 12–31.
24. Khudov, H., Khizhnyak, I., Zots, F., Misiyuk, G., Serdiuk, O. (2020). The Bayes Rule of Decision Making in Joint Optimization of Search and Detection of Objects in Technical Systems. International Journal of Emerging Trends in Engineering Research, 8 (1), 7–12. doi: https://doi.org/10.30534/ijeter/2020/02812020
25. Khudov, H., Lishchenko, V., Lanetskii, B., Lukianchuk, V., Stetsiv, S., Kravchenko, I. (2020). The Coherent Signals Processing Method in the Multiradar System of the Same Type Two-coordinate Surveillance Radars with Mechanical Azimuthal Rotation. International Journal of Emerging Trends in Engineering Research, 8 (6), 2624–2630. doi: https://doi.org/10.30534/ijeter/2020/66862020