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DEVELOPMENT OF AN EXPERIMENTAL-ESTIMATION METHOD FOR ESTIMATING INDICES OF RESIDUAL LIFE OF A RADIO TECHNICAL COMPLEX

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To implement the operation of a radio technical complex according to its technical condition, it is necessary to jointly evaluate its reliability and residual life indices with required accuracy and reliability and minimization of the scope of special tests. The known methods are focused on separate solutions to the problems of estimating these indices as applied to the regulated strategy.

To solve this problem, general provisions have been developed for estimating the indices of residual life of the radio technical complex including the accepted assumptions and limitations for developing the method, the estimated indices, and criteria of limiting state. The developed experiment-calculated method is a set of mathematical models of change of the reliability indices of a radio technical complex depending on calendar duration of operation or total operating time and analytical models of estimating the indices of its residual life.

The mathematical models of change of mean time between failures, the probability of failure-free switching, and the parameter of the flow of failures of the radio technical complex depending on calendar duration of operation or the total operating time were presented in a form of regressive dependences. Analytical models of estimating the residual life indices are ratios for calculating the "average residual service life (resource)" according to the technical and economic criterion using regression-time dependences of the reliability indices.

The developed experiment-calculated method can be used to estimate the indices of residual life of the radio technical complex with acceptable accuracy (no more than 2 quarters) and reliability (no worse than 0.8). In this case, the duration of the intervals of predicting the reliability indices should be 0.5 to 1 year and the corresponding observation intervals should be more than 1 year

Keywords: estimation of indices of residual life, operation according to technical condition, radio technical complex

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1. Introduction

Reduction of operating and repairing costs of present-day radio technical complexes (RECs) at a given efficiency of their operation is possible through the use of maintenance and repair methods according to their technical condition [1].

The introduction of these methods requires development and controlling of the limit state of concrete RECs. This is important for making timely decisions on repair or decommissioning. At the same time, the REC is considered as an object of repeated use with a complex mode of operation characterized by indices of reliability "mean time between failures" (MTBF) and "probability of failure-free switching" (PFFS) [1, 2].

In addition, the REC belongs to restorable and repairable objects and, accordingly, it must be characterized by residual life indices "average residual life". The REC is operated in cycles which requires a solution to the problem of estimating the reliability indices (RI) with the required accuracy and reliability and their results are used to control the operation [1, 2].

The problem of estimating the reliability indices should be solved according to the data of operational observations, functional tests, and, if necessary, the results of special tests for reliability and durability which are provided for when controlling the limiting state (CLS).

Special tests mean the tests for reliability organized specifically for the purpose of estimating their indices [1, 3]. At the same time, quantitative estimates of these indices are used to make a decision on the limiting (nonlimiting) state of the REC and plan measures to manage its operation and repair.

The main requirements to the quality of the results of experimental RI estimation are as follows [3]: accuracy and reliability of the estimation results, the efficiency of tests (minimization of test duration), etc. Application of known methods to solving these problems is ineffective since they, as a rule, provide for separate solution of the problems of estimation of reliability and durability for a group of similar products. Carrying out such tests requires allocation of a group of homogeneous products, additional expenditure of the technical resource of the REC for special tests, significant financial and time resources which is unacceptable when operating the REC according to its technical condition.

To implement operation and repair of the REC according to its technical condition, it is necessary to develop methods for joint assessment of its reliability indices and residual life. At the same time, it is necessary to ensure specified accuracy and reliability of assessment of these indices while minimizing the cost of special tests. Only the problem of estimating and controlling the REC reliability index was solved in [1] on the assumption of the need for a subsequent solution to the problem of estimating the indices of residual life.

In this regard, the development of methods for estimating the indices of residual life of radio technical complexes operated according to their technical condition with a minimum scope of special tests is urgent.

2. Literature review and problem statement

The present-day radio-engineering complexes refer to controllable, maintainable, restorable, and repairable products of repeated use, usually in a complex operating mode [2, 4–6]. It was shown in [1] that when estimating the RI "probability of failure-free switching on", it is possible to use the data of operational observations in a form of a number of REC starts at certain operation intervals and their results. The disadvantage of [1] consists in that the use of operational observation data to estimate the RI "mean time between failures" of the REC is not taken into account.

In addition to the reliability indices, life ratio [5, 7] is an important technical-economic feature. Various concepts of "service life" are used in [3, 5, 7]. According to [3, 5], service life is understood as its own "technical operating life", i.e. the operating time of the object from the beginning or resumption of operation after repair until the onset of limiting state. The concept of "technical operating life" has different interpretations depending on the purpose and specifics of the product functioning. It depends on how the initial point of time is chosen, which units are used to measure the service life and what does the limiting state mean. Rules of choosing a measure of a lifetime are not considered in [3, 5, 7].

The concept of "lifetime" is unambiguously associated in [7] with the amount of financial resources for which a given product can be sold in the market in a certain limited period in the future. This concept is broader in comparison with the concept of "technical operating time" since it includes economic indices as well. The disadvantage of [7] consists in the lack of clear criteria for estimating lifetime indices.

It was shown in [5] that any non-decreasing parameter characterizing the duration of the object operation can be chosen as a measure of the "lifetime". Operating time in hours is the natural measure for an electronic equipment lifetime, mileage in kilometers for cars, the number of switching cycles for products of cyclic use, etc. [5, 7]. They characterize the product specificity. The approach in [5] requires the development of special methods for calculating various lifetime indices; therefore, it is advisable to use a universal measure of a lifetime in a form of time units.

Methods for estimating the residual lifetime are analyzed in [3, 6, 8–14], namely:

– parametric methods;

– methods based on the use of diffuse distributions;

– methods for analyzing time series using residual lifetime models, etc.

Parametric methods [3, 6, 14] assume knowledge of the type of lifetime distribution functions (service life) and are applied in mechanical engineering, radio electronics, etc. products. The disadvantage of these methods consists in their use, as a rule, for non-recoverable products. Methods based on the use of diffuse distributions [12, 13] assume the use of a monotonic diffuse distribution for mechanical products, non-monotonic diffuse distribution for radio electronics products as a model of resource distribution. The above methods require experimental estimation of parameters of these distribution functions for a group of homogeneous products which limits their area of application. The methods of time series analysis [8–11] assume the known time series of resource values, that is, a set of resource meanings fixed at certain points in time. The construction of such models makes it possible to obtain a satisfactory forecast only for stable data, for example, under conditions of stable production. The disadvantage of the methods discussed in [8–11] consists in the need to know values of the product lifetime at fixed points in time which imposes significant restrictions on their application.

Methods are known in the literature for the separate solution of the problems of estimating RIs and durability indices [3, 6, 14]. Normative documents recommend using the most completely developed methods for estimating RIs or durability indices with known distribution functions of operating time to failures or resources [3, 6, 14]. Analysis of these methods shows that their application to solving the problems of operation according to technical condition (OATC) is inadvisable because of the need to identify groups of homogeneous products and conduct special tests for reliability and durability.

Methods of estimating RIs of the systems with time redundancy at the development stage are considered in [15–17]. Methods of estimating the reliability of software and hardware in the development of diagnostic systems are considered in [18]. A model of estimating the stationary availability factor of a mechatronic system was developed in [19]. A method is considered in [20] for estimating the reliability of a product with cold backup and the priority of its devices for operation or recovery. However, the models and methods in [15–20] make it possible to solve the problems of estimating the reliability indices in relation only to normative methods of operation.

An analytical method of estimating the reliability of a product with a multilevel hierarchical structure and various redundancy options and its application to the substantiation of various options for product designing is considered in [21]. This approach is applicable only for non-recoverable systems of continuous long-term use in a simple mode of operation.

A method of predicting the reliability of general-purpose technical systems is considered in [22]. It is based on a model of the continuous Markov degradation process. The method makes it possible to estimate RIs of such systems at a design stage. This method is only applicable for non-recoverable technical systems of continuous long-term use.

A method was developed in [23] for estimating the reliability of a recoverable technical system taking into account equipment failures and operator errors. The method is applicable to assess the reliability of such systems based on experimental data as well as to control an operator or equipment reliability level. However, the issues of estimating the indices of residual lifetime of the system are not considered.

Thus, the known methods of estimating the reliability indices are focused on separate solutions of the problems of estimating the indices of reliability or durability and are inapplicable to estimating the indices of the residual life of a REC operated according to its technical condition.

It follows from the above that it is necessary to develop an experiment-calculated method of estimating the indices of the residual life of the REC operated according to its technical condition providing for an interconnected solution of these estimation problems.

3. The aim and objectives of the study

The study objective implied developing an experiment-calculated method of estimating the residual life indices of the REC which will ensure its operation according to its technical condition.

To achieve the objective, the following tasks were set:

– develop general provisions of estimating indices of residual life of the REC;

– construct mathematical models of dependence of the indices of the REC reliability on calendar duration of operation or full operating time;

– construct analytical models of estimating the indices of the residual REC life;

– study characteristics of the experiment-calculated method of estimating the indices of the residual REC life.

4. The study materials and methods

The methods of probability theory, mathematical statistics, reliability theory, system analysis, mathematical modeling were used in this study. A computer algebra system from the class of computer-aided design systems Mathcad 15.0 M05 (the USA) was used in the experimental study. When validating the proposed solutions, analytical and empirical methods of comparative analysis were used.

The following restrictions and assumptions were adopted during the study:

– a search lighting and targeting radar (STR) of an anti-aircraft missile system of S-300PS type (range of action: up to 75 km) was taken as a multiple-use REC [24, 25];

– reusable REC was taken as a controllable, restorable, maintainable, and repairable facility;

– operating conditions were assumed to be regular;

– post-repair operation of the REC was considered with an assumption of monotonous decrease in the level of its reliability in terms of the mean time between failures (MTBF) and the probability of no-failure switching on (PNFS);

– repair technology has been worked out and provided in full at the REC under study;

– repair schedule according to the technical condition was established based on the results of CLS;

– maximum permissible values of PNFS and MTBF of the REC were taken equal to 0.948 and 12 hours, respectively.

5. The results obtained in the study of the method of estimating the indices of residual life of the radio technical complex

5. 1. Development of general provisions for estimating the indices of residual life of the radio technical complex

A possible variant of implementation of the REC operation according to its technical condition (Fig. 1) assuming selection of cycles was considered in [1]. At each cycle, it was envisaged to solve the problems of estimating and controlling the REC reliability indices and estimating the indices of the REC residual life. At the same time, minimization of the costs of time and technical resources for testing the REC for reliability was achieved by working out the data of operational observations and tests as the results of combined reliability and durability tests.

Features of estimating and controlling the reliability indices of the REC operated according to its technical condition are considered in [1]. Features of estimating the indices of the REC residual life using the combined method of estimating and controlling the reliability indices of the REC are considered below.

The features of estimating the residual life indices of a REC operated according to its technical condition are as follows:

– as a rule, assessment is made sequentially at various adjacent intervals ΔT of operating cycles in the direction of increasing the operation duration (Fig. 1);

– carrying out technical maintenance and repairs in the process of operation does not lead to an increase in the RI value;

– the conditions of carrying out special tests and operation in intervals ΔT correspond to the modes of normal REC operation.

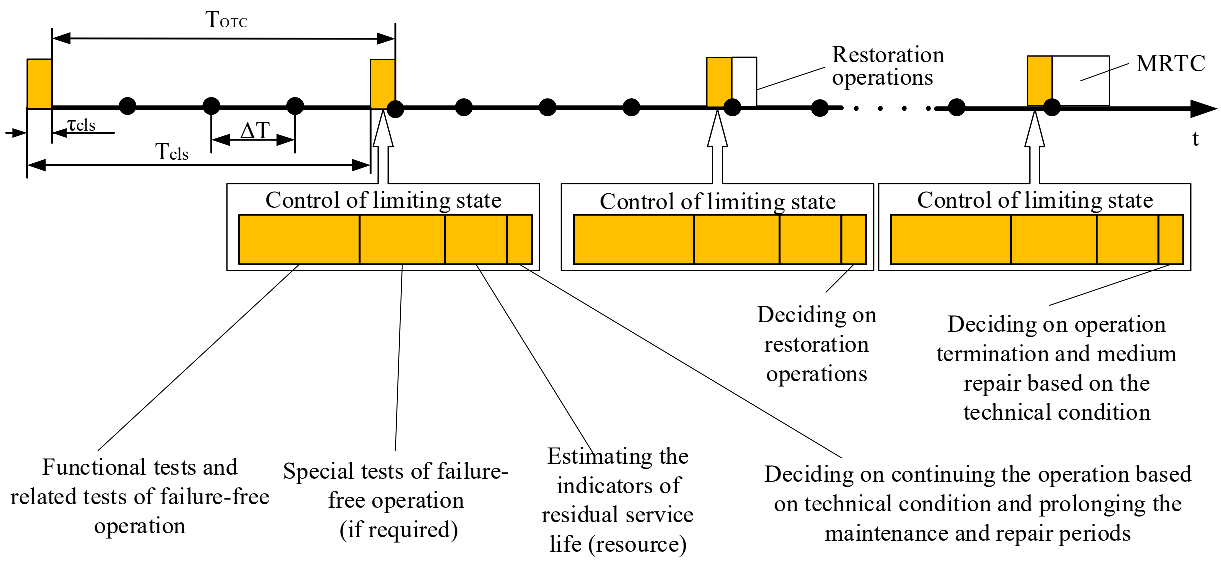

Fig. 1. Graphic representation of the possible variant of implementing the operation of RTC based on technical condition: T_{OTC} – cycle of operation; T_{cls}, τ_{cls} – the frequency and duration of control of the limiting state, respectively; ΔT – duration of the operational cycle interval; MRTC -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

When estimating the indices of residual life of the REC, the following assumptions were made:

– the results of estimation and control of RI of the REC operated according to the technical condition in the operation intervals ΔT are known;

– the conditions of applying the methods of regression analysis are fulfilled, i.e. the approximation errors ε_ℓ of the regression dependences are uncorrelated normally distributed random variables with mathematical expectations equal to zero and the same variances;

– the conditions of application of the combined method of assessment and control of the REC reliability indices are fulfilled [1].

When operating the REC according to its technical state, it is necessary to evaluate the indices of residual life of the REC with required accuracy and reliability based on the data of operation observations and operation tests. Requirements for accuracy and reliability of estimation of indices of residual life of the REC are considered known (set).

When estimating the indices of residual life of the REC, patterns of change of its reliability are found. At the same time, the physics postulate formulated by K. Shannon is used: "the basic patterns that were observed in the past will be preserved in the future". It was proposed to forecast RI based on some history of changes in this index. The ability to predict for a given forestalling interval T_f is determined by the duration of development of the pre-failure state T_{pfs} which should not be less than the required length of the prehistory, that is $T_{pfs}\geq T_c$. As a rule, the prehistory length should be 2–3 times longer than the forestalling time T_f and the condition $T_c>T_f$, $T_{pfs}\geq T_f$ should be met [5].

Average residual service life, average residual resource, and their one-sided lower confidence limits (OLCL) were proposed as indices of the REC durability. To implement the methods of the REC operation according to its technical condition, it is necessary to solve the problem of their assessment.

The problem of estimating the index of residual life of the REC was proposed to be solved based on the results of point estimation of RI at intervals ΔT of the OATC cycles, operational tests carried out during the control of the limiting state (CLS), and other OATC measures (Fig. 1) [1].

Reduction of value of MTBF and/or PNFS lower than the maximum permissible was assumed as a technical criterion of the REC limit state. The minimum intensity of total costs for its OATC was taken as an economic criterion.

At the same time, it was proposed to construct paired regression dependences for MTBF, PNFS, and the parameter of the flow of the REC failures on the calendar duration of operation (T) and the total operating time (t_T) in the calendar duration of operation (T). Let us denote these dependences as $T_0(T)$, $T_0(t_T)$, $P_{on}(T)$, $P_{on}(t_T)$, $\omega(T)$, $\omega(t_T)$. Corresponding point estimates of the average residual service life T_{res}^{MTBF}, T_{res}^{PNFS} average residual life t_{res}^{MTBF}, t_{res}^{PNFS} are found according to the technical criterion with known MTBF and PNFS dependences and their maximum permissible values of $T_{0\,ls}$ and $P_{on\,ls}$. Estimates of T_{res}^{e} and t_{res}^{e} of the REC are found based on the economic criterion of the limit state using regressive dependences $\omega(T)$. Using the known estimates of the index of residual life calculated by technical and economic criteria, indices of residual service life of the REC are found according to the technical and economic criterion.

The set of these problems is supposed to be solved through the development of an experiment-calculated method of estimating the indices of residual life of the REC.

5. 2. Development of mathematical models of change of reliability indices of the radio technical complex depending on the calendar duration of operation or total operating time

Models of change of the REC reliability indices depending on the calendar duration of operation or the total operating time are presented in a form of regression dependences $T_0(T)$, $T_0(t_T)$, $P_{on}(T)$, $P_{on}(t_T)$, $\omega(T)$, $\omega(t_T)$ for the REC operated according to its technical condition. To construct the models, quantitative estimates of the REC RI are used at various operation intervals ΔT (Fig. 1) obtained using the method from [1].

To implement the OATC method with a cycle of one year, the duration of intervals of predicting the REC reliability indices should be from 0.5 to 1 year and the corresponding observation intervals should be more than 1 year. Besides, the accuracy of the RI estimates obtained at operation intervals ΔT based on the results of operational observations and operational tests differ. Therefore, the weighted least squares method was used when constructing the regressive dependences.

It was proposed to construct the corresponding regressive dependences based on the set of two-dimensional points $\{\hat{T}_{0i},T_i\}$, $\{\hat{T}_{0i},t_i\}$, $\{\hat{P}_{on},T_i\}$, $\{\hat{P}_{omi},t_i\}$, $i=\overline{1,n}$, obtained at intervals ΔT for the duration of the REC operation at least 1 year. These include dependences of the MTBF and PNFS and the parameter of failure flow (PFF) on the calendar duration of operation T and/or the total operating time t_T, i. e., the dependences $\tilde{T}_0(T)=f_1(T)$, $\tilde{T}_0(t_T)=f_2(t_T)$, $\tilde{P}_{on}(T)=f_3(T)$, $\tilde{P}_{on}(t_T)=f_4(t_T)$, $\tilde{\omega}(T)=f_5(T)$, $\tilde{\omega}(t_T)=f_6(t_T)$.

Let us consider the order of construction of these dependences using the example of regression $\tilde{\omega}(T)=f_5(T)$. The following requirements are imposed in the form of regressive equations:

– equations should be linear (or be amenable to linearization) according to the estimated parameters. This makes it possible to use the well-developed mathematical apparatus of linear regression analysis;

– equations should be convenient for subsequent use;

– the adopted model should not contradict the given field of experimental data.

The expediency of these requirements is determined by the short duration of the considered intervals of operation as regards technical condition, the minimum number of mutually independent factors to be taken into account. At the same time, in accordance with [5], the construction of a multidimensional regressive dependence is impractical since its factors must be independent and the factors under study are stochastic dependent quantities. These factors include calendar duration of operation T, total operating time t_T, number of starts in the calendar duration T. In this regard, it is proposed to construct paired regressive dependences on the most significant factor with checking the significance of coefficients of the regression model and its adequacy.

The proposed procedure for constructing regression-time dependences $\tilde{\omega}(T)$ assumes the choice of the best (optimal) form of REC dependences $\tilde{\omega}(T)$ in the sense of minimum residual variance. This choice is based on a sequential enumeration of variants of statistically significant regressions (linear, quadratic, cubic, etc.) until the residual variance of the regression begins to grow. Among the possible variants of regressions, the regressive dependences that are non-linear by the estimated parameters subject to linearization can be considered.

It is assumed that data on the number of failures d_ℓ in intervals of operation $[T'_{\ell-1},T'_\ell]$, $\ell=\overline{1,n}$ with duration $\Delta T_\ell=T'_\ell-T'_{\ell-1}$. were obtained according to the REC operation data in conformity with the adopted system of collecting and processing of information. The results of observation of the REC operation in these intervals can be considered the results of reliability test in correspondence with the plan [1MT] where T corresponds to the duration of the operation interval ΔT_ℓ and the moment T'_ℓ. Considering the value of the PFF is a constant in the ℓ-th interval of operation $[T'_{\ell-1},T'_\ell]$, let us use the calculation formula for the point estimation of the PFF recommended in [3] for the test plan [1MT]:

$$\hat{\omega}_\ell=\frac{d_\ell}{\Delta t_\ell},\quad \ell=\overline{1,n}, \tag{1}$$

where Δt_ℓ is the total operating time of the REC in time ΔT_ℓ.

In this case, the point estimate $\hat{\omega}_\ell$ corresponds to the calendar duration of the REC operation $T_\ell=(T'_{\ell-1}+T'_\ell)/2$. Duration of operation intervals $[T'_{\ell-1},T'_\ell]$ is chosen in such a way as to be sufficient for the accumulation of an acceptable number of failures and not to be so large that the reliability of the product does not change significantly during this interval. Duration of the operation intervals must be consistent with the frequency of the REC maintenance set by the designer. Let us consider for example the REC operated in a normal mode with annual resource consumption of at least 300 hrs. To estimate the PFF ω of such REC, intervals of operational observations measure one quarter [5]. Based on the set of n two-dimensional points $\{\hat{\omega}_\ell,T_\ell\}$, obtained from (1), construct a regressive dependence of the REC PFF on the calendar duration of operation.

Taking into account the requirements presented as the regression equation, the regression model can be reduced to the following form:

$$\hat{\omega}_\ell=\alpha_0+\alpha_1 T_\ell+\varepsilon_\ell,\quad \ell=1,2,\dots,n, \tag{2}$$

where α_0, α_1 are approximation coefficients; ε_ℓ is approximation error (remainder); n is the number of ΔT_ℓ intervals for the OATC interval under study.

Fulfillment of these conditions ensures optimality of the obtained estimates of the regression equation coefficients [24]:

$$\tilde{\omega}_\ell=a_0+a_1 T_\ell, \tag{3}$$

where α_0, α_1 are estimates of the unknown parameters α_0, α_1.

In this case, the method of least squares (MLS) is the main method for calculating the coefficients of approximation of the dependence (3). In accordance with this method, estimates a_0, a_1 are chosen such that the following quantity takes a minimal value:

$$\Theta_{res}=\sum_{\ell=1}^{n}\varepsilon_\ell^2=\sum_{\ell=1}^{n}\left(\hat{\omega}_\ell-a_0-a_1T_\ell\right)^2. \tag{4}$$

Then the formulas for estimating a_0, a_1 take the form [24]:

$$a_1=\sum_{\ell=1}^{n}\left(T_\ell-\overline{T}\right)\left(\hat{\omega}_\ell-\overline{\omega}\right)\Big/\sum_{\ell=1}^{n}\left(T_\ell-\overline{T}\right)^2, \tag{5}$$

$$a_0=\overline{\omega}-a_1\overline{T}, \tag{6}$$

where

$$\overline{\omega}=\sum_{\ell=1}^{n}\hat{\omega}_\ell\Big/n,\quad \overline{T}=\sum_{\ell=1}^{n}T_\ell\Big/n.$$

Checking the significance of the regression model coefficients (3) is reduced to checking the hypotheses of equality to zero of the regression coefficients a_0, a_1. In this case, t-statistics is used [26]:

$$t_{ni}=\frac{a_i}{S_{ai}}, \tag{7}$$

where S_{ai} is the estimate of the root-mean-square error of the parameter a_i, i=1, 2.

Estimate of the parameter a_i differs significantly from zero if

$$t_{ni} > t(n-2, 1-\alpha), \qquad (8)$$

where $t(n-2, 1-\alpha)$ is the quantile of level $(1-\alpha)$ of the Student's distribution with $(n-2)$ degrees of freedom.

If inequality (8) is satisfied, then it is considered that difference of the estimate of the coefficient a_i from zero is not accidental with a given level of significance α, the coefficient a_i is statistically significant and must be preserved in the model (3).

After estimating the regression coefficients, checking their significance, and constructing a confidence interval, it is necessary to check the adequacy of the regression model (3). If the regressive dependence (3) is selected correctly, then the following conditions must be met:

– the remainders ε_ℓ are a normally distributed random variable with mean 0 and variance σ^2, that is, $\varepsilon_\ell \sim N(0, \sigma^2)$;

– the remainders ε_ℓ, ε_u are uncorrelated, that is, $\mathrm{cov}\{\varepsilon_\ell, \varepsilon_u\}=0$ at $\ell \neq u$.

Let us briefly consider the procedures of checking the fulfillment of these conditions. To check the condition $M(\varepsilon_\ell)=0$, equality of the mean residuals to zero is checked, i. e., meeting the condition $\sum_{\ell=1}^{n} \varepsilon_\ell / n \cong 0$.

If this condition is not met, then a conclusion can be drawn that some conditions of observing the quantity $\hat{\omega}$ were not taken into account. These conditions can include a change in the average annual temperature, humidity, etc.

To check the condition $\varepsilon_\ell \sim N(0, \sigma^2)$, one can apply the goodness-of-fit criterion omega-square ω^2 [26, 27]. This criterion is based on direct observations of values of a random variable.

To account for the inhomogeneity of variance of the residuals, the methods of "softening" it are used. In this case, unknown variances $S^2_{\hat{\omega}_\ell}$, are first estimated, then weights of the residuals $\eta_\ell = 1/S^2_{\hat{\omega}_\ell}$ are calculated and then estimates of the regression coefficients a_0, a_1 according to the relations [26, 27]:

$$a_1 = \sum_{\ell=1}^{n} \left(\hat{\omega}_\ell - \overline{\omega}\right)\left(T_\ell - \overline{T}\right) \cdot \eta_\ell \times \left(\sum_{\ell=1}^{n} \left(T_\ell - \overline{T}\right)^2 \right)^{-1}, \qquad (9)$$

$$a_0 = \overline{\omega} - a_1 \overline{T}. \qquad (10)$$

In a similar way, regressive dependences are constructed for MTBF and PNFS, respectively, and their quality is checked:

$$\tilde{T}_0(T) = b_0 + b_1 T, \qquad (11)$$

$$\tilde{P}_{on} = f_0 + f_1 T. \qquad (12)$$

To check the fulfillment of the assumption about non-correlatedness of regression residuals (3), the method of graphical analysis of residuals, the method of series, etc. can be used [26].

Reliability of the developed models is confirmed by correct formulation of the problem for their construction, correct application of methods of probability theory, mathematical statistics, reliability theory, system analysis, mathematical modeling, analytical and empirical methods of comparative analysis. Adequacy of the models to real processes of changing the REC reliability was verified by comparing the reliability levels in the observation and forecasting intervals. At the same time, estimates of the reliability indices were obtained using the constructed models and test results when controlling the limit state at appropriate points in time. Reliability levels were compared using Student's criterion.

Sensitivity of the constructed models was analyzed through assessment of the sensitivity index of the i-th final characteristic of the model y_i known in the theory of sensitivity, by the j-th parameter k_j [28–30]:

$$S_i(j) = |dy_i/dk_j| \cdot |k_j| / |y_i|.$$

The following relations for this index are obtained for regression models (3), (11), (12) in terms of the parameters b_0, f_0, a_0:

$$S_{MTBF}(b_0) = |b_0|| / |b_0 + b_1 T|,$$

$$S_{PNFS}(f_0) = |f_0|| / |f_0 + f_1 T|,$$

$$S_{PFF}(a_0) = |a_0|| / |a_0 + a_1 T|.$$

Values of these indices are equal to 1 at $T=0$ and the corresponding models are characterized by strong sensitivity with respect to the parameters b_0, f_0, a_0. For T at which $0{,}3 \leq S_{MTBF}(b_0) < 1$, $0{,}3 \leq S_{PNFS}(f_0) < 1$, $0{,}3 \leq S_{PFF}(a_0) < 1$, the models are characterized by average sensitivity in terms of parameters b_0, f_0, a_0.

Ratios for the sensitivity indices in terms of parameters b_1, f_1, a_1 are as follows:

$$S_{MTBF}(b_1) = |b_1 T|| / |b_0 + b_1 T|,$$

$$S_{PNFS}(f_1) = |f_1 T|| / |f_0 + f_1 T|,$$

$$S_{PFF}(a_1) = |a_1 T|| / |a_0 + a_1 T|.$$

Regression models (3), (11), (12) in terms of indices b_1, f_1, a_1 are characterized by an increase in the sensitivity index with an increase in T from weak to strong sensitivity (varies in the range from 0 to 1).

5. 3. Construction of analytical models of estimating the indices of residual life of the radio technical complex

Calculation of the average residual service life of the REC and its one-sided lower confidence limit (OSLCL) was proposed to be carried out in the following sequence using the technical and economic criteria [27]. Estimates of indices T_{res}^{MTBF}, T_{res}^{PNFS}, T_{res}^{e} are found first. Then the sought index of residual life is found as a minimum of the above values.

To estimate the average residual service life T_{res}^{MTBF} of the REC for MTBF, use the regression equation (11) constructed from the data of operational observations and operational tests for the considered operation interval. The duration of this interval must be at least two periods of the KLS and the end of the interval is determined by the set moment τ_{cls} of estimation of the index of residual life. Then the regressive dependence for the REC MTBF (11) in the considered interval takes the following form:

$$\tilde{T}_0(T/\tau_{cls}) = \begin{cases} \tilde{T}_0(\tau_{cls}), T = \tau_{cls}; \\ \tilde{T}_0(\tau_{cls}) + b_1 T, \quad > \tau_{cls}, \end{cases} \qquad (13)$$

where $\tilde{T}_0(\tau_{cls}) = b_0 + b_1 \tau_{cls}$.

In accordance with the technical criterion, an estimate of the value $\underline{T}_{res}^{MTBF}(\tau_{cls})$ is found from the condition that the value of MTBF in this interval is not lower than the established limit $T_{0\,ls}$, that is, from the condition that the inequality $\tilde{T}_0(T/\tau_{cls}) \geq T_{0ls}$ is satisfied, where $T\geq\tau_{cls}$ Then, as a result of solving the equation $\tilde{T}_0(\tau_{cls})+b_1T=T_{0ls}$ with respect to the unknown T, the following relation is obtained for calculating the mean residual service life according as regards the MTBF:

$$T_{res}^{MTBF}(\tau_{cls})=\frac{T_{0ls}-\tilde{T}_0(\tau_{cls})}{b_1}. \qquad (14)$$

Relation (14) is valid at a significant difference between b_1 and 0. Graphs of dependences $\tilde{T}_0(T)$ for τ_{cls}], $\tilde{T}_0(T/\tau_{cls})$ for $T\geq\tau_{cls}$; $T_{0\,ls}(T)$ explaining the derivation of relation (14) for calculating the index of the residual life are shown in Fig. 2. When plotting the dependences in Fig. 2, restrictions and assumptions given above were taken, namely:

– the search lighting and targeting radar (STR) of the anti-aircraft missile system of S-300PS type was considered as a REC of multiple use;

– the STR is considered as a controllable, restorable, maintainable, and repairable facility;

– operating conditions are assumed to be regular;

– the post-repair operation of the STR is considered with the assumption of a monotonous decrease in the level of its reliability in terms of the values of MTBF and PNFS;

– the limit permissible values of PNFS and MTBF of the STR are taken equal to 0.948 and 12 hours, respectively;

– it was assumed that the STR repair technology has been worked out and provided in full;

– according to the results of the CLS, the moments of repair are established according to the technical condition.

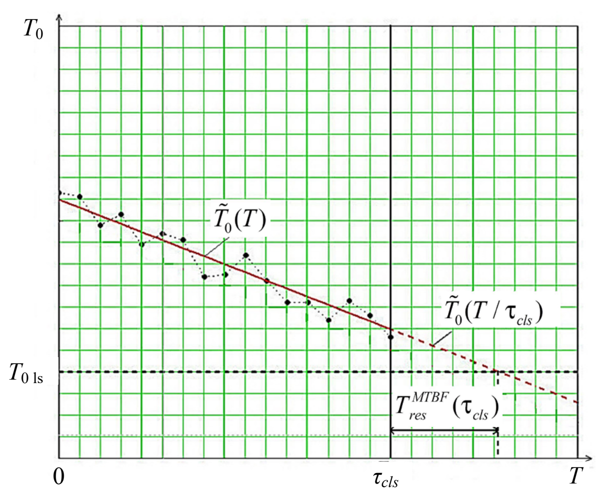

Fig. 2. Graphs of dependences $\tilde{T}_0(T)$, $\tilde{T}_0(T/\tau_{cls})$ and $T_{0\,ls}(T)$ explaining the method of estimating the index $T_{res}^{MTBF}(\tau_{cls})$

Ratios for estimating the OLCL of the mean residual service life of the REC of level γ according to the MTBF index can be obtained by solving the equation for T:

$$\underline{T}_{0_\gamma}(T/\tau_{cls})=T_{0ls}, \qquad (15)$$

$$\underline{T}_{0\gamma}(T/\tau_{cls})=\tilde{T}_0(T/\tau_{cls})-t(n-2;\gamma)\times$$
$$\times\sqrt{1+\frac{1}{n}+\frac{(T-\overline{T})^2}{\sum_{i=1}^{n}(T_i-\overline{T})^2}\cdot S_{MTBF}}, \qquad (16)$$

$$S_{MTBF}=\sum_{i=1}^{n}(\hat{T}-b_0-b_1T_i)^2, \qquad (17)$$

where S_{MTBF} is the sum of squares of deviations of $\hat{T}_{0i}$ values from the regression line $\tilde{T}_0(T_i)$, characterizing the forecast accuracy.

Equation (15) is reduced to a standard quadratic equation of the form $a_\gamma x^2+b_\gamma x+c_\gamma=0$ solved using a well-known formula.

Derivation of relations for estimating the index of residual life of the REC according to PNFS $T_{res}^{PNFS}(\tau_{cls})$ is feasible by performing appropriate transformations similar to those set out above for the MTBF. As a result, the following is obtained:

$$T_{res}^{PNFS}(\tau_{cls})=\frac{P_{onls}-\tilde{P}_{on}(\tau_{cls})}{f_1}, \qquad (18)$$

where $P_{on\,ls}$ is the maximum permissible value of the REC PNFS.

Relation (18) is valid when f_1 significantly differs from 0. An estimate of the OLCL of level γ of the mean time between failures of the REC for PNFS is found from the ratios similar to (15) to (17).

Next, find the relations for estimating the mean residual service time of the REC T_{res}^{e} according to the economic criterion. To this end, the function of total costs of operating the REC depending on operation duration T taking into account the cost of periodic controlling the limit state and the residual value of the product $C_{res}(T)$ at the moment T is presented as follows:

$$C_\Sigma(T)=C_{res}(T)+C_m\Omega(T)+$$
$$+(I_m+I_{iu})\times T+C_{cls}\frac{T}{T_{cls}}+C_{RO}\Omega_{RO}(T), \qquad (19)$$

where C_m, C_{RO} are average costs of eliminating one failure at RR and restoration operations (RO), respectively; I_m, I_{iu} are intensities of maintenance costs and intended use, respectively; Ω(T), Ω_{RO}(T) are the leading functions of the flow of failures eliminated by RR and RO, respectively; C_{cls}, T_{cls} are the cost and frequency of performing the CLS.

The relations for Ω(T) and Ω_{RO}(T) are proposed to be found from the known dependences of the PFF ω(t) and ω_{RO}(T) which are eliminated by servicing and restoration, respectively. These dependences are found from the data of operational observations and tests of the REC operated according to its technical condition using the methods of regression analysis [25].

The residual value of the product at the moment T relative to the moment τ_{cls} can be calculated from the formula

$$C_{res}(T)=C_{res.0}(\tau_{cls})-\frac{C_{res.0}(\tau_{cls})}{T_{res.ls}}\times T,$$

$$0<T\leq T_{res.ls}, \qquad (20)$$

where $C_{res\,0}(\tau_{cls})$ is the residual value of the REC at the time point of CLS; $T_{res\,ls}$ is the maximum permissible value of residual service life when the REC is decommissioned.

According to the economic criterion, it was proposed to determine the economically advantageous duration of operation by the moment when the function of the intensity of total costs $I_\Sigma(T)=C_\Sigma(T)/T$ reaches the minimum value, i. e., the moment $T^e_{res}=\arg\min\left(C_\Sigma(T)/T\right)$.

When linear dependences $\omega(t)=\omega_0+\omega_1 t$ and $\omega_{RO}(t)=\omega_{0RO}+\omega_{1RO}t$, use (19) to find the economically optimal value of T from equation $dI_\Sigma(T)/dT=0$. As a result, the following is obtained:

$$T^e_{res}(\tau_{cls})=\sqrt{\frac{2C_{res0}(\tau_{cls})}{C_m\omega_1+C_{RO}\omega_{1RO}}}. \qquad (21)$$

It follows from relation (21) that for a REC characterized by $\omega(t)=\omega_0$ and $\omega_{RO}(t)=\omega_{0RO}$, there is no economically beneficial residual service life. In this case, estimates of quantities ω_1 and ω_{1RO} are statistically insignificant: $(\omega_1=\omega_{1RO}=0)$ and $T^e_{res}(\tau_{cls})\to\infty$. In addition, if the total cost of servicing and restoration works to eliminate the failures caused by the growth of PFF in an interval of duration $T^e_{res}(\tau_{cls})$ is $C_{res\,0}(\tau_{cls})$, then this duration is economically beneficial. The above analysis testifies in favor of the adequacy of the constructed analytical models.

With known estimates of the mean residual service life with regard to the indices MTBF (14), PNFS (18), and the economic criterion (21) and in accordance with the above, the following ratio for estimating the average residual service life of the REC is obtained according to technical and economic criterion:

$$T_{res\,m}(\tau_{cls})=\min\left(T^{MTBF}_{res}(\tau_{cls});T^{PNFS}_{res}(\tau_{cls});T^{e}\ (\tau\ )\right). \qquad (22)$$

Accuracy and reliability of estimates of the index of residual life T^{MTBF}_{res}, T^{PNFS}_{res} of the REC are characterized by the value of the confidence probability and the corresponding width of their confidence intervals. Confidence intervals for these indices can be found graphically from the known maximum permissible values of $T_{0\,ls}$, $P_{on\,ls}$ and the preliminarily constructed confidence region for regression-time dependences $\tilde{T}_0(T)$ and $\tilde{P}_{on}(T)$ of the REC with a given confidence probability γ.

It can be seen from the above ratios that the accuracy of calculations of the index of residual life according to the technical criterion is determined by the accuracy of constructing the regression-time dependences $\tilde{T}_0(T)$ and $\tilde{P}_{on}(T)$. The accuracy of calculating the index of durability $T^e_{res}(\tau_{cls})$ is determined by the accuracy of constructing regression dependences of the PFF $\tilde{\omega}(T)$ and $\tilde{\omega}_{RO}(T)$ as well as the accuracy of specifying the values $C_{res.\,0}(\tau_{cls})$, C_m, C_{RO}.

Reliability of the constructed analytical models is confirmed by correct formulation of the problem of their construction, correct application of methods of the probability theory, mathematical statistics, reliability theory, system analysis, mathematical modeling, analytical and empirical methods of comparative analysis. Adequacy of analytical models of estimating indices of residual life is confirmed by the results of modeling and their convergence, in particular cases, with the known results. The sensitivity of the analytical models was verified by analyzing the effect of the change of the model parameters on the output index.

Analysis of sensitivity of the constructed models of estimating the residual service life indices (14), (18) in terms of the index b_1, or f_1 leads to the following relationships [28–30]:

$$S_{MTBF\,res}(b_1)=1$$

and

$$S_{PNFS\,res}(f_1)=1.$$

The sensitivity of models (14), (18) is strong with respect to parameters b_1 and f_1.

Analysis of sensitivity of the model (21) in terms of indices ω_1 and ω_{1RO} leads to the following relationships for the sensitivity indices [28–30]:

$$S_e(\omega_1)=C_m|\omega_1|/2|C_m\omega_1+C_{RO}\omega_{1RO}|,$$

$$S_e(\omega_{1RO})=C_{RO}|\omega_{1RO}|/2|C_m\omega_1+C_{RO}\omega_{1RO}|.$$

When ω_1 changes from 0 to ω_{1ls} or when ω_{1RO} changes from 0 to ω_{1ROls}, the sensitivity values change from 0 to 0.5. Sensitivity of the model (21) with respect to the parameters ω_1 and ω_{1RO} is weak or middle depending on their magnitude.

5. 4. Studying the characteristics of the experiment-calculated method of estimating indices of residual life of the radio technical complex

The experiment-calculated method of estimating indices of residual life of the REC is presented in Fig. 3 as a sequence of actions.

Let us consider the accuracy and reliability of estimation of the index of residual life of the REC to ensure its operation according to its technical condition as the characteristics of the experiment-calculated method. These characteristics are determined by indices of quality of the regression models of dependence of MTBF, PNFS, and PFF of the REC on the calendar duration of operation and analytical models of estimating the indices of their residual life.

The characteristics were studied using a computer algebra system from Mathcad 15.0 M05 computer-aided design system. Also, the following restrictions and assumptions were taken:

– 5N63S STR of the S-300PS anti-aircraft missile system was considered as a multiple-use REC;

– the STR was considered as a controllable, restorable, maintainable, and repairable facility;

– operating conditions were assumed to be regular;

– post-repair operation of the STR was considered with an assumption of monotonous reduction of the level of its reliability according to the indices of MTBF and PNFS;

– the repair technology has been worked out and provided in full for the REC under study;

– based on the CLS results, the time points of repair were established according to the technical condition;

– maximum permissible values of the STR PNFS and MTBF were taken equal to 0.948 and 12 hrs, respectively;

– other simulation parameters are given below in the examples of graphs and table.

For the established intervals of controlling the STR operation and maintenance, the REC OATC cycle equal to 1 year was selected, operation intervals ΔT for estimating the MTBF, PNFS, PFF were taken equal to 1 quarter.

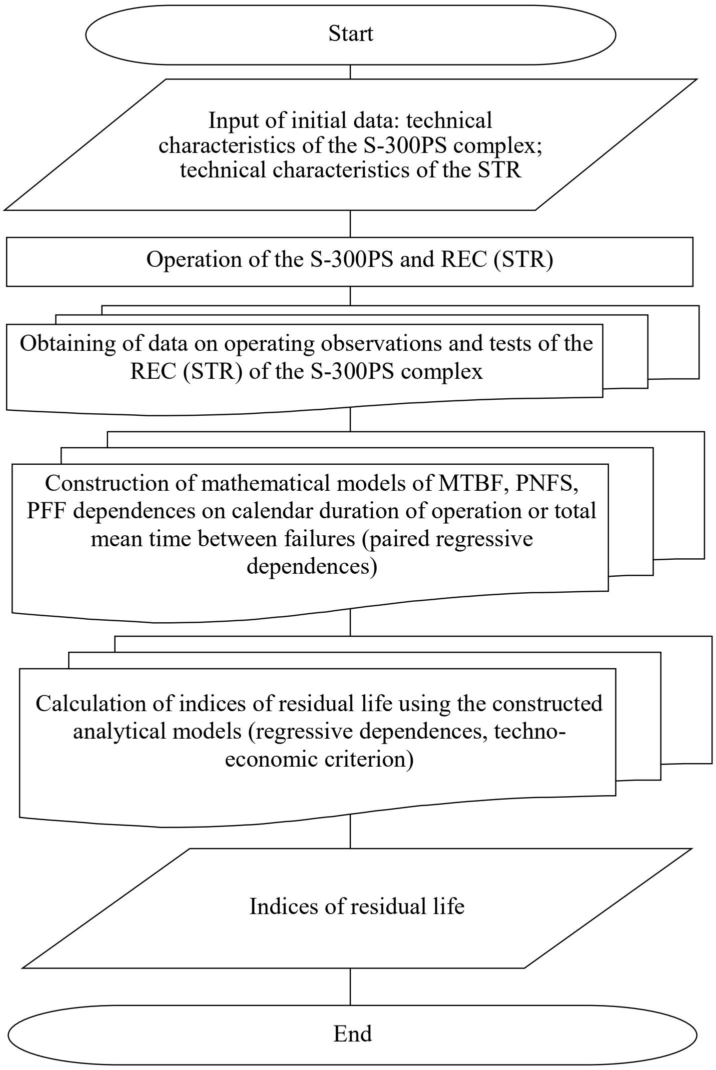

Fig. 3. The sequence of actions of the experiment-calculated method of estimating the indices of residual life of the REC

The CLS STR were not carried out in the considered interval of operation and only field observation data were used for estimating the RI and the index of residual life. The results of switching at each interval of operation were processed independently of each other and were used to assess and control the PNFS RI. At the same time, the results of operational observations in the operating time between failures during the REC operation at corresponding operation intervals ΔT were used to assess and control the MTBF RI.

RI in these intervals was controlled "by the control method using confidence limits without preliminary test planning" [13, 14].

In total, 20 operation intervals were considered which corresponds to 5 years of a controlled operation.

The data of operational observations recorded in the operational documentation during the intervals ΔT were considered as the results of operational tests for reliability:

– according to the plan [1MT] for MTBF;

– according to the plan $\{k_i U \Delta T_i\}$ for PNFS.

Further, point estimates of MTBF $\hat{T}_{0i}$, PNFS $\hat{P}_{oni}$ and PFF $\hat{\omega}_i$, were calculated for corresponding intervals and used to construct corresponding regressive dependences. An example of initial data and the results of estimating the parameters of the regressive dependence of the REC MTBF on the calendar duration of the operation is given in Table 1.

The regressive dependences for MTBF, PNFS and STR PFF constructed according to the corresponding data of operational observations in the considered interval of operation take the form:

$$T_0(T) = 0.122 + 4.29 \cdot 10^{-3} T, \quad (23)$$

$$P_{on}(T) = 0.974 - 1.212 \cdot 10^{-3} T, \quad (24)$$

$$\omega(T) = 0.122 + 4.29 \cdot 10^{-3} T. \quad (25)$$

The initial data and the results of estimating the parameters of regression dependence of the STR MTBF on the calendar duration of operation are given in Table 1. Data on the operating time, the number switching, and their results in the intervals under consideration were obtained from the data of the controlled post-repair operation of the STR [24, 25].

Table 1

Initial data and results of estimating the parameters of regression dependence of the STR MTBF depending on the calendar duration of operation

Running number of the operation interval	Number of failures d, during operation	Point estimate of MTBF, hr.	Estimates of parameters of regression dependence of anti-aircraft complex STR MTBF	
			b_0, hr.	b_1, hr./quarter
1	3	16.5		
2	4	16.9		
3	4	15.7		
4	4	15.3		
5	4	16.2		
6	5	14.4		
7	4	15.5		
8	4	14.4		
9	5	15.2		
10	4	14.1	16.458	−0.19
11	4	15.2		
12	5	14.5		
13	5	14.2		
14	4	13.6		
15	5	14		
16	4	13.3		
17	5	13.5		
18	5	12.9		
19	5	13.2		
20	6	12.7		

To confirm adequacy and reliability of the constructed mathematical models of changing the REC reliability indices, analytical models of estimating the indices of residual life of the REC, as well as reliability of the experiment-calculated method of estimating the indices of residual life of the REC, it is necessary to check the quality of the constructed regressions. The quality of the constructed regressions was proved by checking the significance of the regression coefficients and adequacy of the regression dependences. The significance of coefficients of the regression models was checked by testing the hypotheses about equality of the coefficients of the regressive dependences (3), (11), (12) using relations (7), (8). According to the test results, the regression coefficients (23) to (25) are statistically significant at a set level α=0.1.

To check the adequacy of the linear dependences used in the constructed models, their determination coefficients *R* were calculated [26]. It was concluded that 94 %, 95.4 %, and 97.7 % variances of the regressions for MTBF, PNFS, and PFF, respectively, at the considered intervals of operation of the studied AAC REC are explained by the constructed regression dependences.

Fig. 4, 5 show the regression dependences of MTBF and STR PNFS and their OSLCL (γ=0.8) on the calendar duration of operation of the S-300PS anti-aircraft complex (AAC). Black dots (the dots numbered 3) indicate operational data. Curve 1 shows the regression dependence obtained using the constructed mathematical models. In accordance with the developed method, the index of residual life of the STR was calculated. According to the calculation results at the time of conducting the STR CLS (τ_{cls}=5 years), these indices have the values $T_{res}^{MTBF}(5\text{ years})=3.7$ a quarter, $T_{res}^{PNFS}(5\text{ years})=4.9$ a quarter, average residual service life of the STR according to the technical criterion is $T_{res}^{t}(5\text{ years})=\min(3.7;4.9)=3.7$ a quarter.

The results of calculations of the OSLCL of average residual service life at the level of γ=0.8 were $\underline{T}_{res\gamma}^{MTBF}(5\text{ years})\approx 2$ a quarter for the MTBF, $\underline{T}_{res\gamma}^{PNFS}(5\text{ years})\approx 3$ a quarter for the PNFS. At the same time, the estimation accuracy determined by the width of the one-sided confidence interval in terms of the MTBF and PNFS indices was 1.5 a quarter.

Calculation of estimates of mean residual service life according to the economic criterion was carried out for initial data: C_{res}. 0(τ_{cls})=2·106 Hrn, *Cm*=104 Hrn, C_{RO}=105 Hrn., ω_1=1,23 1/quarter2 and $\omega 1_{RO}$=0.6 1/quarter2. These data were obtained from the results of operation and modeling at quarterly consumption of the STR resource of 300 hrs. The value of the residual service life according to the economic criterion was 7.4 quarters and the estimate of average residual service life. The STR according to the ratio (22) was 3.7 quarters. At the same time, the value of the OSLCL of this index was 2 quarters with a probability of 0.8.

The modeling results show that the point and interval estimates of the average residual service life of the REC according to the indices of MTBF and PNFS obtained by means of the developed method provide accuracy and reliability acceptable for the OATC. This, in turn, ensures making substantiated decisions on the choice of the time of carrying out the CLS, the time and scope of repairs, and other measures to control the REC operation according to its technical condition.

Based on the results of the STR CLS carried out at the end of the controlled operation period of 5 years, its non-limiting state was established. This confirms the adequacy and reliability of the constructed models, as well as the correctness of the developed experiment-calculated method of estimating the index of residual life. This means that the estimate of the index of the residual life of the STR obtained from the data of actual post-repair operation at the period of 5 years and the results of the CLS correspond at the same moment. This fact also testifies in favor of adequacy and reliability of the constructed models and reliability of the developed method.

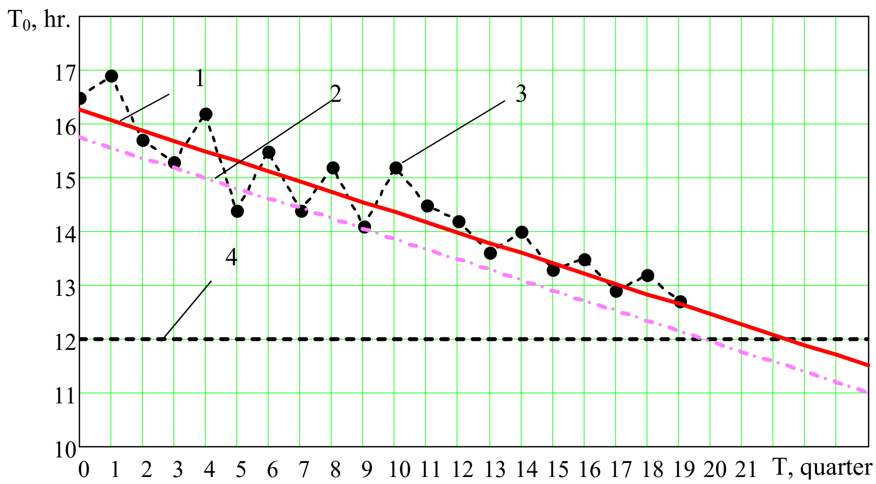

Fig. 4. Graphs of dependences of the estimates of the mean time between failures of the radio technical complex on the calendar duration of operation: 1 — regression dependence of the mean time between failures $T_0(T)$; 2 — dependence of the one-sided lower confidence limit of the mean time between failures $\underline{T}_{0_\gamma}(T)$ at γ=0.8; 3 — the points corresponding to the values of point estimates of the MTBF; 4 — graph of dependence for $T_{0\,ls}(T)$=12 hrs

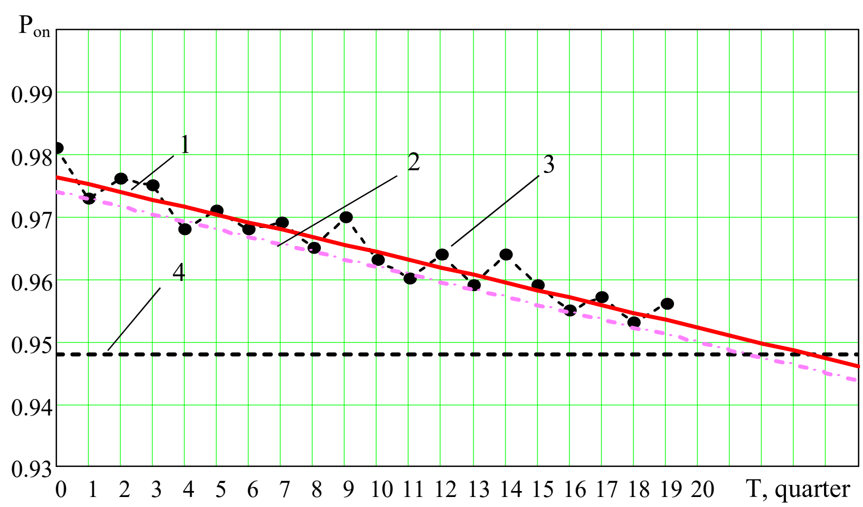

Fig. 5. Graphs of dependences of estimates of the probability of failure-free switching on of the radio-engineering complex on calendar duration of operation: 1 — regression dependence of PNFS P_{on}(T); 2 — dependence of the one-sided lower confidence limit of the probability of failure-free switching on $\underline{P}_{on\gamma}(T)$ at γ=0.8; 3 — the points corresponding to the values of point estimates of PNFS; 4 — the graph of dependence of $P_{on\,ls}$(T)=0.948

Estimation of the index of residual life of the REC according to test results using known methods [3, 14] is reduced to estimating the function of distribution of service life (resource) or, in some cases, directly from the results of life tests without estimating this distribution function. In this case, N RECs identical from the point of view of estimating the REC durability are taken for testing under the same conditions up to the occurrence of a set number of resource failures or a set duration of the operation is reached. The scopes of these tests are significant and the results of estimation of the index of residual life is averaged over N products. This corresponds to the regulated operation of the REC and is unacceptable for the OATC of concrete RECs. In contrast to the known methods, the proposed method was developed for concrete RECs operated according to their technical condition. Known methods of estimating the index of residual life in relation to such RECs operated according to their technical condition cannot be applied. The known methods of estimating indices of reliability are focused on separate solutions of problems of estimating indices of reliability or durability and are inapplicable for estimating the indices of residual life of a REC operated according to its technical condition. Therefore, the developed and known methods of estimating the indices of durability by estimating quality or efficiency were not compared because of different test plans and conditions.

6. Discussion of the results obtained in studying the characteristics of the developed experiment-calculated method of estimation

Operation of present-day RECs of repeated use according to their technical condition requires solving the problems of estimating the index of residual life with specified accuracy and reliability, for example, accuracy not more than 2 quarters, reliability not worse than 0.8 (Fig. 4, 5, relations (14), (18), (21)). At the same time, for the effective operation of the RECs according to their technical state, it is necessary to monitor the limit state in each OATC cycle with a reliability of at least 0.9 and minimize the scope of special reliability and durability tests.

The developed experiment-calculated method makes it possible to ensure accuracy and reliability of estimation of the index of residual life acceptable for the operation of the REC in terms of its technical state with minimization of costs for special tests (Fig. 4, 5). This is achieved through the use of operational observation data (Table 1) and, if necessary, special reliability tests with subsequent use of their results for estimating the index of residual life.

The developed experiment-calculated method (Fig. 3) of estimating the index of residual life of a REC operated according to its technical condition is based on:

– solving the problems of estimating MTBF, PNFS, and PFF according to the data of operational observations during individual intervals ΔT and, if necessary, the results of special tests using the combined method of assessment and control [1]. At the same time, the RI is estimated with an accuracy not worse than 0.1–0.15 with a confidence probability not less than 0.9 and reliability of their control not worse than 0.9;

– construction of mathematical models of dependences of MTBF, PNFS, and PFF of the REC on calendar duration of operation or total operating time in a form of paired regression dependences (relations (23) to (25) according to the data of point estimation of RI in the intervals ΔT);

– calculation of indices of residual life of the REC applying the developed analytical models with the use of the constructed regression dependences and the proposed technical and economic criteria (relations (14), (18), (21), (22)).

The results of modeling the processes of estimating the indices of reliability and residual life of the REC were obtained from the data of its controlled operation in a form of regression dependences (relations (22) to (25)). The results of estimating the levels of significance of the coefficients of regressive dependences (0.1) and the values of the coefficients of determination (94 %, 95.4 %, and 97.7 %) of these models confirm the theoretical validity of the developed method.

The developed method involves the application of well-known statistical methods of estimating and predicting the reliability indices for finding residual life indices. At the same time, the development of the models of changing the REC RI is aimed at obtaining regression dependences with the smallest possible number of members and a large value of the coefficient of determination with checking meeting the conditions that ensure their theoretical validity. The method takes into account specifics of the initial data obtained during the operation of the REC according to its technical condition (Fig. 1) and provides a solution to the problem of joint assessment of indices of reliability and residual life without performing special durability tests.

The reliability of the developed method is confirmed by the fact that the results of estimating the indices of residual life according to the actual operation of the REC do not contradict the results of controlling its limit state after 5 years of post-repair operation (Fig. 4, 5). At the same time, values of the quality indices of the constructed regression models of MTBF, PNFS, and PFF confirm their validity (relations (7), (8)). Adequacy of the developed analytical models of estimating the indices of residual life is confirmed by modeling results (Table 1, Fig. 2, 4, 5) and their convergence, in particular cases, to the known results [14, 16].

It is advisable to use this method to assess indices of residual life of various types of reusable RECs operated according to their technical condition, for example, an anti-aircraft missile system, a radar for ensuring landing, a radar system.

It should be noted that the developed method takes into account peculiarities of operation and repair of the RECs according to their technical condition and to a lesser extent takes into account peculiarities of regulated strategies, as well as the peculiarities of other stages of the life cycle. For example, the models of change of reliability indices depending on the duration of operation were obtained on the assumption that the operation is carried out according to the technical condition and the change in the reliability level at intervals between repairs is characterized by a monotonic dependence, etc. This imposes certain restrictions on the scope of the developed method which can be attributed to its disadvantages. Further studies related to the elimination of these disadvantages should be directed to improving the experiment-calculated method for the stage of reliability testing the developed (modernized) REC, as well as the possibility of its implementation for regulated operation methods. Such a method will have a wider field of application for solving the problems of joint assessment of indices of reliability and residual life of the RECs at different stages of their life cycle and methods of operation and repair.

7. Conclusions

1. The developed general provisions for estimating the indices of residual life of the REC contain a graphical representation of the implementation of the operation according to the technical state with a description of its parameters (operation cycle, periods of control of the limit state, etc.). These include the accepted assumptions and limitations for the development of the method, the estimated indices of residual life, technical and economic criteria for the limiting state of the REC. The average residual service life, the average residual resource, and their one-sided lower confidence limits were proposed as indices of the REC durability.

2. Mathematical models of change of the reliability indices (mean time between failures, PNFS, and PFF) of the RECs operated according to their technical condition depending on calendar duration of operation or the total operating time in a form of regression dependences have been developed. To implement the ETS REC method, duration of the intervals of predicting the reliability indices should be from 0.5 to 1 year and the corresponding observation intervals should be more than one year. The proposed procedure of constructing regression-time dependences involves the selection of the best (optimal) form of the REC dependences in the sense of minimum residual variance based on a sequential enumeration of statistically significant regression options (linear, quadratic, cubic, etc.) until the residual variance of the regression will start to grow.

3. The analytical models of estimating the residual life indices of the REC which are equations for calculating the “average residual service life” and “average residual life” according to the technical and economic criteria using regression-time dependences of the reliability indices. In accordance with the technical criterion, estimation of the required index is based on the condition that the mean time between failures and the probability of a trouble-free start take values not lower than the maximum established ones. In accordance with the economic criterion, an estimate of the desired index is found from the condition of a minimum of the function of the intensity of total costs of operating the REC from its calendar duration. In this case, the total costs of eliminating the failures in this function are determined by regressive dependences for the parameter of failure flow.

The developed experiment-calculated method is a set of mathematical models of change of reliability indices of the REC depending on calendar duration of operation or total operating time and analytical models of estimating the indices of residual life of the REC. The method provides accuracy and reliability of estimates of the residual life indices that are acceptable for the operation of the REC in terms of its technical state for making timely and justified decisions on the management of its operation.

4. In comparison with the known estimation methods, the developed method does not require knowledge of the resource distribution function and/or duration of operation until the onset of the limiting state. The method allows one to find estimates of average residual service life (resource) of RECs and their one-sided lower confidence limits with acceptable reliability (γ=0.8–0.9). These estimates are based on the constructed regressive dependences of the REC reliability indices on the calendar duration of operation with acceptable quality indices (the significance level of the regression coefficients is 0.1 and the coefficients of regression determination are not worse than 0.94). Such regression dependences make it possible to estimate the average residual service life with an accuracy of up to 1.5 quarters and a confidence level of 0.8 which is acceptable when operating the REC according to its technical condition. It is recommended to operate radio technical complexes according to their technical condition with a residual life margin of no more than two quarters. This margin is one to two years when a regulated operation strategy is applied. In this case, assessment of the indices of residual life of the REC must be carried out in accordance with the developed experiment-calculated method.

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