MATHEMATICAL MODELING OF PROCESSES AND SYSTEMS

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EXPONENTIAL MODEL DEVIATIONS IN RELIABILITY PREDICTION OF DURABLE RECOVERABLE SYSTEMS

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Abstract—*Quantitative estimations of lambda-method errors are represented at forecasting of restoration function, failures flow parameter and an average operating time between failures of highly reliable technical systems under conditions of long operation.*

Index Terms— lambda-method deviations, failures distribution model, restore function, failure flow parameter, average life between failures

I. Introduction

Modern hardware components – electronic products – have sufficiently high reliability. In this regard, the expected reliability indicators, which are necessary for technical systems developers, can be estimated only by the parametric method, i.e. by using appropriate theoretical models for the time to failure distribution. At the same time, methodological errors caused by the theoretical model can have significant values. It is generally accepted to use one-parameter exponential distribution to solve the electronic products and systems reliability tasks. This model, being one-parametrical, on the one hand, simplifies the reliability issues solution and on the other hand, imposes significant constrains on the model and makes its tolerance very loose. This is the reason of enormous methodological deviations during solution of major reliability issues. Estimations of these deviations are represented in the monograph [1] for an initial period of systems operation (prior to the first failure occurrence).

This article summarizes researches on reliability within the range of durable systems operation (tens and hundreds thousands of hours) and illustrates the significant deviations which follow the long-range reliability prediction based on exponential distribution. There are examples of lesser-known features of the probabilistic-physical technique for the reliability research [6] carried out in the data set Mathcad by the specific examples of aerospace systems represented.

II. Reasons for Incorrect Behavior of the Exponential System at Long-Range Prediction

Unification of the failure rate with the failure flow parameter which has place in many researchers' exp-practice is the main reason for inadequacy of durability estimation under conditions of recoverable systems durable usage, i.e. in the presence of the failure flow within the operation range. Actually, the analytical expression for the failure flow parameter can be obtained from the integral equation:

$$\omega(t) = f(t) + \int_0^t \omega(\tau) f(t-\tau)\, d\tau,$$

which is durability theory fundamental equation that determines the correlation between failure flow parameter $\omega(t)$, which is formed from the first, second and all the following failures, and from the distribution density of the time to the first failure $f(t)$. Solution of the equation (1) with the aid of Laplace transformation leads to the equality $\omega \equiv \lambda$, from which it follows, that the failures exponential model "does not allow to make distinguish between" the mean time to failure T_o (the indicator of unrecoverable systems reliability) and mean time between failures $T_1(t)$ (the indicator of recoverable systems reliability), as long as:

$$T_o = 1/\lambda = 1/\omega = T_1 = \text{const}.$$

Many specialists do not take into account in their calculations, that actually empirical (real) characteristics of these indicators have different conformities in time [2] – [4], because of "agreement" of indicators ω and λ, and the technique of statistical data obtaining to evaluate the failures rate $\lambda^*(t)$ on the basis of the test plan [NUN] principally differs from the conditions of failure statistics obtaining to evaluate the failures flow parameter $\omega^*(t)$ on the basis of the test plan [NRT]. Methodological deviation of lambda-method in evaluation of real failures rate are researched in the article [6]. There is, in accordance with the probabilistic-physical (PP) technique of reliability research, new scientifically explained survival function for the practical usage given- it is the failure rate $\lambda(t)$. It is represented that this function is appropriately described as "failures intensity" as distinct from known parameter $\lambda^{\exp}$ = const, leaving it the terminology "failure rate", that indicates equally the expected occurrence of the failure after operation $t_o^{\exp} = (\lambda^{\exp})^{-1}$.

In this article, before we take lambda-method deviations at failure flow parameter evaluation to research, let us make a comparative analysis of survival functions $\omega_C(t)$ and $\lambda_C(t)$, obtained from diffusional non-monotonic model of durability [5].

Predicted durability evaluations based on probabilistic-physical methodology [6] and empirical data that coincides with them in terms of failures [5] within all the range of the long-term operation represent the discrepancy between failures flow parameter and failures rate. In particular, let us notice that the failures rate $\lambda_C(t)$ and the failures flow parameter $\omega_C(t)$ of a system at the initial stage of operation do not coincide principally, but it is different for the same survival functions for any systems component [5]. Both of the indicated survival functions have both the same dimensions – [1/hour], but are intended to evaluate the durability under different conditions of a system functioning:

Failures rate $\lambda_C(t)$ determines the reliability during flight operation within the range of working-capacity (from the beginning of operation/moment of the up-state recovery to the system failure occurrence) and is described by the equation

$$\lambda_C(t) = \left\{ \frac{\sqrt{\mu_C}}{v_C t\sqrt{2\pi t}} \exp\left[-\frac{(t-\mu_C)^2}{2v_C^2 \mu_C t} \right] \right\} \cdot \left[\Phi\left(\frac{\mu_C - t}{v_C\sqrt{\mu_C t}} \right) - \exp\left(\frac{2}{v_C^2} \right) \Phi\left(-\frac{\mu_C + t}{v_C\sqrt{\mu_C t}} \right) \right]^{-1}, \quad (1)$$

Failures flow parameter $\omega_C(t)$ determines the reliability during long-term operation (during system life time) under conditions of current structure of technical maintenance and repair and is described by the following equation

$$\omega_C(t) = \frac{d\Omega_C(t)}{dt} = \sum_{i=1}^{N} n_i \left\{ \sum_{m=1}^{\infty} \left[\frac{m\sqrt{\mu_i}}{v_i t\sqrt{2\pi t}} \exp\left(-\frac{(t-m\mu_i)^2}{2v_i^2 t\mu_i} \right) \right] \right\}, \quad (2)$$

where μ_c and ν_c are system failure distribution parameters and are the functions of analogical parameters μ_i and ν_i of components and their quantified components that is characterized, in its turn, by the parameters N and n_i.

Figure 1 illustrates the divergence of functions at the initial stage of the system operation, and the zero valuation at t = 0 proved in [2].

Survival functions $\lambda_C(t)$ and $\omega_C(t)$ in the Fig. 1 are obtained for a system that is a printed-circuit board that is Replaceable Assembly Unit (RAU) as a part of avionics units LRM (Line Replacement Units). Characteristics of RAU-type systems elements are represented in Table I.

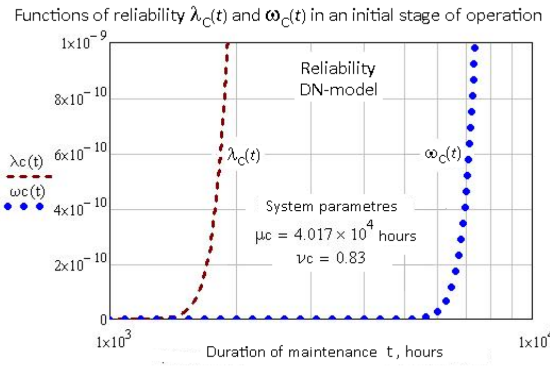


Fig. 1. An illustration of behavior of reliability functions $\lambda_C(t)$ and $\omega_C(t)$ systems

Let us notice the operation ranges, within which, the match values $\lambda_C(t)$ and $\omega_C(t)$ are obtained, for example, 10^{-9} hour^{-1}(the upper limit of graphs in Fig. 1, which corresponds to the impossible event [3]). The given level of failures rate $\lambda_C(t)$ of the type CCE system that is under research, corresponds to the probability of failure state $F(t) \cong 10^{-7}$ (corresponds to low-probability event) and is reached at the total running time of about t = 2000 flight hours after beginning of operation.

TABLE I

STRUCTURAL COMPONENTS OF A SYSTEM (PRINTED CIRCUIT BOARD)

Components	n	MTTF, h	ν
Discrete IBS (IC chip)	20	162618	0.804
Resistors	86	734176	0.99
Capacitors	72	783493	1.02
Contacts (bullet connector)	24	862618	0.62
Multilayer printed circuit board	1	2112880	1.085
Soldered join	660	1718610	0.69

Failures flow parameter $\omega_C(t)$ becomes to this level after its operation during not less than 7000 flight hours, and it is proved by the divergence of reliable indicators $\lambda_C(t)$ and $\omega_C(t)$ of the system within the initial ranges of operation. Their divergence is represented in the Fig. 2 as an illustration of the principal difference of the functions $\lambda(t)$ and $\omega(t)$, also their typical behavior for electronic systems is represented, and the Fig. 3 illustrated the curve of $\lambda(t)/\omega(t)$ correlation.

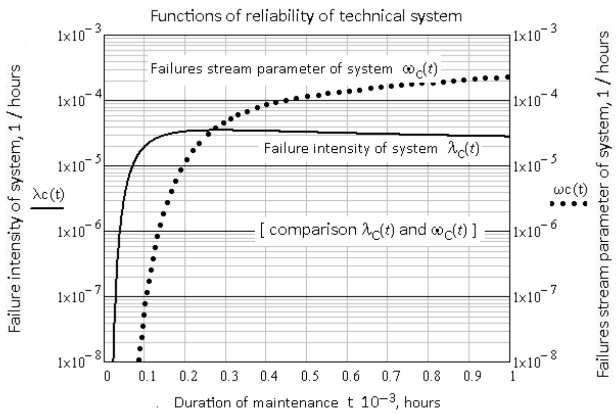


Fig. 2. Behavior of function of non-failure operation $\omega_C(t)$ and $\lambda_C(t)$ systems of type RAU

The discrepancy between values $\lambda(t)$ and $\omega(t)$ at the initial stage of operation within the range $t \in \overline{0, 10^4}$ hours, which corresponds to systems operation to the first failure, is enormous: $\lambda(t)/\omega(t) \sim 10^6 \ldots 10^2$, and cannot be ignored. After occurrence of the system first failure that approximately corresponds to the curses $\lambda(t)$ and $\omega(t)$ intersection area for accepted output data, the discrepancy of the last two is still increasing, staying within the ranges of 10^3 percent to the system limit-state.

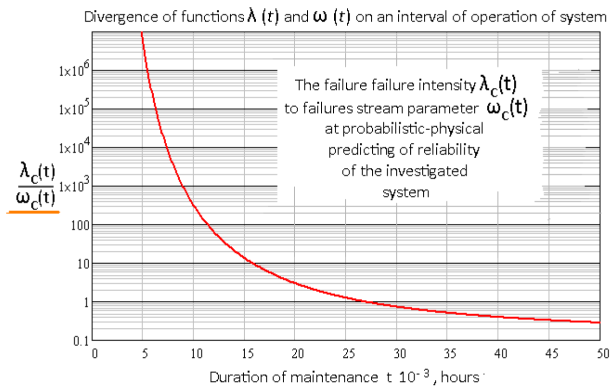


Fig. 3. An illustration of discrepancy of functions of Reliability $\lambda_C(t)$ / $\omega_C(t)$on an interval of operation 5000 … 50000 hours of system of type RAU

Survival functions $\lambda(t)$ and $\omega(t)$ differ one from another essentially, they have different physical meanings that belong to their development in the operation process, belonging to the operation ranges described above. In our opinion, these new survival functions $\lambda(t)$ and $\omega(t)$, which do not existing "lambda" – method of durability calculation, it is appropriate to determine their assigning as "**rate of failures**" $\lambda(t)$ and as "**average number of failures per unit of time**", taking into account their physical meanings of survival function $\omega(t)$ respectively [5].

Another reason for incorrect durability estimation, obtained on the exponential distribution basis, is the model being one-parametrical, the impossibility to take into account spreading of the units operation to failure, as long as the variation coefficient of operating time to failure is fixed at the level 1 in this model.Taking into account, thatthethirdandthefourthmomentsofexponentialdistributionarealsofixed (degree of curvature is always equal to two, and the coefficient of excess – to nine), researches are forced to use mathematical expectation only in calculations, whereas reliability indexes depend essentially on spreading (dispersion) of certain components and systems operation to failure. The deviations of calculations increase significantly, if variation coefficients of the evaluated system element differ from one [7].

Then, the identity equation $\omega \equiv \lambda = \text{const}$, that goes from exponential distribution, means that exponential model of reliability does not take into account ageing, run out and other degradation processes, i.e. it excludes the necessity of choice much more quality materials during units manufacturing or maintenance support holding at operation process [6].

We should also notice that, because of the necessity to take into account the run out and fatigue and because of significant discrepancy in values of variation coefficient for the resource of a unit and a model, the exponential distribution is principally not applicable for calculation of mechanical and electromechanical system reliability.

III. Forecasting of Expected Number of Failures at System Long Operation

Long-term application systems function under conditions of a random failures flow and throughout 20–40 years of the operation repeatedly require restoration of their up state which is supported by current system of a maintenance service and repair.

Probabilistic-physical forecasting provides not only an adequate reliability evaluation on the stage airworthiness of avionics components and systems. In addition, to evaluate their reliability characteristics and indicators on the operational phase during the aircraft lifetime T_{TEF}*.

During long-term operation, the life cycle of the system may be represented by alternating ranges of performance t_i and its elements restoration t_{Bi}, where N is the number of different types of components in the system.

Moments t_i of components failures occurrence are random variables with $\omega(t)$ and $\lambda(t)$, which are

* The operation mean life (T_{TEF}) is determined as: T_{TEF} is the **T**erm of **e**ffective **f**unctioning (**T_{TEF}**)

described by the equations (1) and (2). Similarly, number of failures m within the system operation range (0, T_{TEF}) is random.

Analytical equations for the failure distribution and for the indicators of system dependability within the operating range (0, T_{TEF}) can be obtained on the bases of the system recovery process, which satisfies the following assumptions:

1. Line Replacement Units, as a part of system, is a typical substitute item and spends its resource, beginning with the time moment $t = 0$,
2. Component operation t_i to the failure is a random variable with a non-monotonic diffusion distribution function $F(t)$, which, taking into account equation, has the form

$$F(t)=1-R(t)=\Phi\left(\frac{t-\mu}{\nu\sqrt{\mu t}}\right)+\exp\left(\frac{2}{\nu^2}\right)\Phi\left(-\frac{t+\mu}{\nu\sqrt{\mu t}}\right). \tag{3}$$

3. When the failure occurs, the operation capacity of the system is restored by replacing the failed LRU component by workable analogue from the replacement kit.
4. Replacing a failed LRM is performed immediately after the flight is finished.
5. Restoration duration t_{ri} of a system up state is smaller than its operation period to the next failure, i.e. $t_{ri} << t_i$ (we can assume that a failed item is immediately replaced by working component).
6. A restoration processes of system upstate are independent.
7. Restoration provides the initial level of system dependability (directly prior to a failure occurrence).
8. There are mean values μ_i and variation coefficient ν_i of the operating time to failure of each component of a system.

Taking into account all written above, the expression for the probability m of failures of the ith component with parameters μ_i and ν_i occurrence at operation duration t are obtained in [2], [6] and is written as follows:

$$F_i(m,t)=\Phi\left(\frac{m-X_i}{\nu_i\sqrt{m}}\right)+\exp\left(\frac{2X_i}{\nu_i^2}\right)\Phi\left(-\frac{m+X_i}{\nu_i\sqrt{m}}\right), \tag{4}$$

where $X_i = t/\mu_i$ is the relative (reduced) operating time of ith LRM.

Equation (4) is the distribution function of the number of failures m of ith LRU within the interval of the given operation t, and hence the renewals number distribution function within the interval of operation t, and unites the probability of failure of i-LRM occurrence with its reliability parameters μ_i and ν_i.

As long as the number of LRM failures m during the system life cycle is an integer number, so the distribution function $F(m, t)$ is a discontinuous step function. Graph of the failures number distribution function for producing $t = T_{TEF}$ and failure distribution parameters μ_C and ν_C of the system are shown in Fig. 4.

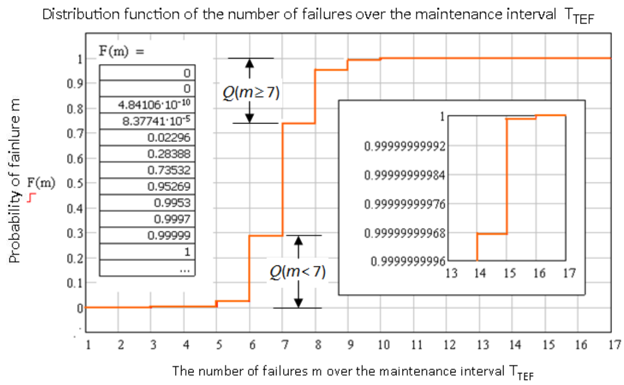


Fig.4. Distribution of failures of the system over the maintenance interval

Schedule $F(m, t)$ is a non-decreasing function whose value starts at 0 and goes in jumps to 1, and at points of discontinuity that correspond to the failures number m, the function $F(m, t)$ is left-continuous and defines the following probability of failures occurrence:

– the probability of m failures occurrence within the interval T_{TEF} is the height of the step at abscissa m;

– the probability that the number of failures is not less than $(m + 1)$ and is equal to the ordinate segment $[1 - F(m)]$ within the range $[m, (m + 1)]$ during the operation life;

– the probability that during T_{TEF} the number of failures is smaller $(m + 1)$ and is equal to the ordinate of the abscissa axis segment to the step within the range $[m, (m + 1)]$.

Based on the failures distribution function of a system, the analytical equations for quantificational values of recoverable systems durability are obtained.

IV. Deviations of Restorable Systems Reliability Forecasting

PP-analysis technology of durability offers analytical expressions of reliability indicators for continuous operation systems (“restorable” systems) that are obtained from the distribution function of the number of failures $F(m, t)$ and that provide the computation of

average failures of *m* during time *t* (AFDT)– $M[m(t)]$, which has another name - **average renewals functioning for time *t*** (ARFT) – $\Omega(t)$;

average failures in unit of time(AFUT) – $\omega(t)$;

mean time between failures (MTBF) – $T_1(t)$.

These indicators of reliability are duration functions of operation described by the following analytical expressions:

$$M\left[m(t)\right]_C = \Omega_C(t) = \sum_{i=1}^{N} n_i \cdot \sum_{m=1}^{\infty}\left[\Phi\left(\frac{t-m\mu_i}{v_i\sqrt{t\mu_i}}\right)+\exp\left(\frac{2m}{v_i^2}\right)\Phi\left(-\frac{t+m\mu_i}{v_i\sqrt{t\mu_i}}\right)\right], \quad (5)$$

$$\omega_C(t) = \sum_{i=1}^{N} n_i \sum_{m=1}^{\infty}\frac{m\sqrt{\mu_i}}{v_i t\sqrt{2\pi t}}\exp\left[-\frac{\left(t-m\mu_i\right)^2}{2v_i^2\mu_i t}\right], \quad (6)$$

$$T_{1C}(t) = \frac{1}{\omega_C(t)} = \left\{\sum_{i=1}^{N} n_i \sum_{m=1}^{\infty}\frac{m\sqrt{\mu_i}}{v_i t\sqrt{2\pi t}}\exp\left[-\frac{\left(t-m\mu_i\right)^2}{2v_i^2\mu_i t}\right]\right\}^{-1}. \quad (7)$$

Let us represent you results of analysis for possible deviations in durability, that are predicted on the basis of exponential distribution, when the researchers are forced to use constant value of failures flow parameter $\omega_C^{\exp} \equiv \lambda_C^{\exp}$. during the computation. Because of the equation the anticipated number of failures is determined by the linear dependability on operation $\Omega_C^{\exp}(t) = \omega_C^{\exp} t$.

The behavior of PP-models of reliability (5) – (7) within the ranges of long-term operated system of RAU-type (see Table I) that is illustrated with graphs in Figs 5, 7 and 9. There are also λ-analogue of reliability indicators $\Omega_C^{\exp}$, $\omega_C^{\exp}$, $T_{1C}^{\exp}$ which are given for comparison and areas of methodological deviation occurrence Δ_1 (uprating) and Δ_2 (downward bias of the result of calculation) of lambda-method in evaluation of indicators of reliability for recoverable systems.

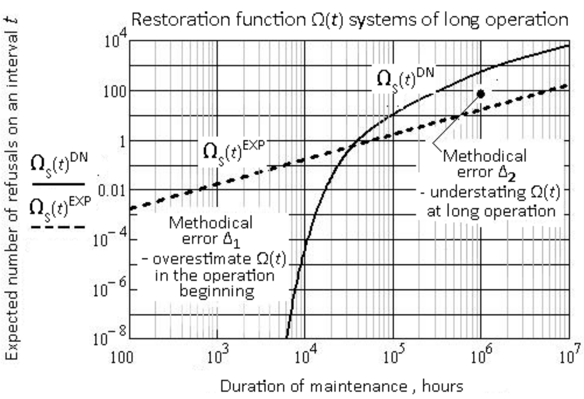


Fig. 5. Expected number of refusals of system of type RAU at long operation

Distribution of methodological deviations Δ_1 and Δ_2 of durability indicators quantification in the form of respective values $\delta\Omega_C^{\exp}$, $\delta\omega_C^{\exp}$, $\delta T_{1C}^{\exp}$ (%%) within the system operation range are represented in the Figs 6, 8 and 10 respectively.

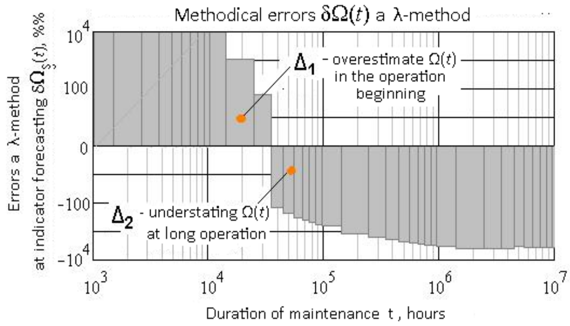


Fig. 6. Errors of forecasting of an average of refusals of system of type RAU

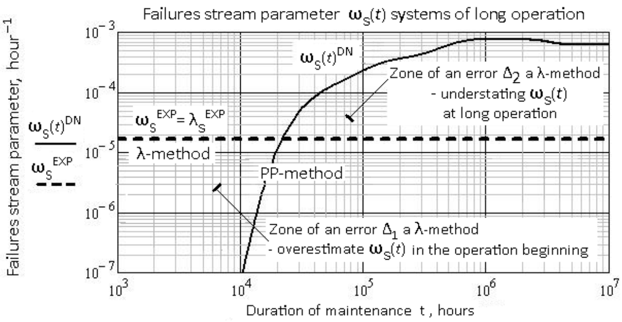


Fig. 7. Methodical an errors λ-method on estimations of indicator $\omega_S(t)$ of system of type RAU

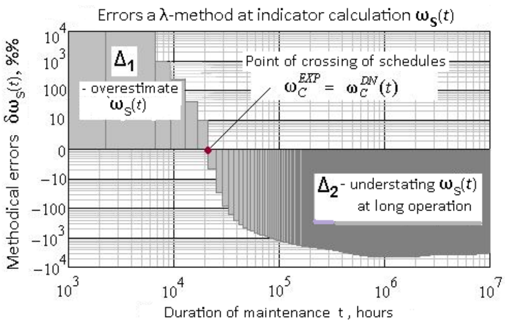


Fig. 8. Errors of forecasting of parameter of a stream of refusals of system

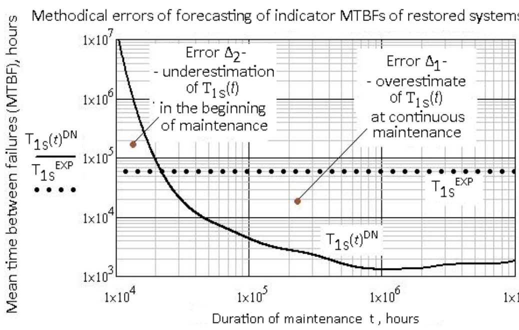


Fig. 9. Methodical an errors λ-method on estimations of indicator $T_{1S}(t)$of system of type RAU

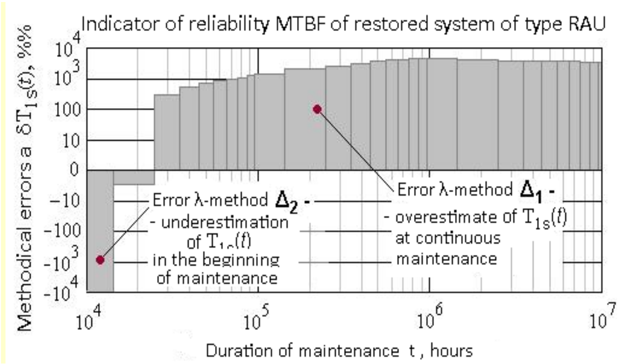


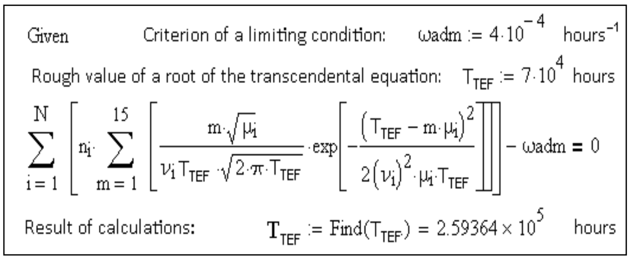
Fig. 10. Errors of forecasting of a mean time between failures of system of type RAU

V. System Life Forecasting

The survival functions which are represented here, provide analytical forecasting of system life at giving the criterion of the limitation state in the form of accepted values Ω_{adm}, ω_{adm} and T_{1adm}. For example, when failure flow parameter $\omega_C(t)$ reaches the quantity of the limitation state criterion $\omega_{adm} = 4\cdot 10^{-4}$ hours^{-1} the transcendental, relatively to the $t = T_{TEF}$, equation (6) transforms to the form:

$$\omega_{adm} = \sum_{i=1}^{N} n_i \sum_{m=1}^{\infty} \frac{m\sqrt{\mu_i}}{\nu_i T_{TEF}\sqrt{2\pi T_{TEF}}} \exp\left[-\frac{(T_{TEF} - m\mu_i)^2}{2\nu_i^2 \mu_i T_{TEF}}\right]. \quad (8)$$

The equation (8) solution for the RAU-type system with known distribution parameters of failures μ_i and ν_i quantity n_i of ith type elements is given in the Fig. 11, where the predicted value T_{TEF} = 259360 flight hours.



Given Criterion of a limiting condition: $\omega adm := 4\cdot 10^{-4}$ hours^{-1}

Rough value of a root of the transcendental equation: $T_{TEF} := 7\cdot 10^{4}$ hours

$$\sum_{i=1}^{N}\left[n_i\cdot\sum_{m=1}^{15}\left[\frac{m\cdot\sqrt{\mu_i}}{\nu_i T_{TEF}\cdot\sqrt{2\cdot\pi\cdot T_{TEF}}}\cdot\exp\left[-\frac{(T_{TEF}-m\cdot\mu_i)^2}{2(\nu_i)^2\cdot\mu_i\cdot T_{TEF}}\right]\right]\right]-\omega adm = 0$$

Result of calculations: $T_{TEF} := \mathrm{Find}(T_{TEF}) = 2.59364\times 10^{5}$ hours

Fig. 11. Analytical forecasting of average service life of system

Prediction of gamma-percentile system life circle at given value of the probability not to reach the limit state γ is carried out on the example RAU. The algorithm and result of the prediction is given in the Figs. 12 and 13.

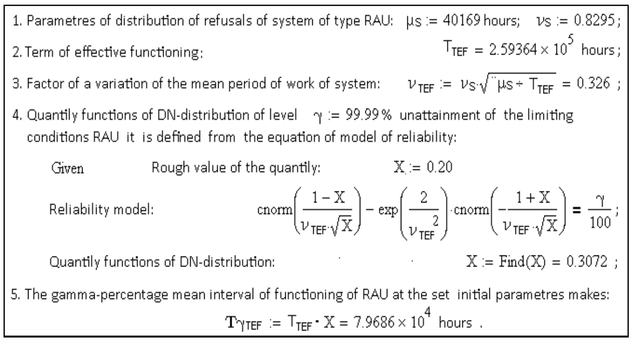
VI. Conclusions

The performance of computation for recoverable systems reliability based on exponential distribution obtains methodological deviations, that reach hundreds and thousands percent in comparison with evaluations based on PP-technology, which practically coincides with empirical results.

So significant deviations in designing calculations of reliability indicators and in evaluations of integral levels of critical systems safety and technological processes exclude the usage of methods based on exponential distribution of possible situations of failures.

Exponential-model of failures, which was accepted of the reliability as a science on the quality of technique in the very beginning and which corresponded to the reliability level of the current components data, and was introduced to industries standards on reliability. Nevertheless, with the occurrence of highly reliable and multi-functional components, in particular, large integrated circuit and very-large-scale integration circuit these lambda-methods lost their opportunities to be used in modern components data and so lead to incorrect evaluation of reliability indicators for technical systems.

The examples of quality indicators of recoverable systems evaluation which were given in this article, in particular, the forecasting of predicted number of failures at long-term operation illustrate some of the various possibilities of probabilistic-physical technique of the reliability research, usage of which in designing of aerospace on-board systems that provide the correspondence of their reliability to the given requirements.



1. Parametres of distribution of refusals of system of type RAU: $\mu s := 40169$ hours; $\nu s := 0.8295$;

2. Term of effective functioning: $T_{TEF} = 2.59364\times 10^{5}$ hours;

3. Factor of a variation of the mean period of work of system: $\nu_{TEF} := \nu s\cdot\sqrt{\mu s \div T_{TEF}} = 0.326$;

4. Quantly functions of DN-distribution of level $\gamma := 99.99\%$ unattainment of the limiting conditions RAU it is defined from the equation of model of reliability:

Given Rough value of the quantly: $X := 0.20$

Reliability model: $\mathrm{cnorm}\left(\frac{1-X}{\nu_{TEF}\sqrt{X}}\right) - \exp\left(\frac{2}{\nu_{TEF}^{2}}\right)\cdot\mathrm{cnorm}\left(-\frac{1+X}{\nu_{TEF}\cdot\sqrt{X}}\right) = \frac{\gamma}{100}$;

Quantly functions of DN-distribution: $X := \mathrm{Find}(X) = 0.3072$;

5. The gamma-percentage mean interval of functioning of RAU at the set initial parametres makes:

$T\gamma_{TEF} := T_{TEF}\cdot X = 7.9686\times 10^{4}$ hours.

Fig. 12. PP-forecasting of gamma-percentage service life of system

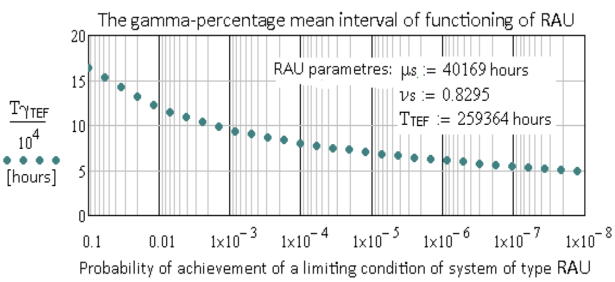


Fig. 13. Gamma-percentage durability of system of type RAU

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В. М. Грібов, О. В. Кожохіна, Ю. В. Грищенко. Про похибки експоненційної моделі в розрахунках надійності відновлюваних систем тривалого використання

Представлено кількісні оцінки похибок лямбда-методу у разі прогнозування функції відновлення, параметра потоку відмов і середнього напрацювання на відмову високонадійних технічних систем за умов тривалої експлуатації.

Ключові слова: похибки лямбда-методу; модель розподілу відмов; функція відновлення; параметр потоку відмов; середнє напрацювання на відмову.

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В. М. Грибов, Е. В. Кожохина, Ю. В. Грищенко. О погрешностях экспоненциальной модели в расчетах надежности восстанавливаемых систем длительного использования

Представлены количественные оценки погрешностей лямбда-метода при прогнозировании функции восстановления, параметра потока отказов и средней наработки на отказ высоконадёжных технических систем в условиях продолжительной эксплуатации.
Ключевые слова: погрешности лямбда-метода; модель распределения отказов; функция восстановления; параметр потока отказов; средняя наработка на отказ.

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