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MATHEMATICAL MODELS FOR CALCULATING THE RESIDUAL LIFE OF THE RECOVERABLE COMPONENTS OF THE AIRCRAFT ELECTRONIC SYSTEM

The **subject** matter of the article are the processes of functioning of the radio electronic system of a modern aircraft, its components, functional units and functional systems as an object for determining and calculating indicators of residual life. The **goal** is the analysis and improvement of the existing mathematical apparatus used to calculate the indicators of the residual resource of the aircraft radio-electronic system restored components. The **tasks**: To develop and generalize mathematical models for calculating the indicators of the residual life of the restored components of the aircraft radio-electronic system. Analyzed **models** are: models for the indicators of the residual life of the restored object of the aircraft radio-electronic system, the failure flow model with a finite number of minimal updates, reliability models of the "load-strength" type. The following **results** were obtained: Mathematical models have been developed for calculating the indicators of residual life and residual operating time of a recoverable product with one resource element with a complete restoration of component elements of the aircraft radio-electronic system. **Conclusions.** Mathematical models have been developed for calculating the indicators of the residual life and the residual operating time of a restored product with one resource element with a complete restoration of component elements. A generalization of these models for a product restored by several resource elements during their complete restoration is obtained. Calculated ratios are obtained for the indicators of the residual resource and the residual operating time of functional devices and functional systems with a finite number of minimal updates of resource elements. Relationships are obtained for determining the limiting number of minimal restorations of functional devices and functional systems of the aircraft radio-electronic system.

Keywords: residual life; residual operating time; aircraft; mathematical model; indicator; electronic system; technical condition.

Introduction

The scheme of calculation of indicators of residual resource of radio electronic system (RES) of the plane offered in [11, 12] provides division of all accessories (AS), functional devices (FD) and functional systems (FS) of RES of the plane into non-renewable or renewable with various depth of recovery, with continuous or periodic monitoring of the technical condition, with a finite or unlimited number of failures during the specified service life, and the calculation of residual life (RL) for selected types of AS, then for FD and FS.

Literature analysis

In the scientific and technical literature, the relevant scientific and methodological support for solving the above problems is not fully developed, there are works [4, 5, 7], which consider mathematical models of complete restorations, minimal and incomplete restorations. However, their application to solve the problems of extending the resources of the aircraft fleet is almost absent.

The following are mathematical models for calculating the indicators of the residual life of non-renewable AS, renewable FD of aircraft RES for complete, incomplete and minimal restorations with a finite number of restorations and continuous monitoring of the technical condition.

In the considered mathematical models the resource is understood as "technical resource", as total operating time of a product from the beginning of its operation or its restoration after repair before transition to a limit state. The residual resource in accordance with [1] means the total operating time of the product from the moment of control of its technical condition to the transition to the limit state.

The aim of the article is to develop mathematical models for calculating the residual life of renewable components of the electronic system of the aircraft.

Main part

Residual resource and residual operating time of renewable products and mathematical models for calculation of their indicators at full restoration of accessories.

Under the residual life of the renewable product (FD, unit, FS or RES of the aircraft) we will understand the total operating time of the product from the moment of control of its technical condition to the resource failure. This assumes possible non-resource failures of the product, i.e. failures not related to the transition of the recoverable product to the limit state. Non-resource failures or simply product failures can be caused by the transition to non-operational state of renewable or non-renewable removable elements. Resource failure of the product is associated with the transition to the limit state of one or more resource elements. Under the resource elements of the product are those products, the expiration of which leads to the end of the product life (FD, FS or RES of the aircraft). Non-resource elements are those elements whose resource ends not earlier than the product resource, i.e. simultaneously with reaching the product limit, or after reaching the product limit, provided that this element can be used in another product of the same or similar purpose. The number of resource elements in the product may be different, and the restoration of the resource element at a particular seat may be complete, incomplete or minimal. In addition, the number of product element replacements at a particular seat cannot be unlimited. Depending on the type of elements, their load-bearing structures, other factors, it is possible to determine the maximum number of their repairs and (or) restorations. Thus, for electronic assemblies made on printed circuit boards, the maximum number of resolders at a certain circuit position is the final value. In this case, the impossibility of restoring or repairing the FD occurs when the number of performed restorations (repairs) associated with the replacement of elements in a particular circuit position is equal to the limit l_t and the next failure of the element. The maximum allowable number of repairs (repairs) of the FD RES aircraft may be determined by economic constraints (l_{ec}), safety requirements and (or) environmental performance (l_{sr}), the actual reliability of the product (l_{ra}), and other reasons. In the case of simultaneous action of several factors, the maximum allowable number of restorations of a certain circuit position can be found as the minimum of these values, i.e.

$$l = \mathbf{min}\{l_t, l_{ec}, l_{sr}, l_{ra}\}. \qquad (1)$$

The maximum allowable number of restores l of a certain circuit position corresponds to the maximum allowable number p of its failures

$$p = l + 1.$$

We now formalize the RL concept for a renewable product, which includes one resource element or one circuit position, for which the maximum number of failures is set. Let ξ_j is the operating time of the selected circuit position of the product between failures (fig. 1); $X_i = \sum_{j=1}^{i} \xi_j$ is the total operating time of the circuit position to the i-th failure. Then $X_{l+1} = X_p$ is the total operating time of the selected circuit position to the resource failure of the product.

The residual life of the product after the moment τ of control of its technical condition (fig. 1) is determined by the ratio:

$$\xi_{\tau\Sigma} = \begin{cases} X_{l+1} - \tau, \ \tau < X_{l+1}, \\ 0, \ if\, X_{l+1} \le \tau. \end{cases} \qquad (2)$$

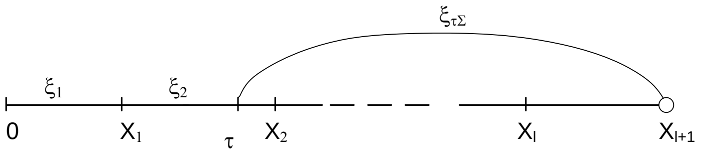

Fig. 1. Determination of the residual life of the renewable product

Note that the restoration of the selected circuit position, which determines the resource of the product, can be complete, incomplete or minimal. In the case of complete recovery, ξ_i are independent equally distributed random variables, and the recovery process of this schematic position is a general recovery process with a finite number of failures, in the case of incomplete recovery, ξ_j random variables with different parameters or distribution laws, and the corresponding recovery process is complex with a finite failure rate. In the case of minimal recovery of the selected circuit position, the failure and recovery flow is described by the failure flow model with a finite number of minimum restorations. These models are considered in [11, 12].

Let us now consider the basic relations for RL indicators at full restoration of the circuit position, which determines the LS of the recoverable product.

Since the operating time of the selected circuit position ξ_i can be considered as independent equally distributed random variables and the average recovery time of the circuit position FD or FS of the aircraft RES is very small compared to the average operating time of the circuit position on failure, such a flow of failures and recovery of circuit position can be considered as full instant restorations. Denote $F_i(t) = P(X_i < t)$ where the distribution function is determined recursively

$$F_i(t) = \int_0^1 F_{i-l}(t-x)\,dF(x),\ F(t) = F_l(t);\ f(t) = F'(t),\ i = \overline{l, l+1}. \qquad (3)$$

Let's find the RL distribution function of the product. Since the $(l+1)$-th failure of the selected circuit position is a resource failure of the product, the distribution function $F_{(l+1)}(t)$ is a function of the distribution of the product resource. Then we get

$$F_{\tau\Sigma}(t) = P(\xi_{\tau\Sigma} < t) = \frac{F_p(t+\tau) - F_p(\tau)}{l - F_p(\tau)}. \qquad (4)$$

Now let's find the probability of the event $\xi_{\tau\Sigma} > t$, i.e. the probability that the value of RL will be not less than the specified operating time t or otherwise the probability of operation of the product without resource failures during operation t, starting from the moment τ, provided the product operates on the segment $[0, \tau]$ without resource failures. From (4) we have

$$P_{\tau\Sigma}(t) = P(\xi_{\tau\Sigma} > t) = 1 - F_{\tau\Sigma}(t) \ \text{or}\ P_{\tau\Sigma}(t) = \frac{\overline{F}_p(t+\tau)}{\overline{F}_p(\tau)}.$$

RL indicators such as average RL $R(\tau)$ and gamma-percentage residual life $R_\gamma(\tau)$ of the recoverable product can be found by substituting in them instead of the probability of failure-free operation $P(t)$ the probability of operation of the recoverable product without resource failures during operation t, i.e. $P_{l+1}(t) = \overline{F}_{l+1}(t)$ where the distribution function $F_{l+1}(t)$ is found by expression (3) or is a distribution function operating time before failure of the resource element of the product. Thus, if the distribution function $F(t)$ of the operating time between the failures of the circuit position, which determines the resource failure of the product, is a normally distributed random variable with mathematical expectation T_0 and standard deviation σ, the distribution function $F_{l+1}(t)$ is also a normally distributed random variable with mathematical expectation T_0 and standard deviation $\sigma\sqrt{p}$.

Let's find the probability of failure-free operation of the renewable AS during operation time y at the end of the assigned resource τ (fig. 2), i.e. let's find the probability of the event $\xi_{\tau \mathrm{i}} > \mathrm{y}$, where the value $\xi_{\tau \mathrm{i}}$ is determined by the ratio:

$$\xi_{\tau i} = \begin{cases} X_i - \tau, \ if \ (X_{i-l} < \tau) \wedge (X_{i-l} > \tau), \ i = \overline{1, p}; \\ 0, \ if \, X_p \le \tau. \end{cases} \quad (5)$$

From (5) and fig. 2 it can be seen that the value $\xi_{\tau \mathrm{i}}$ is the operating time of the circuit position of the restored product from the moment τ to the next i-th failure of the circuit position, which we will call the residual operating time (RO) of the circuit position of the restored product. Note that for a non-renewable product and a product that cannot be repaired, the concepts of "residual operating time" and "residual life" is equivalent.

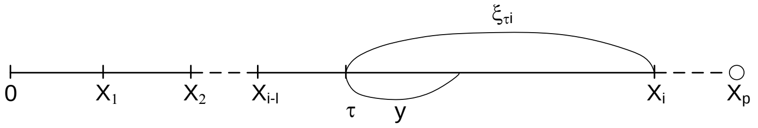

Fig. 2. Determination of the residual operating time of the circuit position of the restored product

The event $\xi_{\tau i}$ can happen in $l+1$ ways:

1) by the time $\tau + y$ there was no failure of the circuit position, the probability of this event is equal to $\overline{F}(\tau + y)$;

2) on the interval $(u, u+du)$, there was an i-th failure of the circuit position, $i = \overline{1, l}$ (the probability of this event is equal to $f_i(u)du$) and after this moment $\tau + y$, there were no failures until the moment $\tau + y$ (the probability of this event is equal to $\overline{F}(\tau + y - u)$). Integrating the product $\overline{F}(\tau + y - u) \times f_i(u)du$ over all $u(0 \le u \le \tau)$, we obtain the probability of an event $\xi_{\tau i+1} > y$, provided that there were i failures on the interval $(0, \tau)$.

Summarizing the found probabilities at i for all $i = \overline{1, l}$ we obtain the desired probability

$$P(\xi_{\tau H} > y) = \overline{F}(\tau + y) + \sum_{i=1}^{l} \int_0^{\tau} \overline{F}(\tau + y - u) f_i(u) du . \quad (6)$$

Formula (6) shows that the probability $P(\xi_{\tau H} > y)$ is a non-stationary coefficient of readiness of the recoverable product with a limited number of complete recoveries. Therefore, in the future we will denote this probability $K_{\text{г}}(\tau, y)$, assuming that the value y is the total failure-free operation of the circuit position in the interval $(\tau, \tau + y)$, where τ is the value of the assigned resource.

We now find the function of the distribution of the residual operating time of the selected circuit position of the product to failure. Since $P(\xi_{\tau H} < y) = 1 - P(\xi_{\tau H} > y)$, from formula (6) follows

$$P(\xi_{\tau H} < y) = F(\tau + y) - \sum_{i=1}^{l} \int_0^{\tau} \overline{F}(\tau + y - u) f_i(u) du . \quad (7)$$

Other indicators of the reliability of the selected circuit position in the RO interval, used to solve problems of continuation of resources, is the average RO and gamma-percent RO $T_\gamma(\tau)$. For the selected circuit position, we will find these indicators by the ratio

$$T(\tau) = \int_0^{\infty} P(\xi_{\tau H} > y) dy , \quad (8)$$

$$P\left(\xi_{\tau H} > T_\gamma(\tau)\right) = 0{,}01\gamma \quad (9)$$

Let's consider the asymptotic behavior of the RO of the selected circuit position, which determines the resource of the recoverable product, i.e. we investigate the behavior of a random variable $\xi_{\tau H}$ at $\tau \to \infty$ and $l \to \infty$. Since $l \to \infty$ then $P(\xi_{\tau H} > y) = \overline{F}(\tau + y) + \int_0^{\tau} \overline{F}(\tau + y - u) \omega(u) du$ and

$$\lim_{\tau \to \infty} P(\xi_{\tau H} > y) = \lim_{\tau \to \infty} \int_0^{\tau} \overline{F}(\tau + y - u) \omega(u) du .$$

By the Smith's theorem [3] we find that this limit is equal to

$$P(\xi_{\tau H} > y) = \frac{1}{T_0} \int_0^{\infty} \overline{F}(\tau + y) d\tau = \frac{1}{T_0} \int_y^{\infty} \overline{F}(z) dz . \quad (10)$$

As a result, we obtain the distribution of stationary residual operating time of the selected circuit position of the restored product. In particular, for $\tau \to \infty$ and $l \to \infty$ the value of the average RO $T(\infty)$ is found by the formula

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$$T(\infty)=\int_0^\infty P(\xi_{\tau H}>y)\,dy=\frac{T_0}{2}+\frac{\sigma^2}{2T_0}\,. \qquad (11)$$

Note that expressions (10) and (11), and not expressions (6), (8), (9) are used in engineering practice. However, in the tasks of continuing the RES resources of the aircraft, we are more interested in the non-stationary interval of operation of AS, FD, FS RES of aircraft and its components, i.e. $t\le(0{,}1-0{,}3)T_0$, where T_0 is the average failure time of the device, unit, AS or AE. Therefore, the calculations of RL and RO products must be performed for the non-stationary interval of their operation according to the formulas for non-stationary RL indicators and other reliability indicators in the RO interval.

Consider how to calculate the indicators of the recovery of a renewable product with one circuit position, which determines the resource of the product.

Let's denote Y_j as the operating time of the renewable product to the j-th failure, $f_{yj}(t)$ is the density of the distribution of the random variable Y_j, X_p is the operating time of the selected circuit position to the resource failure. Then the RO of the product to the next failure (fig. 3) can be determined by the ratio:

$$\xi_{\tau j}^{prod}=\begin{cases}Y_j-\tau,\ \mathit{if}\ (Y_{j-1}-\tau)\wedge(Y_j>\tau)\wedge(Y_j\le X_p),\ j=\overline{1,l_{prod}};\\ 0,\ \mathit{in\ other\ cases.}\end{cases}$$

Residual operating time of the recoverable product before failure differs from the definition (2) by the presence of an additional condition: the event $\{Y_j<X_p\}$ that the accidental operating time of the product before the next j-th failure should not exceed the total operating time of the product (circuit position determining the product resource) to resource failure. Therefore, the above indicators of the residual resource (6), (7), (9) of the type "probability", in terms of the situation under consideration, are conditional. To calculate the unconditional indicators of the recovery of the recoverable product to the next j-th failure, we find the probability of the event (conditions) $P\{Y_j<X_p\}$. We have

$$P\{Y_j<X_p\}=\int_0^\infty \overline{F_p}(t)\,f_{yj}(t)\,dt\,,$$

where $f_{yj}(t)$ is the density of the distribution of the operating time of the product to the j-th failure; $F_p(t)$ is the function of the distribution of the operating time of the circuit position, which determines the resource of the product, to the resource failure.

To calculate this probability, we can use mathematical models of reliability of the type "load - strength" for different functions of load distribution and strength [9]. Then the probability that the RO of the recoverable product will be not less than the set y, we find by the ratio

$$P\left(\xi_\tau^{вир}>y\right)=\overline{F}(\tau+y)+\sum_{i=1}^{l}P\{Y_i<X_p\}\int_0^\tau \overline{F}(\tau+y-u)\,f_i(u)\,du\,. \qquad (12)$$

Other indicators of RO, for example average RO, gamma-percent RO of the restored product is calculated by a ratio (8), (9) by substitution in them of the unconditional probability $P\{Y_j<X_p\}$ $\xi_\tau>y$ found by the formula (12).

We obtain calculation formulas for determining the indicators of RO for the case when the operating time between failures of the selected circuit position, which determines the resource failure of the product, has a truncated normal distribution with mathematical expectation T_0 and standard deviation σ, i.e.

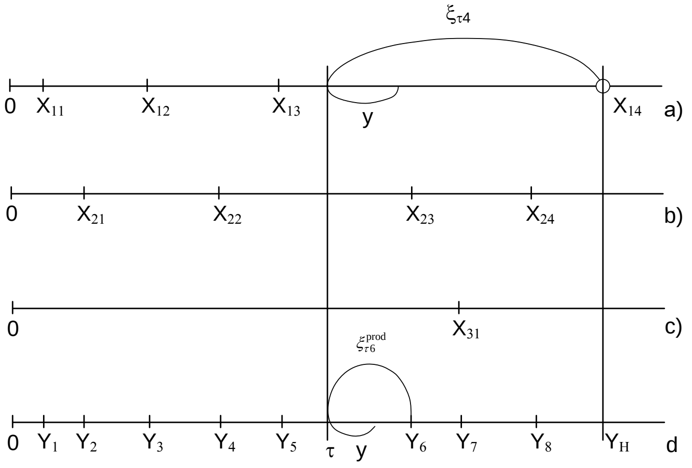

Fig. 3. Determination of residual operating time of the recoverable product: a) the failure flow of the 1st circuit position, which determines the resource of the product; b), c) failure flows of the 2nd and 3rd circuit positions, which do not determine the resource of the product; d) product failure flow; X_{ij} - development of i-th schematic position to j-th failure; $\xi_{\tau 6}^{prod}$ – residual operating time to the next (sixth) failure; $\xi_{\tau 4}$ – residual operating time of the circuit position, which determines the resource of the product, to the resource failure

$F(x)=\frac{a}{\sigma\sqrt{2\pi}}\int_{-\infty}^{x} e^{-\frac{(t-T_0)^2}{2\sigma^2}}dt$; $f(x)=\frac{a}{\sigma\sqrt{2\pi}}\,\mathbf{exp}\left[-\frac{(t-T_0)^2}{2\sigma^2}\right]$, $a=\left[\Phi\left(\frac{T_0}{\sigma}\right)\right]^{-1}$ To calculate the probability $P(\xi_\tau > y)$ we use relations (6). We have: $\overline{F}(\tau+y)=a\Phi\left(\frac{T_0-\tau-y}{y}\right)$; $f_i(x)=a_i\left(\sigma_i\sqrt{2\pi}\right)\mathbf{exp}\left[-\frac{(x-T_0)}{2\sigma_i^2}\right]$. $T_i=iT_0$, $\sigma_i=\sigma\sqrt{i}$, $a_i=a^i$.

Then

$$P(\xi_\tau > y)=a\Phi\left(\frac{T_0-\tau-y}{\sigma}\right)+\sum_{i=1}^{l}a^{i+1}\int_0^{\tau}\Phi\left(\frac{T_0-\tau-y+u}{\sigma}\right)f\left(\frac{u-T_i}{\sigma_i}\right). \tag{13}$$

To calculate the integral in formula (12) we use the results:

$$\int\Phi(a+bx)\varphi(x)dx=T\left(x,\frac{a}{x\sqrt{1+b^2}}\right)+T\left(\frac{a}{\sqrt{1+b^2}},\frac{x\sqrt{1+b^2}}{a}\right)-T\left(x,\frac{a+bx}{x}\right)-T\left(\frac{a}{\sqrt{1+b^2}},\frac{ab+x\left(1+b^2\right)}{a}\right)+F(x)F\left(\frac{a}{\sqrt{1+b^2}}\right), \tag{14}$$

where $T(h,a)=\int_0^a\frac{\varphi(x)\varphi(hx)}{1+x^2}dx$, $0<a<\infty$, $-\infty<h<\infty$, $\varphi(u)=\frac{1}{\sqrt{2\pi}}e^{-\frac{u^2}{2}}$.

We reduce the calculation of the integral in expression (13) to the basic Owen integrals. From expressions (13) and (14) we have $x=\frac{u-T_i}{\sigma_i}$, $a+bx=\frac{T_0-\tau-y-u}{\sigma}$ or $a=\frac{T_0-T_u-\tau-y}{\sigma}$, $b=\frac{\sigma}{\sigma_i}$, $\int_0^{\tau}\Phi\left(\frac{T_0-\tau-y+u}{\sigma}\right)\cdot\varphi\left(\frac{u-T_i}{\sigma_i}\right)du=\int_{-T_i/\sigma_i}^{(\tau-T_i)/\sigma_i}\Phi(a+bx)\varphi(x)dx$.

Let us now use the properties of a definite integral and the property of an Owen integral: $T(h,-a)=-T(h,a)$.

Let’s consider two cases: $\tau<T_{0i}$ and $\tau>T_{0i}$. Get for $\tau<T_{0i}$;

$$\int_{-T_i/\sigma_i}^{(\tau-T_i)/\sigma_i}\Phi(a+bx)\varphi(x)dx=\int_0^{T_i/\sigma_i}\Phi(a+bx)\varphi(x)dx-\int_0^{(T_i-\tau)/\sigma_i}\Phi(a+bx)\varphi(x)dx, \tag{16}$$

and for $\tau>T_{0i}$;

$$\int_{-T_i/\sigma_i}^{(\tau-T_i)/\sigma_i}\Phi(a+bx)\varphi(x)dx=\int_0^{T_i/\sigma_i}\Phi(a+bx)\varphi(x)dx+\int_0^{(T_i-\tau)/\sigma_i}\Phi(a+bx)\varphi(x)dx. \tag{17}$$

The results of probability calculations $P(\xi_\tau > y)$ for the ratio (13) (17) show that the nature of the obtained dependences of the probability $P(\xi_\tau > y)$ on the value of the residual operating time at different values of the assigned resource τ corresponds to the expected, which indicates the correctness of the obtained ratios.

Now consider how to calculate other indicators of reliability of the restored FD (FS) of aircraft RES in the range of RO.

In accordance with the recommendations of the method [11] we distinguish a set of AE, the technical condition of which is not controlled, and a set of controlled on the considered interval of operation of AE.

In this case, the controlled elements, in turn, are divided into continuously controlled and periodically controlled, renewable with varying degrees of resource recovery: FR, IR and MR. Next is a block diagram of the reliability of the FD (FS) of the aircraft RES. According to the known structural scheme of reliability $S(x)$ of the FC of the aircraft RES, the reliability indicators are calculated on the interval of residual operating time, by substituting into the function of the previously calculated reliability indicators of the FD (FS) elements of the aircraft RES:

$$R_{\text{г}}(\tau,y)=S\left(K_{\text{г}1}(\tau,y),K_{\text{г}2}(\tau,y),\ldots,P_j(\tau+y),\ldots\right), \tag{18}$$

where $K_{\text{г}i}(\tau,y)$ is a non-stationary coefficient of readiness of the i-th renewable FC element FU; $P_j(\tau+y)$ is the probability of failure-free operation $(\tau+y)$ for the operation of uncontrolled and non-renewable j-th element in the considered time interval.

If necessary, calculate other indicators, for example, the average residual operating time FD (FS) in relation (8), gamma-percentage residual operating time FD (FS) according to formula (9).

Note that the developed approach is focused on the fact that during the next current repair of FD (FS) of the aircraft RES restores the resource (in full at FR, partially - at IR and at zero at MR) AE FD (FS) only in the variable (or renewable) AE. The resource of other AE FD (FS) is not restored. The difference between other approaches to calculating the reliability of RES is that the recovery of PC FD (FS) by replacing failed AE involves complete recovery of the resource of all FD (FS), which is unacceptable in the case of calculating the indicators of OR and ON when solving resource renewal tasks.

To perform calculations on the ratio (18) it is necessary to pre-calculate the coefficients of operational readiness of the elements of FD (FS), the resource of which is restored in full, incomplete or minimal. We use for this purpose the calculated relations for the failure flow parameter obtained in [11] for flows with FR, IR and MR with a limited number of recoveries. Thus, for the case of FR, the probability that the residual operating time before the failure of the element of a certain circuit position, FD, FS will be not less than a given value, we find the formula

$$K_{г}^{(1)}(\tau,y)=P(\tau+y)+\int_{0}^{\tau}P(\tau+y-u)\,\omega_1(u)\,du\,, \quad (19)$$

or substituting in (19) we obtain

$$K_{г}^{(1)}(\tau,y)=P(\tau+y)+\sum_{k=1}^{l_1}\int_{0}^{\tau}P(\tau+y-u)\,f_k(u)\,du\,, \quad (20)$$

where l_1 is a the maximum possible number of complete AE recoveries for the considered total operating time $(\tau+y)$.

We now write the corresponding formula for the case of the MR element. In [11] the basic relations for processes with instantaneous MR were considered. Then, conducting reasoning similar to the above in deriving formula (6), we obtain

$$K_{г}^{(2)}(\tau,y)=P(\tau+y)+\sum_{k=1}^{l_2}\int_{0}^{\tau}P(u,\tau+y-u)\,f_k^{(2)}(u)\,du\,, \quad (21)$$

where $P(u,\tau+y-u)$ is the probability of failure of the minimally recoverable element FD (FS) in the interval $(u,\tau+y-u)$; $f_k^{(2)}$ is the distribution density of the operating time of the element to the k-th MR; l_2 is the maximum possible number of MR element FD (FS) for the considered operating time.

Substituting in (21) the appropriate formulas for the process with instant recovery, we obtain the following relationship

$$K_{г}^{(2)}(\tau,y)=e^{-\Lambda(\tau+y)}+\sum_{k=1}^{l_2}\int_{0}^{\tau}\frac{\left[\Lambda(u)\right]^k}{k!}e^{-\Lambda(u)}e^{-\Lambda(u,\tau+y-u)}\,d\Lambda(u)\,,$$

where $\Lambda(u)=\int_{0}^{u}\lambda(x)\,dx$.

After performing the transformation, we obtain the final expression for the probability that the residual operating time of the minimum renewable element of a certain circuit position FD (FS) RES of the aircraft will be not less than the specified value y.

$$K_{г}^{(2)}(\tau,y)=e^{-\Lambda(\tau+y)}\sum_{k=0}^{l_2}\frac{\Lambda(u)^k}{k!}=P(\tau+y)\sum_{k=0}^{l_2}\frac{\Lambda(\tau)^k}{k!}\,. \quad (22)$$

We now obtain the ratio for the probability of failure of the element, the resource of which is restored in case of failure in an incomplete volume, for an extended period of operation $(\tau,\tau+y)$. In [11] it is shown that the model of this process is a complex recovery process. Carrying out arguments similar to the above ((6), (14)), we obtain

$$K_{г}^{(3)}(\tau,y)=P_1(\tau+y)+\sum_{k=1}^{l_3}\int_{0}^{\tau}P_{k+1}(\tau+y-u)\,f_k^{(3)}(u)\,du\,, \quad (23)$$

where $P_{k+1}(x)$ is the probability of failure of the element during operation x after the k-th incomplete recovery; $f_k^{(3)}(u)$ – operating time distribution density to the k-th IR.

These calculated ratios allow to calculate the residual life and other indicators of the reliability of the renewable FD (FS) for an extended period of operation for the case when there is one circuit position that determines the resource FD (FS).

Consider now the case where the number of circuit positions that determine the life of the renewable FD or FS RES aircraft, more than one. Further we will not make distinctions between a resource element of a product and the schematic position defining a product resource.

Let M is the set of resource elements FD (FS). Let's divide this set into disparate subsets M_s, $s=\overline{1,n}$, based on the same number of maximum allowable number of replacements l_s and the same characteristics of failure (the second condition is not required). For the operation of "splitting" the set of resource elements M, the relations are performed

$$M=M_1\cup M_2\cup\ldots\cup M_n\,,$$
$$M=M_1\cap M_2\cap\ldots\cap M_n=\varnothing\,.$$

Let $R_{\gamma s}$ is the lower estimate of the value of the gamma-percent resource of the elements of the subset M_s. Then the lower estimate of the gamma percentage resource FD can be found by the formula

$$R_{\gamma}=\min_{s}\left\{R_{\gamma s}\right\}. \quad (24)$$

A similar relationship can be written for the lower estimate of the gamma percentage residual FD resource

$$R_\gamma(\tau) = \min_s \left\{ R_{\gamma s}(\tau) \right\}. \tag{25}$$

It is assumed that the resource failure of the element limits the reliability of any subset M_s leads to the resource failure of the FD (FS). Then the value R_γ (or $R_\gamma(\tau)$) is determined by the time during which there will be no resource failure of the elements of the subset M_s, the moment of which, in turn, is determined by the earliest moment of occurrence the (l_s+1)-th element failure for all elements that make up the subset M_s.

Let the subset M_s consist of $\|M_s\| = m_s$ elements that limit the reliability of the FD (FS) RES of the aircraft. We will consider the distribution functions as a set m_s of independent random variables $\left\{T_1, T_2, \ldots, T_{m_s}\right\}$ that represent the development of circuit positions of a subset M_s of elements to resource failures. Let's find the distribution function $G_s(t)$ and the distribution density $g_s(t)$ of a random variable $T_{(s)}$:

$$T_{(s)} = \min\left(T_1, T_2, \ldots, T_{m_s}\right), \tag{26}$$

which is a random run of a subset of FD (FS) elements to a resource failure. We have:

$$\begin{gathered} G_s(t) = P\left(T_{(s)} < t\right) = 1 - P\left(T_{(s)} > t\right) = \\ = 1 - \prod_{i=1}^{m_s} P\left(T_i > t\right) = 1 - \prod_{i=1}^{m_s} \left(1 - F_i(t)\right), \\ g_s(t) = \frac{dG_s(t)}{dt} = \sum_{j=1}^{m_s} f_j(t) \prod_{i=1}^{m_s} \left[1 - F_i(t)\right] \Big/ \left[1 - F_j(t)\right]. \end{gathered} \tag{27}$$

Random value T_i in relation (26) is a random operation of the i-th circuit position

$$T_i = \sum_{k=1}^{l_s+1} t_{ki},$$

where t_{ki} is the operating time of the element at a certain i-th circuit position to k-th replacement.

In the case of complete restorations, random variables t_{ki} can be considered as independent equally distributed random variables, and the random variable distribution function T_i can be found as a convolution of the (l_s+1)-th order of random variables. If all elements of the subset M_s have the same functions of distribution $F_s(t)$ of a random variable T_i, then it follows from expression (27)

$$\begin{gathered} G_s(t) = 1 - \left(1 - F_s(t)^{m_s}\right) = 1 - \overline{F_s}(t)^{m_s}, \\ g_s(t) = m_s f_s(t) \overline{F_s}(t)^{m_s - 1}. \end{gathered} \tag{28}$$

The relation for the residual resource distribution function of the subset M_s of FD elements is obtained by conducting similar considerations for the residual resource distribution function $F_{\tau\Sigma}^{(i)}(t)$ of the element at the i-th circuit position

$$F_{\tau\Sigma}^{(1)}(t) \frac{F_p(t+\tau) - F_p(\tau)}{1 - F_p(\tau)}$$

and the probability that during the residual operating time t there will be no failures of the i-th circuit position element

$$P_{\tau\Sigma}^{(i)}(t) = 1 - F_{\tau\Sigma}^{(i)}(t).$$

Then the distribution function of the residual resource of the subset of elements M_s is found by the relation (28):

$$G_{s\tau}(t) = 1 - \left(P_{\tau\Sigma}(t)\right)^{m_s}. \tag{29}$$

We now obtain the calculated ratios for the quantities $R_{\gamma s}$ and $R_{\gamma s}(\tau)$.

From relation (28) and the definition of the gamma-percent resource follows $P\left(T_{(s)} > R_{\gamma s}\right) = 1 - G_s\left(R_{\gamma s}\right) = \gamma$ or

$$\overline{F_s}\left(R_{\gamma s}\right) = \gamma^{\frac{1}{m_s}}. \tag{30}$$

Solving equation (30) according $R_{\gamma s}$ to the given value γ and various parameters m_s of all subsets M_s of FD (FS) elements, we obtain the corresponding values of gamma-percent resources. Next at the expression (24) we find the lower estimate of the gamma-percent resource FD (FS) of the aircraft RES.

The calculated ratios for the FD gamma-percentage residual resource are obtained by conducting similar considerations for the distribution function of the OP $F_{\tau\Sigma}^{(i)}(t)$ of the i-th circuit position. From expression (29) it follows that

$$P_{\tau\Sigma}\left(R_{\gamma s}(\tau)\right) = \gamma^{\frac{1}{m_s}}, \tag{31}$$

or

$$P_\Sigma\left(R_{\gamma s}(\tau) + \tau\right) = P_\Sigma(\tau)\,\gamma^{\frac{1}{m_s}}, \tag{32}$$

where $P_\Sigma(t) = 1 - F_{ps}(t)$.

Solving equation (32) according to $R_{\gamma s}$ for different subsets M_s of FD (FS) of the aircraft RES, we obtain the corresponding values $R_{\gamma s}(\tau)$. The lower estimate of the gamma-percentage residual resource FD can be found from the expression (25).

We now obtain the calculated ratios for the gamma-percentage residual resource of subsets M_s of FD elements on the example of different functions of the distribution of operating time to failures of its elements.

A. The operating time before the failure of the elements of the subset M_s has a normal distribution with a mathematical expectation μ_s and standard deviation σ_s, and $\mu_s > 3\sigma_s$. Then the function of the distribution of the operating time of these elements to the resource failure has the form

$$F_s(t)=\Phi\left(\frac{t-\mu_s(l_s+1)}{\sigma_s\sqrt{l_s+1}}\right),$$

where $\Phi(z)=\frac{1}{\sqrt{2\pi}}\int\limits_{-\infty}^{z} e-\frac{y^2}{2}dy$.

Equation (30) for this distribution function is as follows:

$$\Phi\left(\frac{\mu_s(l_s+1)-R_{\gamma s}}{\sigma_s\sqrt{l_s+1}}\right)=\gamma^{\frac{1}{m_s}}. \qquad (33)$$

Let's mark $\alpha_s=\gamma^{\frac{1}{m_s}}$. Solving equation (33) as for the value $R_{\gamma s}$ we obtain

$$R_{\gamma s}=\mu_s(l_s+1)-U_{\alpha s}\sigma_s\sqrt{l_s+1}, \qquad (34)$$

where $U_{\alpha s}$ is an α_s - quantile of normal distribution.

Equation (32) for finding the gamma-percentage residual resource has the form:

$$\Phi\left(\frac{\mu_s(l_s+1)-R_{\gamma s}-\tau}{\sigma_s\sqrt{l_s+1}}\right)=\gamma^{\frac{1}{m_s}}\Phi\left(\frac{\mu_s(l_s+1)-\tau}{\sigma_s\sqrt{l_s+1}}\right). \qquad (35)$$

Let's mark $\alpha_s(\tau)=\gamma^{\frac{1}{m_s}}\Phi\left(\frac{\mu_s(l_s+1)-\tau}{\sigma_s\sqrt{l_s+1}}\right)$.

The solution of equation (35) has the form

$$R_{\gamma s}(\tau)=\mu_s(l_s+1)-\tau-U_{\alpha s}(\tau)\sigma_s\sqrt{l_s+1}. \qquad (36)$$

B. The operating time before failure of the elements of the subset M_s is distributed exponentially with the parameter λ_s. Consideration of such distribution for an estimation of indicators of a residual resource represents more theoretical interest, the results of calculations received thus can be used for comparison with results of calculations on VFI-distributions.

The function $\overline{F_s}(t)$ for subset M_s elements has the form

$$\overline{F_s}(t)=\sum_{k=0}^{l_s}\frac{(\lambda_s t)^k}{k!}\mathbf{exp}(-\lambda_s t). \qquad (37)$$

Substituting (37) into (30) we obtain

$$\sum_{k=0}^{l_s}\frac{(\lambda_s R_{\gamma s})^k}{k!}\mathbf{e}^{-\lambda_s R_{\gamma s}}=\gamma^{\frac{1}{m_s}}. \qquad (38)$$

To solve equation (38) we use the Poisson distribution $\Theta_d=\sum\limits_{k=d}^{\infty}\frac{\alpha^k}{k!}e^{-\alpha}$, the tables we have. To do this, multiply both parts of equation (38) by (-1) and add 1. As a result, we obtain

$$\sum_{k=d}^{\infty}\frac{\alpha^k}{k!}e^{-\alpha}=1-\gamma^{\frac{1}{m_s}}, \qquad (39)$$

where

$$\alpha=\lambda_s R_{\gamma s}. \qquad (40)$$

Then, for known quantities $\Theta_{l_s+1}=1-\gamma^{\frac{1}{m_s}}$ and l_s+1 according to Poisson tables, we find the corresponding parameter α. The desired value $R_{\gamma s}$ is found from the expression (40) $R_{\gamma s}=\frac{\alpha}{\lambda_s}$.

Equation (32) for finding the gamma-percentage of OR has the form

$$\begin{aligned}&\sum_{k=0}^{l_s}\frac{\lambda_s^k\left[R_{\gamma s}(\tau)+\tau\right]^k}{k!}\mathbf{exp}\left(-\lambda_s\left[R_{\gamma s}(\tau)+\tau\right]\right)=\\&=\gamma^{\frac{1}{m_s}}\sum_{k=0}^{l_s}\frac{(\lambda_s\tau)^k}{k!}\mathbf{exp}(-\lambda_s\tau)\end{aligned}. \qquad (41)$$

Let's mark $\beta_s(\tau)=\gamma^{\frac{1}{m_s}}\sum\limits_{k=0}^{l_s}\frac{(\lambda_s\tau)^k}{k!}\mathbf{exp}(-\lambda_s\tau)$.

Next, performing transformations similar to the above, we obtain the equation

$$\sum_{k=l_s+1}^{\infty}\frac{\alpha}{k!}e^{-\alpha}=1-\beta_s(\tau), \qquad (42)$$

where

$$\alpha=\lambda_s\left[R_{\gamma s}(\tau)+\tau\right]. \qquad (43)$$

Then for the values $1-\beta_s(\tau)$ and l_s+1 according to Poisson tables we find the parameter α. The desired value of gamma-percentage RL is found as $R_{\gamma s}=\dfrac{\alpha}{\lambda_s}-\tau$.

Other reliability indicators of FD (FS) of the aircraft RES in the interval of residual operating time are found according to the block diagram given in [12].

Conclusions

1. Mathematical models for calculation of indicators of residual resource and residual operating time of the restored product with one resource element at full restoration of accessories are developed. The generalization of these models for the product which is restored by several resource elements at their full restoration is received.

2. The calculated ratios for the indicators of the residual resource and the residual operating time of functional devices and functional systems with a finite number of minimal renewals of resource elements are obtained. A relation is obtained to determine the limit number of minimum restorations of functional devices and functional systems of the aircraft electronic system.

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МАТЕМАТИЧНІ МОДЕЛІ ДЛЯ РОЗРАХУНКУ ПОКАЗНИКІВ ВІДНОВЛЮВАНИХ ВИРОБІВ РАДІОЕЛЕКТРОННОЇ СИСТЕМИ ЛІТАКА

Предметом вивчення в статті є процеси функціонування радіоелектронної системи сучасного літака, її комплектуючих елементів, функціональних вузлів та функціональних систем як об’єкта визначення та розрахунку показників залишкового ресурсу. **Метою** є аналіз та вдосконалення існуючого математичного апарату, що застосовується для розрахунку показників залишкового ресурсу відновлювальних комплектуючих виробів радіоелектронної системи літака. **Завдання**: Розробити та узагальнити математичні моделі для розрахунку показників залишкового ресурсу відновлювальних комплектуючих виробів радіоелектронної системи літака. Аналізованими **моделями** є: моделі для показників залишкового ресурсу відновлюваного об'єкта радіоелектронної системи літака, модель потоку відмов з кінцевим числом мінімальних відновлень, моделі надійності типу "навантаження – міцність". Отримані такі **результати**. Розроблено математичні моделі для розрахунку показників залишкового ресурсу і залишкового напрацювання відновлюваного виробу з одним ресурсним елементом при повному відновленні комплектуючих елементів радіоелектронної системи літака. **Висновки**. Розроблено математичні моделі для розрахунку показників залишкового ресурсу і залишкового напрацювання відновлюваного виробу з одним ресурсним елементом при повному відновленні комплектуючих елементів. Отримано узагальнення цих моделей для виробу, який відновлюється декількома ресурсними елементами при їх повному відновленні. Отримано розрахункові співвідношення для показників залишкового ресурсу і залишкового напрацювання функціональних пристроїв і функціональних систем при кінцевому числі мінімальних відновлень ресурсних елементів. Отримано співвідношення для визначення граничного числа мінімальних відновлень функціональних пристроїв і функціональних систем радіоелектронної системи літака.

Ключові слова: залишковий ресурс; залишкове напрацювання; літак; математична модель; показник; радіоелектронна система; технічний стан.

МАТЕМАТИЧЕСКИЕ МОДЕЛИ ДЛЯ РАСЧЕТА ПОКАЗАТЕЛЕЙ ОСТАТОЧНОГО РЕСУРСА ВОССТАНАВЛИВАЕМЫХ КОМПЛЕКТУЮЩИХ ИЗДЕЛИЙ РАДИОЭЛЕКТРОННОЙ СИСТЕМЫ САМОЛЕТА

Предметом изучения в статье являются процессы функционирования радиоэлектронной системы современного самолета, ее комплектующих элементов, функциональных узлов и функциональных систем как объекта определения и расчета показателей остаточного ресурса. **Целью** является анализ и совершенствование существующего математического аппарата, применяемого для расчета показателей остаточного ресурса восстанавливаемых комплектующих изделий радиоэлектронной системы самолета. **Задачи**: Разработать и обобщить математические модели для расчета показателей остаточного ресурса восстанавливаемых комплектующих изделий радиоэлектронной системы самолета. Анализируемыми **моделями** являются: модели для показателей остаточного ресурса восстанавливаемого объекта радиоэлектронной системы самолета, модель потока отказов с конечным числом минимальных обновлений, модели надежности типа "нагрузка – прочность". Получены следующие **результаты**. Разработаны математические модели для расчета показателей остаточного ресурса и остаточной наработки восстанавливаемого изделия с одним ресурсным элементом при полном восстановлении комплектующих элементов радиоэлектронной системы самолета. **Выводы**. Разработаны математические модели для расчета показателей остаточного ресурса и остаточной наработки восстанавливаемого изделия с одним ресурсным элементом при полном восстановлении комплектующих элементов. Получено обобщение этих моделей для изделия, восстанавливаемого несколькими ресурсными элементами при их полном восстановлении. Получены расчетные соотношения для показателей остаточного ресурса и остаточной наработки функциональных устройств и функциональных систем при конечном числе минимальных обновлений ресурсных элементов. Получены соотношения для определения предельного числа минимальных восстановлений функциональных устройств и функциональных систем радиоэлектронной системы самолета.

Ключевые слова: остаточный ресурс; остаточная наработка; самолет; математическая модель; показатель; радиоэлектронная система; техническое состояние.

Бібліографічні описи / Bibliographic descriptions

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