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CONSTRUCTION OF A GENERALIZED PROBABILISTIC-PHYSICAL MODEL OF RELIABILITY OF A TWO-LEVEL ACTIVE PHASED ANTENNA ARRAY

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Представлено побудову узагальненої ймовірнісно-фізичної моделі надійності дворівневої АФАР багатофункціональної РЛС.

При розробці фізичної моделі АФАР сформульовано визначення відмов випромінюючих каналів і антеною решітки в цілому. Обрані визначальні параметри АФАР: потужність випромінювання, коефіцієнт посилення на передачу і верхній рівень ближніх бічних пелюсток. Це дозволило сформулювати узагальнені критерії відмов АФАР в режимах на передачу і на прийом, а також визначити допустиму кількість відмов випромінюючих каналів і прийомних модулів. Фізична модель надійності АФАР формалізується рівнянням, що описують відхилення визначальних параметрів антеною решітки за допустимі межі. При цьому знаходяться граничні (допустимі) значення числа випромінюючих каналів і прийомних модулів, що відмовили, які забезпечують мінімально допустимі (критичні) значення визначальних параметрів АФАР.

Для побудови ймовірнісної моделі надійності АФАР проведена ідентифікація антеною решітки як ізотропної ієрархічної системи і виведена формула для визначення середньої кількості працездатних випромінюючих каналів в багаторівневої структурі АФАР. Побудована і формалізована структурна схема надійності приймальної і передавальної підрешіток, приймальної та передавальної АФАР. Сформульовано визначення відмов приймальної і передавальної підрешіток, приймальної і передавальної АФАР. Це дозволило вивести аналітичні вирази для визначення середнього наробітку до відмови, імовірності безвідмовної роботи, щільності розподілу наробітку до відмови і інтенсивності відмов підрешіток і АФАР. В якості моделей відмов СВЧ елементів, транзисторів, випромінюючих каналів і прийомних модулів застосовувалося експоненціальне розподіл (для раптових відмов), дифузійний немонотонний розподіл (для поступових відмов) і композиція експоненціального та дифузійного немонотонного розподілів (при спільному прояві раптових і поступових відмов). У статті представлений ілюстративний приклад розрахунку середнього наробітку до відмови дворівневої АФАР, що включає 6400 випромінюючих каналів

Ключові слова: середній наробіток до відмови, фазована антенна решітка, критерії відмови, канали що випромінюють

1. Introduction

Phased antenna arrays (PAA) have found worldwide application in terrestrial, marine, aeronautical and space radiotechnical means of location, navigation and communication in recent years. In the course of space exploration, phased arrays have found widespread use in IRIDIUM and other satellite systems [1, 2]. S-300, S-400, terrestrial and shipborne military Pantsir-S radars with Fort, Fregat-M, Poliment-Redut and other PAA were developed and are widely used in Russia. Radars with PAA of 80K6T and other types were developed in Ukraine.

Complex mathematical models are developed in the course of designing multifunctional military radar stations (RS) with active phased antenna arrays (APAA) making it possible to optimize characteristics of antenna arrays [3].

Functional parameters and reliability indices are the main characteristics of RS APAAs. Military radars are designed in accordance with DSTU 2863-94 and GOST V 15.206-84 under the Program of Reliability Assurance (PRA) at the stage of development (hereinafter, all terminology used in this article is applied in accordance with DSTU 2860-94, GOST 27.002-2015, GOST 23282-91).

Analysis of existing or construction of new models of reliability of designed devices (including APAA) and systems is the main element of the PRA at the stage of radar draft design. Using the chosen (developed) reliability models,

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reliability indices (RI) of designed RS systems at all stages of life cycle are calculated in accordance with GOST 27.301-95 and GOST 27.003-2016 [4, 5].

To calculate the RS reliability indices, structural (probabilistic) or physical methods of calculating reliability indices are applied. As stated in GOST 27.301-95, «Calculation of reliability indices by structural methods includes in a general case the object representation in a form of a block-diagram of reliability (BDR) describing logical relationship between states of the object's elements and the object as a whole taking into consideration structural and functional relationships and interaction of elements, adopted service strategy, types and methods of reservation and other factors; description of the constructed BDR of the object by an adequate mathematical model which enables calculation of the object's RI within the framework of introduced presumptions and assumptions based on the data of reliability of its elements under conditions of their use.

Physical reliability methods are used to calculate failure-free operation, durability and persistence of the objects for which mechanisms of their degradation under the influence of various external and internal failure (limiting state) generating factors during operation (storage) are known. The methods are based on description of corresponding degradation processes using adequate mathematical models which make it possible to calculate the RI taking into consideration design, manufacturing technologies, modes and conditions of the object operation according to reference or experimentally determined physical and other properties of substances and materials used in the object».

Numerous active transceiver (radiating) modules are the main elements of APAA. Their failure results in fallout of the APAA as a whole and hence in serious operational, tactical and financial losses. Therefore, design of a highly reliable and effective RS with APAA is one of the most important problems of the present-day instrument-making industry.

It follows from the above that development and study of new probabilistic-physical models of reliability of the APAA designed for multifunctional RS is important and relevant.

2. Literature review and problem statement

Deterioration of the APAA characteristics such as gain factor, effective aperture area, radiation pattern (in particular, radiation pattern of central and side lobes) caused by module failures was determined in [6] using the statistical theory of antennas and reliability indices of transmitting and receiving modules. For a more accurate description of the APAA characteristics, a model of its reliability has been proposed. Such a model should take into consideration energy parameters of the modules and their elements, dependence of efficiency (and operating temperature) on the output power level, dependence of temperature on the design parameters of the cooling system, a more accurate description of module failure rate based on analysis of failure rate of module elements. A model of reliability of a single-level APAA of a multifunctional RS was developed in [7, 8]. A formula for calculating the mean-time-between-failures (MTBF) of the antenna array was proposed. The APAA failure is understood as achievement of a critical level of maximum amplitude of the first three side lobes of amplitude-phase distribution of the antenna.

Requirements to the architecture of promising APAA of US naval radar systems were considered in [9]. The need to ensure high reliability of radiating transceiver modules of the antenna (of the order of hundreds of thousands of hours) was especially noted. Reliability of the APAA as a whole should ensure failure-free operation of an unattended RS during its entire service life prior to the scheduled repair. This will allow the RS maintenance personnel not to perform failure recovery of the APAA during its operation and significantly reduce operating costs and requirements to qualification and size of the maintenance personnel.

A method for assessing reliability indices of functional-algorithmic systems as a part of multifunctional radar stations with varying failure rates was considered in [10]. It was shown that to describe statistics of failures of functional-algorithmic systems during operation, it is necessary to use the Weibull distribution. Graphs of reliability indices of structural elements of radar stations for various distribution laws were presented to demonstrate the potential possibility of improving accuracy of probability of failure-free operation in comparison with the use of the exponential distribution law.

A method for calculating reliability of the APAA with a multi-level structure of functional blocks of early warning RS of a new generation was considered in [11]. The reliability calculation was performed for the APAA structure as a recoverable redundant system including internal control. To obtain calculation formulas, the APAA was considered as a device consisting of N transceiver elements linked with taking into consideration structural redundancy.

A failure criterion for a single-level APAA was formulated in [12] and a formula was derived for determining the mean time to the APAA failure at an exponential distribution of the element failures. It was shown that the use of this formula in comparison with the classical reliability model for non-recoverable redundant systems with fractional multiplicity [13] gives an error of $\Delta=0.10$ % in determining the mean time to failure at the number of radiating modules $N_0=200$. With an increase in the number of modules in the array, N_0, the error Δ tends to zero. The reliability model proposed in [12] is convenient to use for calculation at the number of radiating modules in the array, $N_0>200$. At the same time, application of the classical formula leads to cumbersome engineering calculations. A mathematical model of a single-level APAA structure at arbitrary distributions of radiating module failures was proposed in [14, 15] and a transcendental equation was derived to determine the mean time between the PPA failures. Nomograms have been built to calculate probability of failure-free operation and the mean time to failure of the single-level APAAs at various laws of distribution of failures of transceiver modules: exponential, Weibull, diffusion non-monotonic and generalized exponential distributions. Advantage of the proposed APAA reliability model was shown compared with the reliability model of redundant non-recoverable systems with fractional multiplicity.

The review of studies on the APAA reliability models has shown the following.

1. The number of works devoted to development and study of the APAA reliability models is insignificant. This relates to the fact that the studies on development of military radars are practically classified (or half-classified) and information about their reliability is only published in closed or corporate collections.

2. Currently, when calculating the APAA reliability indices, a probabilistic model of reliability is used for non-recoverable redundant systems with a fractional multiplicity. The main disadvantage of the probabilistic reliability model is

that it can only be used to determine reliability indices of the single-level APAA (per hundreds of radiating modules) at sudden failures of radiating modules.

3. Experts in electrodynamics have attempted to construct a physical model of the APAA reliability using the statistical theory of antennas and taking into consideration failures of the transceiver modules of the antenna array.

4. Mathematical modeling of the amplitude-phase characteristics of the APAA was performed to determine the permissible number of failures of the radiating transmitting modules, receiving modules and secondary power supply modules according to the value of permissible reduction of the maximum amplitude of the first three side lobes. This has made it possible to formulate a failure criterion for the physical model of the APAA reliability.

5. The developers investigated behavior of the APAA reliability indices under various laws of distribution of failures of radiating transmitting modules, receiving modules and secondary power supply modules taking into consideration sudden and gradual failures of the elements.

Analysis of the published materials presented in the review has shown the following disadvantages:

– identification of block-diagrams of reliability of the APAA and its component parts is not complete enough;

– the issues of formulation of criteria of failures of the APAA and its component parts remain insufficiently developed;

– the probabilistic model (structural methods of reliability calculation) or the physical model (statistical modeling of the APAA parameters at the radiating module failures) are used as mathematical models of the APAA reliability;

– the models of reliability of the APAA elements and modules that take into consideration joint manifestation of sudden and gradual failures are not considered;

– only simple probabilistic models of reliability are considered for a single-level structure of an APAA that includes no more than 200 radiating modules;

– complex probabilistic models of reliability of a two-level or multi-level structure of the APAA with several thousand (tens of thousands) radiating channels (modules) are not considered.

3. The aim and objectives of the study

The study objective is to construct and investigate a generalized probabilistic-physical model of reliability of a two-level structure of a multifunctional RS APAA for the laws of distribution of failures of the antenna array modules which take into consideration sudden and gradual failures of the elements. In theoretical terms, this will enable the following:

– derivation of analytical expressions for indices of reliability and durability of the APAA and its components;

– optimization of the APAA structures by the criterion of minimum cost;

– establishment of reliability standards for the APAA components.

In operational terms, this will make it possible to develop algorithms for the preparation of optimal (or as-is) regulations for the APAA maintenance and build a system of provision with the required number of spare parts, etc.

To achieve the objective, the following tasks were set:

– identify and determine indices of efficiency of the APAA block-diagram;

– formulate criteria of failures of the APAA and its component parts;

– construct a generalized probabilistic-physical model of reliability of the two-level structures of the APAA of multifunctional RS at arbitrary laws of distribution of failures of the antenna array modules;

– investigate reliability indices of a promising two-level structure of the RS APAA at a joint manifestation of sudden and gradual failures of the radiating channels.

4. Identification and determination of efficiency indices of the APAA block-diagram. The block-diagram of reliability of the two-level APAA of the multifunctional RS

4. 1. Identification and determination of efficiency indices of the APAA block-diagram

By its structure, the APAA can be identified as a hierarchical system with a branching multi-level structure, therefore, when constructing a mathematical model of the APAA, mathematical apparatus of isotropic hierarchical systems is used [13].

The main indicator of the efficiency of the operation of an APAA is the number of working emitting modules, determined by the formula:

$$E=\sum_{k=0}^{\infty}\frac{M^{(k)}}{k!}\left.\frac{d^k\Phi(z)}{dZ^k}\right|_{z=0}, \tag{1}$$

where $M^{(k)}$ is the k-th initial moment of distribution of the number of operable radiating modules; $d^k\Phi(z)/dz^k\big|_{z=0}$ is the k-th derivative of $\Phi(z)$ by z with a further substitution; $z=0$ provided that the $\Phi(z)$ function is differentiable.

The initial moments $M^{(k)}$ can be found based on the following recurrence relation for the moment generating function:

$$\varphi_n(z)=\varphi_{n-1}((r_n e^z+q_n)^{a_n}), \tag{2}$$

where n is the number of APAA levels; a_i is the factor of branching of the i-th level, that is, the number of elements of the i-th level which are subordinate to one element of the (i–1)-th level; r_i is the value of probability of failure-free operation of the element of the i-th level; q_i is the value of probability of failure of the i-th level element.

The first initial moments (mathematical expectation and the second initial moment of the number of operable radiating modules) take the form [13]:

$$M_n^{(1)}=M_{n-1}^{(1)}a_n r_n=r_0\prod_{i=1}^{n}a_i r_i, \tag{3}$$

$$M_n^{(2)}=M_{n-1}^{(2)}(a_n r_n)^2+M_{n-1}^{(1)}r_n q_n a_n. \tag{4}$$

Thus, the average number of operable radiating modules in the multi-level structure of the APAA is determined from formula (3).

4. 2. Building a block-diagram of reliability of a two-level APAA of a multi-functional RS

Block-diagrams of reliability of a two-level APAA with 6400 radiating channels are presented in Fig. 1–3.

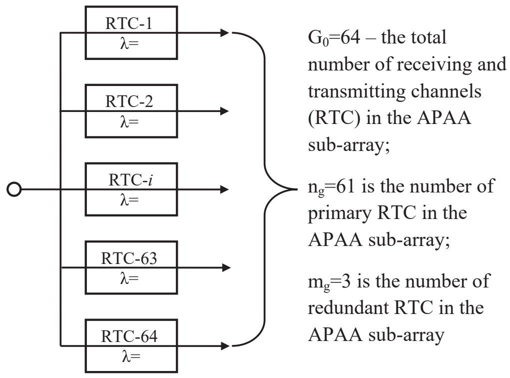

Fig. 1. Block-diagram of reliability of the receiving and transmitting (radiating) sub-array

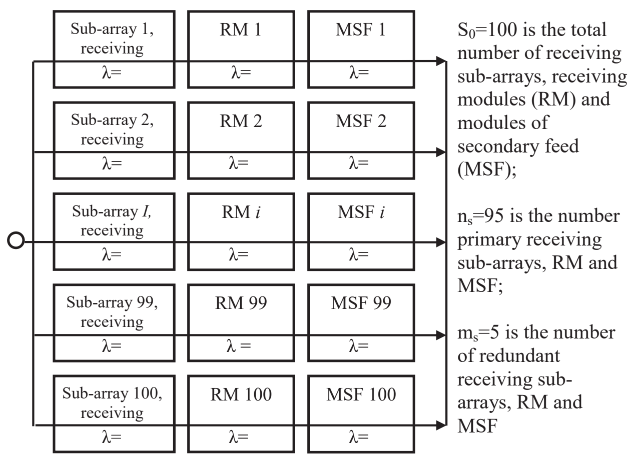

Fig. 2. Block-diagram of reliability of the receiving APAA

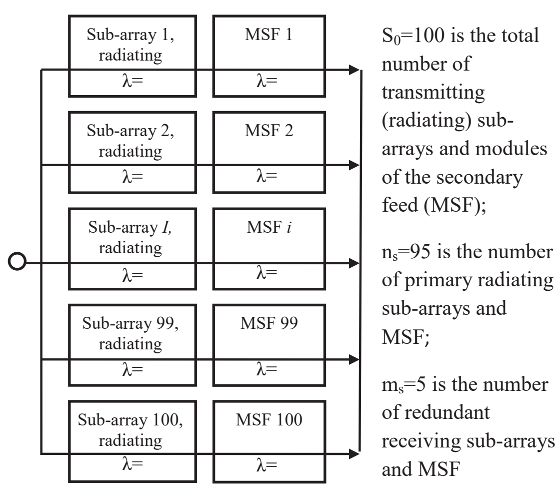

Fig. 3. Block-diagram of reliability of the transmitting APAA

Functionally, the generalized block-diagram of the APAA includes S_0 sub-arrays, each consisting of:

– the aperture of the sub-array with G_0 emitters;
– k antenna transceiver modules (ATM);
– receiving module of sub-array (RMS);
– secondary power supply (SPS).

The ATM modules are the most numerous ($S_0 \cdot k$) and powerful transistor SHF modules of the APAA. Each antenna transceiver module includes:

– d transceiver channels (TC);
– one microstrip divider-adder of SHF signals;
– one computing device for phase and amplitude distribution;
– a sealed housing with sealed inserts for connecting the SHF emitters with a coaxial connector.

Each transceiver channel includes a multi-bit controlled phase shifter, a preamplifier of the transceiver channels, a low-noise amplifier, a power amplifier and a secondary power supply.

When the PAA works for transmission (radiation) of the SHF signal, a multi-bit controlled phase shifter, a preamplifier of the transmitting channel, a power amplifier and a secondary power supply are used in the TC. During operation of the PAA for receiving of the SHF signal, a multi-bit controlled phase shifter, a preamplifier of the receiving channel, a low-noise amplifier and a secondary power supply module are used in the TC.

Hereinafter, the APAA sub-array which operates in the receiving mode will be called the receiving sub-array. The APAA sub-array which operates in the transmission (radiation) mode will be called the transmitting (radiating) sub-array.

The APAA sub-array is a hierarchical structure of the first level, and the RS APAA as a whole is a hierarchical structure of the second level.

5. Formulation of criteria of failures of the multifunctional RS APAA

An active phased antenna array is a complex set of quasi-redundant systems consisting of a number of primary and auxiliary systems. The primary ones include a radiating system and systems of excitation, control and power supply. The auxiliary systems include a control system, a cooling system, etc. [3].

The main parameters of the APAA include radiation power P_{RAD}, transmission amplification coefficient G, directivity coefficient (DC) D, radiation pattern width (RPW) $2Q_{0.5}$, the side lobe level $F_{\sigma i}$, offset of the radar boresight $\Delta\Theta$, polarization parameters, bandwidth $\Delta f_{\notin}$, etc.

Depending on the purpose of the RS, one or more of these parameters are most significant. The APAA state is estimated by the change of these parameters. We will further call them key parameters. For the systems that are part of the PAA, key parameters according to which their operability is assessed are also established.

To construct a mathematical model of the APAA reliability, it is necessary to formulate the concepts of failure for radiating elements and the APAA as a whole in accordance with GOST 23282-91, GOST 27.002-2015, GOST 27.310-95 [16–18].

Definition 1. *Failure of the radiating element of the system is understood as its state in which amplitude and phase of the field (current) in its aperture will go beyond the limits of the tolerance zone established by specifications at any position of the beam in a given scanning sector and subject to the absence of failures in other systems.*

Definition 2. *The APAA failure is understood as its condition in which its key parameters go beyond the limits established by technical documentation.*

Based on the above definitions of failure, the following **generalized criteria** of failures of the multifunctional RS APAA are formulated:

– reduction of radiated power and the APAA gain in the transmission (radiation) mode by more than ΔG (%) which corresponds to the admissibility of a failure with a redundancy factor $C_{RED.RAD}$. % of transmitting (radiating) channels;

– decrease in the level of near side lobes of the APAA in the receiving mode to the level $F_{\sigma i}$ (db) corresponding to the admissibility of failure at the redundancy coefficient $C_{RED.REC}$. % of the receiving modules.

The permissible number of failures of the transceiver channels, receiving modules and secondary power supply modules is determined by specialists in electrodynamics and radars with the help of special programs of computer simulation of the APAA amplitude-phase distribution.

The block-diagram of reliability of the receiving RS APAA is a two-level hierarchical structure. The first level of the receiving APAA is the sub-array (in the receiving mode) which is formed from G_0 transceiver channels (Fig. 1). The second level of the receiving APAA is formed from S_0 sub-arrays, receiving modules and secondary power supply modules of which $m_{REC.MOD}=C_{RED.REC.}S_0$ sub-arrays and modules are quasi-redundant (Fig. 2).

The block-diagram of reliability of the transmitting APAA is a two-level structure. The first level of the transmitting APAA is the (radiating) sub-array (Fig. 1) which is formed from G_0 emitting (transceiver) channels. The second level of the transmitting APAA is formed from S_0 radiating sub-arrays and secondary power supply modules of which $m_{RAD.SLAPAR.}=C_{RED.RAD.}S_0$ sub-arrays are quasi-redundant (Fig. 3).

It follows from [7] that the redundancy factors for the present-day RS with APAA include $C_{RED.RAD.}=10–20$ % (0.10–0.20) for the transmitting APAA and $C_{RED.REC.}=5–10$ % (0.05–0.10) for the receiving APAA.

For the two-level receiving structure of the APAA, the redundancy coefficient at the sub-array level (first level) and at the level of the APAA as a whole (second level) is $C_1=C_{RED.REC.}/2$.

For the transmitting two-level structure of the APAA, the redundancy coefficient at the sub-array level (the first level) and at the level of the APAA as a whole (the second level) is $C_2=C_{RED.RAD.}/2$.

6. Constructing a generalized probabilistic-physical model of reliability of two-level structures of the multifunctional RS APAA at arbitrary laws of distribution of failures of the antenna array modules

The generalized criteria of the APAA failures formulated in Section 5 determine equations describing deviation of the key parameters: the emitted power, the gain and the level of the first side lobes of the antenna array radiation pattern beyond the permissible limits:

$$P_{RAD.\min} \geq \left[P_{RAD.0} - \Delta P_{RAD.\min}\% / 100\right]_{\lim}, \tag{5}$$

$$G_{\min} \geq \left[G_0 - \Delta G_{\min}\% / 100\right]_{\lim}, \tag{6}$$

$$F_{\sigma\_\min} \geq \left[F_{\sigma\_\min}\right]_{\lim}. \tag{7}$$

Equations (5)–(7) are the physical model of the APAA reliability. As a result of implementation of the physical model of reliability, the redundancy coefficients $C_{RED.REC.}$ and $C_{RED.RAD.}$ are determined for the receiving and transmitting APAAs.

The mathematical (probabilistic) reliability model is based on the use of redundancy coefficients for the receiving and transmitting APAAs when calculating the reliability indices of the reliability block-diagram.

To characterize failures of passive elements, SHF transistors and the APAA modules, the following is used [19, 20]:

– a probabilistic model of reliability (exponential distribution) for sudden failures;

– a probabilistic-physical model of reliability (diffusional non-monotonic distribution) for description of gradual failures;

– a probabilistic-physical model of reliability (a composition of exponential and non-monotonic distributions) for describing the combined effects of sudden and gradual failures.

Using the physical model of the APAA reliability, the mathematical (probabilistic) model of reliability and probabilistic-physical models of SHF transistors and the APAA modules, a generalized probabilistic-physical model of reliability of APAA is formed [21].

The total number of operable transceiver channels (working for reception) in the receiving sub-array (at the first level of the receiving APAA) when operating in accordance with formula (3) is calculated as follows:

$$G_{REC.}(t) = G_0 P_{REC.CHAN.}(t). \tag{8}$$

The total number of operable sub-arrays at the second level of the structure of the receiving RS APAA in accordance with formula (3) is calculated as follows:

$$S_{REC.}(t) = S_0 P_{REC.MOD.}(t) P_{SPS}(t) P_{REC.SLAPAR}(t), \tag{9}$$

where $P_{RES.CHAN.}(t)$, $P_{RES.MOD.}(t)$, $P_{SPS}(t)$, $P_{REC.SLAPAR}(t)$ are probabilities of failure-free operation of the transceiver channels (in the receiving mode), the receiving modules, the secondary power supply modules and the receiving sub-array, respectively.

The total number of operable transceiver channels (operating for radiation) in the transmitting sub-array of the APAA during operation in accordance with formula (3) is calculated as follows:

$$G_{RAD.}(t) = G_0 P_{RAD.CHAN.}(t). \tag{10}$$

The total number of operable sub-arrays at the second level of the transmitting RS APAA structure in accordance with formula (3) is calculated as follows:

$$S_{RAD.}(t) = S_0 P_{SPS}(t) P_{RAD.SLAPAR}(t), \tag{11}$$

where $P_{RAD.CHAN.}(t)$, $P_{SPS}(t)$, $P_{RAD.SLAPAR}(t)$ are the probabilities of failure-free operation of the transceiver channels (in the radiation mode), the modules of the secondary power supply and the transmitting sub-array, respectively.

To formalize the criteria of failure of transmitting and receiving RS APAA, it is advisable to make four new definitions:

Definition 3. *A decrease in the total number of operable transceiver channels, $G(t)$, per one channel below the permissible level equal to $G_0(1-C_1)$ is considered to be a failure of the receiving sub-array of the receiving APAA.*

Then the number of operable transceiver channels at the time of failure of the receiving sub-array is calculated as follows:

$$G\left(T_{0\_REC.SLAPAR}\right) = G_0\left(1 - C_1 - \frac{1}{G_0}\right) = G_0 - m_{REC.CHAN.}, \tag{12}$$

where $m_{REC.CHAN.}$ is the permissible number of failures of the transceiver channels in the receiving sub-array, $T_{0\_REC.SLAPAR}$ is the average time to failure of the receiving sub-array,

$$m_{REC.CHAN.}=G_0C_1+1. \quad (13)$$

Definition 4. *Reduction of the total number of operable radiating channels, G(t), per one channel below the permissible level equal to: $G_0(1-C_2)$ is considered to be a failure of the radiating sub-array of the transmitting APAA.*

Then the number of operable radiating channels at the moment of failure of the radiating sub-array is calculated as follows:

$$G\left(T_{0\_RAD.SLAPAR}\right)=G_0\left(1-C_2-\frac{1}{G_0}\right)=G_0-m_{RAD.CHAN.}, \quad (14)$$

where $m_{RAD.CHAN.}$ is the permissible number of failures of the radiating channels in the sub-array, $T_{0\_REC.SLAPAR}$ is the average time to failure of the transmitting sub-array,

$$m_{RAD.CHAN.}=G_0C_2+1. \quad (15)$$

Definition 5. *A decrease in the total number of operable receiving modules, S(t), per one receiving module below the permissible value equal to $S_0(1-C_1)$ is considered to be a failure of the receiving APAA.*

Then the number of operable receiving modules at the moment of failure of the receiving APAA ($t=T_{0\_APAR}$) is calculated as follows:

$$S\left(T_{0\_APAR}\right)=S_0\left(1-C_1-\frac{1}{S_0}\right)=S_0-m_{REC.SLAPAR}, \quad (16)$$

where $m_{REC.SLAPAR}$ is the permissible number of failures of the receiving sub-arrays (the receiving modules and the secondary power supply modules) in the receiving APAA:

$$m_{REC.SLAPAR}=S_0C_1+1. \quad (17)$$

Definition 6. *A decrease in the total number of operable sub-arrays, $S_{RAD.}(t)$, per one sub-array below the permissible value equal to $S_0(1-C_2)$ is considered to be a failure of the transmitting APAA.*

Then the number of operable sub-arrays at the moment of failure of the transmitting APAA ($t=T_{0\_RAD.APAR}$) is calculated as follows:

$$S\left(T_{0\_APAR}\right)=S_0\left(1-C_2-\frac{1}{S_0}\right)=S_0-m_{RAD.SLAPAR}, \quad (18)$$

where $m_{RAD.SLAPAR}$ is the permissible number of failures of the radiating sub-arrays (secondary power supply modules) in the transmitting APAA:

$$m_{RAD.SLAPAR}=S_0C_2+1. \quad (19)$$

A transcendental equation is derived from formulas (8), (12), (13). Its solution gives the value of the mean time to failure of the APAA receiving sub-array, $T_{0\_REC.SLAPAR}$:

$$P_{REC.CHAN.}(T_{0\_REC.SLAPAR})=1-C_1-\frac{1}{G_0}. \quad (20)$$

A transcendental equation is derived from formulas (10), (14), (15). Its solution gives the value of the mean time to failure of the transmitting APAA sub-array, $T_{0\_RAD.SLAPAR}$:

$$P_{RAD.CHAN.}(T_{0\_RAD.SLAPAR})=1-C_2-\frac{1}{G_0}. \quad (21)$$

A transcendental equation is derived from formulas (9), (16), (17). Its solution gives the value of the mean time to failure of the receiving APAA, $T_{0\_REC.APAR}$:

$$P_{REC.MOD.}(t=T_{0\_REC.APAR})P_{SPS}(t=T_{0\_REC.APAR})\times$$
$$\times P_{REC.SLAPAR}(t=T_{0\_REC.APAR})=1-C_1-\frac{1}{S_0}. \quad (22)$$

A transcendental equation is derived from formulas (11), (18), (19). Its solution gives the value of the mean time to failure of the transmitting APAA, $T_{0\_RAD.APAR}$:

$$P_{SPS}(t=T_{0\_RAD.APAR})P_{RAD.SLAPAR}(t=T_{0\_RAD.APAR})=$$
$$=1-C_2-\frac{1}{S_0}. \quad (23)$$

Using the formula for binomial distribution [13], the following is determined:

– probability of failure-free operation of the receiving sub-array according to the formula:

$$P_{RES.SLAPAR.}(t)=P_{REC.MOD.}(t)P_{SPS}(t)\times$$
$$\times\sum_{i=0}^{m_{REC.CHAN.}}C_{G_0}^{i}[P_{REC.CHAN.}(t)]^{G_0-i}[Q_{REC.CHAN.}(t)]^{i}, \quad (24)$$

– probability of failure-free operation of the transmitting sub-array according to the formula:

$$P_{RAD.SLAPAR.}(t)=P_{SPS}(t)\times$$
$$\times\sum_{i=0}^{m_{RAD.CHAN.}}C_{G_0}^{i}[P_{RAD.CHAN.}(t)]^{G_0-i}[Q_{RAD.CHAN.}(t)]^{i}, \quad (25)$$

– the probability of failure-free operation of the receiving APAA according to the formula:

$$P_{REC.\ PAR}(t)=$$
$$=\sum_{i=0}^{m_{REC.SLAPAR}}C_{S_0}^{i}[P_{RES.SLAPAR}(t)]^{S_0-i}[Q_{REC.SLAPAR}(t)]^{i}, \quad (26)$$

– the probability of failure-free operation of the transmitting APAA according to the formula:

$$P_{RAD.\ PAR}(t)=$$
$$=\sum_{i=0}^{m_{RAD.SLAPAR}}C_{S_0}^{i}[P_{RAD.SLAPAR}(t)]^{S_0-i}[Q_{RAD.SLAPAR}(t)]^{i}. \quad (27)$$

Taking derivative

$$f(t)=-\frac{dP(t)}{dt}$$

from the probability of failure-free operation (formulas (24)–(27)), it is possible to determine density of distribution of the time between failures for the sub-arrays and the APAA as a whole. The most informative indicator of reliability of sub-arrays and the APAA as a whole is the failure rate which is defined as the quotient from dividing the probability density of the operating time to failure by the probability of failure-free operation:

$$\Lambda(t)=\frac{f(t)}{P(t)}. \quad (28)$$

The average resource and the gamma-percentage resource of the receiving and transmitting sub-array, the receiving and transmitting APAA are the most important indicators of the APAA reliability indices. The gamma-percentage resources of the sub-array and the APAA are calculated approximately by solving transcendental equations (24)–(27) against the probability of gamma. The average resource of the APAA (for an unattended antenna array) corresponds to the average time to failure.

Theorem. If distribution of failures of radiating channels of the APAA is characterized by an exponential distribution (only sudden failures are taken into consideration), that is:

$$P_{RAD.CHAN.}(t)=\exp(-\lambda_{RAD.CHAN.}t), \quad (29)$$

then the mean time to failure of the transmitting sub-array of the APAA is determined from the expression:

$$T_{0\_SLAPAR}=\frac{\ln\left(\frac{1}{1-C_2-\frac{1}{G_0}}\right)}{\lambda_{RAD.CHAN.}}. \quad (30)$$

Proof. A module of a multifunctional RS APAA with a two-level structure is formed on the basis of S_0 antenna sub-arrays with each of the sub-arrays including G_0 emitting transceiver channels.

Failure of the transmitting sub-array of the APAA (Definition 3) is understood as a decrease in the number of operable radiating channels below the permissible level calculated as follows:

$$G\left(T_{0\_RAD.SLAPAR}\right)=G_0\left(1-C_2-\frac{1}{G_0}\right)=G_0-m_{RAD.CHAN.}.$$

It is known that the time point of failure of the APAA sub-array corresponds to the time to failure of this antenna sub-array, that is, $t_{failure\,SLAPAR}$. Then the average value of time points of failure of the APAA sub-array (mathematical expectation) will correspond to the mean time to failure of the APAA sub-array:

$$M(t_{failure\_SLAPAR})=T_{0\_RAD.SLAPAR}.$$

The number of operable radiating channels in the transmitting sub-array at the time point of failure is calculated by the formula (21):

$$P_{RAD.CHAN.}(T_{0\_RAD.APAR})=1-C_2-\frac{1}{G_0}.$$

Substitution of formula (29) into equation (21) gives equation (31) which after logarithmizing the both parts is converted into formula (30) for determining the mean time to failure of the APAA:

$$\exp(-\lambda_{RAD.CHAN.}T_{0\_RAD.CHAN.})=1-C_2-\frac{1}{G_0}. \quad (31)$$

The theorem is proved.

7. The study of reliability indices of the promising two-level structure of the RS APAA at a joint manifestation of sudden and gradual failures of the radiating channels

In the course of designing (when performing a refined calculation of reliability of the RS APAA) and during operation, it is necessary to consider both catastrophic (sudden) failures and parametric (gradual) failures of SHF channels (modules). To take into consideration gradual failures of electronic and radio elements, it is advisable to use a diffusional non-monotonic distribution (DND) [19, 20] when calculating reliability of the APAA modules. When using the DND, the operational failure rates of the elements are considered to be time-varying statistical characteristics depending on external and internal influencing factors such as ambient temperature, electrical load, etc.

The average time to failure of the element for the DND, T_{0_MOD}, is determined by solution of the transcendental equation:

$$\lambda_{MOD\_DNR}(t_{M.O.T.})=$$

$$=\frac{\frac{\sqrt{T_{0\_MOD}}}{t_{M.O.T.}\sqrt{2\pi t_{M.O.T.}}}EXP\left[-\frac{\left(t_{M.O.T.}-T_{0\_MOD}\right)^2}{2t_{M.O.T.}T_{0\_MOD}}\right]}{\left[\Phi\left(\frac{T_{0\_MOD}-t_{M.O.T.}}{\sqrt{t_{M.O.T.}T_{0\_MOD}}}\right)-EXP(2)\Phi\left(-\frac{T_{0\_MOD}+t_{M.O.T.}}{\sqrt{t_{M.O.T.}T_{0\_MOD}}}\right)\right]}. \quad (32)$$

The element failure rate in formula (25) is understood as the operational rate of complete failures of elements determined from reliability of electric and radio electronic elements [22] for the time point corresponding to the minimum operating time of an element, $t_{M.O.T.}$:

$$\lambda_{SUD.FAIL.MOD.}=\lambda_{MOD.}(t_{M.O.T.}). \quad (33)$$

Probability of failure-free operation of the elements of channels (modules) of the APAA for DND:

$$P_{MOD.}(t)=\Phi\left(\frac{T_{0\_MOD.}-t}{\sqrt{T_{0\_MOD.}t}}\right)-\exp(2)\Phi\left(-\frac{T_{0\_MOD.}+t}{\sqrt{T_{0\_MOD.}t}}\right). \quad (34)$$

To calculate the reliability indices of the elements of channels (modules) of the APAA taking into consideration sudden and gradual failures, it is proposed to use the composition of exponential (ED) and diffusion non-monotonic (DND) distributions of failures [20]. In this case, the complete failure rate of the radiating channel (module), $\lambda_{MOD.}(t_{M.O.T})$, equals to the sum of rates of sudden failures (ER), $\lambda_{MOD.ER}$, and gradual failures (DND), $\lambda_{MOD.DNR(tM.O.T)}$. The channel (module) failure rate is calculated for the point in time corresponding to the minimum channel (module) operation time:

$$\lambda_{MOD.}(t_{M.O.T.})=\alpha_{ER}\lambda_{MOD.}(t_{M.O.T.})+\alpha_{DNR}\lambda_{MOD.}(t_{M.O.T.}); \quad (35)$$

$$\lambda_{MOD.}(t_{M.O.T.})=\lambda_{MOD.ER}+\lambda_{MOD.DNR}(t_{M.O.T.}); \quad (36)$$

$$\alpha_{ER}+\alpha_{DNR}=1; \quad (37)$$

$$\alpha_{ER}=\frac{\lambda_{MOD\_ER}}{\lambda_{MOD}(t_{M.O.T.})}; \quad (38)$$

$$\alpha_{DNR}=\frac{\lambda_{MOD\_DNR}(t_{M.O.T.})}{\lambda_{MOD}(t_{M.O.T.})}. \quad (39)$$

The probability of failure-free operation of the channel (module) elements of the APAA when using the composition of distributions is determined from formula:

$$P_{MOD.ER\times DNR}(t)=P_{MOD.ER}(t)P_{MOD.DNR}(t), \quad (40)$$

$$P_{MOD\_ER*DNR}(t)=EXP\left(-\frac{t}{T_{0\_MOD\_ER}}\right)\times$$
$$\times\left\{\Phi\left[\frac{T_{0\_MOD\_DNR}-t}{\sqrt{T_{0\_MOD\_DNR}t}}\right]-EXP(2)\Phi\left[-\frac{T_{0\_MOD\_DNR}+t}{\sqrt{T_{0\_MOD\_DNR}t}}\right]\right\}. \quad (41)$$

Formulas (36)–(43) make it possible to calculate reliability indices of the APAA taking into consideration sudden and gradual failures.

The authors have developed a universal program in EXCEL language for calculation of reliability indices of a promising two-level APAA at an exponential and diffusional non-monotonic distribution of the element failures.

Several dozens of graphs were constructed and analyzed for the mean time to failure, probability of failure-free operation, density of distribution of time to failure and failure rates of radiating channels, receiving modules, transmitting and receiving sub-arrays and the APAA as a whole at various distributions of sudden and gradual element failures. When analyzing the graphs for the probability of failure-free operation of sub-arrays and the APAA as a whole, it was determined that all of them are convex curves with values close to 1.00 at the antenna array operating time from 0 to $0.85T_0$. At the array operating time equal to the mean time to failure, T_0, the value of probability of the failure-free operation of the APAA $P(T_0)$=0.44–0.45.

When analyzing the graphs of density of distribution of the time to failure of the sub-array and the APAA as a whole, it was found that all distributions are unimodal.

When analyzing the graphs of failure rates of the sub-arrays and the APAA as a whole, it was established that the rate values slightly increased in the array operating time from 0 to $0.85T_0$ and then, as the operating time increased they rapidly increased tending to infinity. It is clear from analysis of the graphs that the function of the the APAA failure rate belongs to increasing functions of intensity and distribution of the APAA failures is close to the normal distribution.

When analyzing graphs of the average time to failure (T_0) of sub-arrays and the APAA as a whole, it was noted that the smallest T_0 value was observed for the case of sudden element failures, the highest T_0 value was observed for the case of gradual element failures, etc.

Example 1

As an illustrative example, calculation of the average time to failure of a promising two-level APAA of a multifunction RS (Fig. 1–3) was considered with the following parameters:

– S_0=100 is the number of sub-arrays in the APAA;

– G_0=64 is the number of radiating channels in the sub-array;

– k=16 is the number of antenna transceiver modules (ATM) in the sub-array;

– d=4 is the number of and transceiver channels in the ATM;

– $S_0\times k$=1600 is the total number of ATM in the APAA;

– $S_0\times G_0$=6400 is the total number of radiating (transceiver) channels;

– $C_{RED.TRANS.}=C_{RED.REC.}=C_{RED.}$=0.10 are coefficients of redundancy of the transmitting and receiving APAA: $\lambda_{RAD.CHAN.}$, $\lambda_{REC.MOD.}$, λ_{SPS}. are the failure rates of the radiating channel, the receiving module and the secondary power supply modules, respectively.

In case of equality of failure rates of the radiating channels, receiving modules and secondary power supply modules, the average time to failure of the APAA as a whole, $T_{0\_APAR}=T_{0A}$ was determined from solution to transcendental equation:

$$P_{MOD}(T_{0A})^2P_{SLAPAR}(T_{0A})=1-C_2, \quad (42)$$

where

$$P_{SLAPAR}(t)=$$
$$=\sum_{i=0}^{m_{RAD.CHAN.}}C^i_{G_0}[P_{RAD.CHAN.}(t)]^{G_0-i}[1-P_{RAD.CHAN.}(t)]^i.$$

Fig. 4 shows graphs of dependence of the average time to failure of the promising two-level APAA on the reliability indices of radiating channels and modules of the antenna array (according to the initial data of Example 1) that were built using formulas (25), (36)–(42).

It is assumed that all failure rates (of radiating channels, receiving modules and secondary power supply modules) are equal to each other ($\lambda_{RAD.CHAN.}=\lambda_{REC.MOD.}=\lambda_{SPS}$).

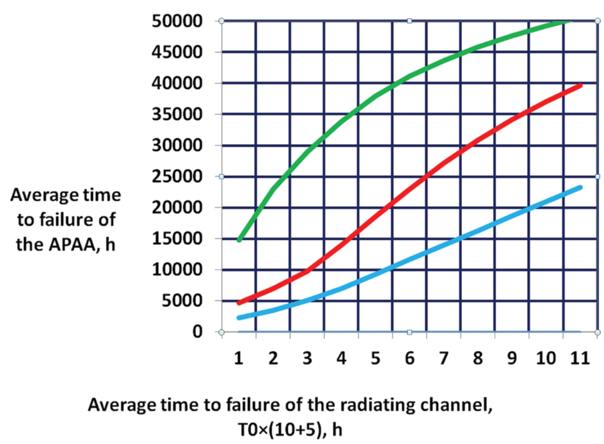

Fig. 4. Graphs of dependence of the average time to failure of a two-level antenna array on the average time to failure of the radiating channel: sudden failures (the blue curve); gradual failures (the green curve); sudden and gradual failures (the red curve)

The rates of sudden and gradual failures of the channel (module) were determined based on the rate of complete channel (module) failures for the point in time corresponding to the minimum channel (module) operating time, $t=t_{M.O.T}$=40,000 h:

$$\lambda_{SUD.FAIL.}=\lambda_{GRAD.FAIL.}(t=t_{n.m.})=\frac{\lambda_{COMP.FAIL.}(t=t_{M.O.T.})}{2}, \quad (45)$$

where $\lambda_{COMP.FAIL.}$ is the rate of complete failure of the channel (module).

It is clear from the nomogram in Fig 4 that with an increase in the average time to failure of channels (modules) from 100 thousand hours to 1 million hours, the average time to failure of the APAA increases:

– from 2.326 h to 23.724 h at exponential distribution of the module failures;

– from 14.794 h to 50.631 h at composition of the exponential and diffusion non-monotonic distributions of module failures;

– from 4.654 h to 39.610 h at diffusional non-monotonic distribution of module failures.

Estimates of the average time to the APAA failure obtained at the joint manifestation of sudden and gradual failures (the green curve in Fig. 4) will be most useful for practice.

8. Discussion of the results obtained in development and study of the generalized probabilistic-physical model of reliability of the two-level APAA of the multifunctional RS

The paper presents construction of a generalized probabilistic-physical model of reliability of a two-level APAA (several thousand radiating modules) of a modern multifunctional RS.

Physical model of the APAA reliability was formalized by a system of equations describing deviation of the key parameters of the antenna array beyond the permissible limits. At the same time, boundary (permissible) values of the number of failed radiating and receiving modules providing the minimum permissible values of the key parameters of the antenna array are found.

Construction of a probabilistic (mathematical) model of reliability of the APAA was provided by construction of a two-level block-diagram of the antenna array reliability, determination of coefficients of redundancy of the receiving and transmitting APAA and construction of analytical expressions for determining indices of reliability of the receiving and transmitting sub-arrays and the receiving and transmitting APAA. The proposed generalized model of the APAA reliability is approximate. Accuracy of the obtained estimates in the generalized model of the APAA reliability was determined by accuracy of estimation of key parameters of the amplitude-phase distribution of the antenna array in statistical modeling of failures of the radiating and receiving modules. More accurate estimates of the APAA reliability can be obtained using methods of the statistical theory of antennas and statistical modeling of reliability.

9. Conclusions

1. The APAA has been defied as an isotropic hierarchical system and a formula has been derived for determining the average number of operable radiating channels in the multi-level APAA structure.

2. Main parameters of the APAA were presented and definitions of failure of the radiating element and the antenna array as a whole were given. Key parameters of the APAA were chosen: radiation power, gain in transmission and the level of near side lobes. This has made it possible to formulate generalized criteria of failure of the APAA operating in the modes of transmission and reception as well as determine the permissible number of failures of radiating channels and receiving modules.

3. Based on the key parameters and the generalized failure criteria, a system of equations describing permissible deviation of the key parameters of the antenna array was formed. This system of equations characterizes physical model of the APAA reliability.

The applied models of failure of the antenna array elements were described by an exponential failure distribution (the probabilistic model) for sudden element failures and a non-monotonic diffusion model (the probabilistic-physical model) for gradual element failures. A composition of the exponential and diffusional non-monotonic distribution was also used at the joint manifestation of sudden and gradual failures of elements.

Probabilistic (mathematical) model of the APAA reliability is based on the use of the block-diagram of reliability of a two-level antenna array and the definitions (criteria) of failures of the receiving and transmitting antenna arrays.

The combined use of a physical model of the APAA reliability, probabilistic and probabilistic-physical models of reliability of the antenna array elements and a probabilistic model of reliability of the APAA block-diagram has made it possible to construct a generalized probabilistic-physical model of reliability of a two-level APAA of a multifunctional RS. The proposed generalized model is approximate. In this case, errors of the estimates obtained in the generalized reliability model are characterized by accuracy of estimates of the key parameters of the amplitude-phase distribution of the antenna array.

Definitions of failures of the receiving and transmitting sub-arrays as well as the APAA as a whole depending on the number of operable radiating channels (the receiving modules) were given. Proceeding from the definitions of failure, analytical expressions were derived for probability of failure-free operation, density of probability of the time to failure, failure rate and gamma-percentage resource for the receiving and transmitting sub-arrays, the receiving and transmitting APAA.

4. Features of non-monotonic distribution of diffusion were considered for description of gradual failures of elements, channels and the APAA modules. Composition of exponential and diffusional non-monotonic distributions was also considered for the case of joint manifestation of sudden and gradual failures of elements. The results of analysis of behavior of the APAA reliability indices depending on the operating time were presented: average time to failure, probability of failure-free operation, time-to-failure distribution and failure rate. It can be seen from the analysis results that the function of the APAA failure rate belongs to the increasing functions of rate and distribution of failures of the APAA is close to the normal distribution.

An illustrative example of calculating the average time to failure of the promising two-level APAA of the multifunction RS with equal failure rates of radiating channels, receiving modules and secondary power supply modules was presented. Behavior of the mean time to failure of the APAA at sudden and gradual (degrading) failures and at a mixture of sudden and gradual failures of elements, channels and modules of the antenna array was considered. The analysis results were presented in the graphs of dependence of the average time to failure of the APAA on the average time to failure of the radiating channel (module). The nature of change of the graphs of average time to failure of the APAA in the graphs corresponds to the physics of processes of degradation and wear of passive elements and SHF transistors.

The formulas obtained in Section 7 for calculation of the mean time to failure, the probability of failure-free operation and the rates of failure of the receiving and transmitting sub-arrays and the antenna array as a whole can be used for practical purposes:

– for drawing up schedules of the APAA maintenance;

– for scheduling medium and major repairs of the multifunctional RS;

– for determining the required number of spare elements, assemblies, radiating channels and modules for maintenance and repair of the APAA.

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