Розроблено алгоритм технічного обслуговування активної фазований антенний решітки з контролем показників надійності в процесі використання. Запропоновано формули для статистичної оцінки показників надійності і довговічності антенний решітки в процесі експлуатації. Представлений алгоритм індивідуального прогнозування показників надійності і ресурсу, часу проведення і обсягу коригувальних замін модулів антенний решітки. Рішення про коректувальний заміні модулів приймається після зниження ймовірності безвідмовної роботи АФАР до рівня 1–γ

Ключеві слова: активна фазована антенна решітка, прогнозування показників надійності , дифузійний немонотонний розподіл

Разработан алгоритм технического обслуживания активной фазированной антенной решетки с контролем показателей надежности в процессе использования. Предложены формулы для статистической оценки показателей надежности и долговечности активной фазированной антенной решетки в процессе эксплуатации. Представлен алгоритм индивидуального прогнозирования показателей надежности и ресурса, времени проведения и объема корректирующих замен модулей антенной решетки. Решение о корректирующей замене модулей принимается после снижения вероятности безотказной работы АФАР до уровня 1–γ

Ключевые слова: активная фазированная антенная решетка, прогнозирование показателей надежности, диффузионное немонотонное распределение

UDC 681.3 (07)
DOI: 10.15587/1729-4061.2018.123430

DEVELOPMENT OF THE ALGORITHM OF RELIABILITY-CENTERED MAINTENANCE OF PHASED ARRAY ANTENNAS

V. Kostanovsky
PhD, Head of Research Department*
E-mail: valerijj-Kostanovskijj@rambler.ru
O. Kozachuk
Head of Research Sector*
E-mail: kozaichyk@gmail.com
I. Rusniak
PhD, Chief Researcher**
E-mail: i_rusnyak@ukr.net
*Research department of reliability and standardization***
Research Department of Optical and Optoelectronic Devices and Systems*
***State Enterprise Research Institut «Kvant»
Fedorova str., 4, Kyiv, Ukraine, 03150

1. Introduction

Definition of tasks and strategies of condition-based maintenance of technical objects has been presented in [1–14]. The theory and practice of condition-based maintenance were most widely elaborated and implemented in the development, manufacture and operation of aviation equipment [1–3].

The strategy of maintenance of technical objects is a set of adopted principles, rules and control actions determining the integrated development of operational properties of the design of facilities, organization methods and production and technical base of maintenance and repair.

There are the following strategies:

– time-based maintenance, in which the list and frequency of operations are determined by the value of the total product time since placed in service or since the overhaul;

– condition-based maintenance, in which the list and frequency of operations are determined by the actual technical condition of the product at the time of the start of maintenance;

The main characteristic of the maintenance strategies is the nature of information on reliability and technical condition, which is used when assigning the frequency and volume of routine maintenance. This information can be divided:

– by the time of receipt and use, into a priori and a posteriori;

– by sources of receipt, into information on the set of objects and on a particular object.

In this case, experience refers to the operation of an object. Combinations of these types of information form four maintenance strategies (Table 1).

Table 1

Maintenance strategies

Nature of information	A priori	A posteriori
On the set of objects	Time-based	Reliability-centered
On a particular object	Time-based for a particular object	Condition-based

Depending on the available opportunities to determine the ultimate limit state of products in the process of operation and on the adopted criterion for establishing the terms of their replacement, the following strategies of operation (use) are distinguished: until the end of service life, until failure, until the pre-failure condition. The maintenance and repair strategies, of course, are associated with the strategies of operation (use) of products (Table 2). For each of the operation strategies, it is possible to choose certain most effective maintenance strategies (marked with +).

Table 2

Interrelation of operation and maintenance strategies

Maintenance strategy	Operation (use) strategy		
	until the end of service life	until the pre-failure condition	until failure
Maintenance			
Time-based	+	–	+
Condition-based	+ –	+	–
Reliability-centered	–	–	+

From Table 2 it follows that for the operation strategy of products until the end of service life, the time-based strategy will be naturally the most effective maintenance strategy.

The specific features of the reliability-centered maintenance strategy include the following. Each of the products under this strategy is operated (used) until failure. Overhaul life is not established for these products. Maintenance of each specific product consists in performing the necessary amount of work on adjustment, calibration, detection of failures and malfunctions and their elimination. For structurally complex products, age replacement of some of their parts may be advisable, if it is possible without the need for disassembling the product under stationary conditions.

With respect to the entire set of similar products, reliability level control is performed. In cases where the actual level of reliability of a particular type of products is below the standard level, a thorough analysis of reasons for deviation is carried out and measures are taken to increase it.

The reliability-centered maintenance strategy is most widely used for products of functional aircraft systems, in particular, air conditioning and pressure control systems, anti-icing, hydraulic and fuel systems, power unit assemblies.

Reliability level control of the set of similar products is carried out by statistical methods. This kind of control covers, as a rule, the majority of units and assemblies, regardless of the maintenance and repair strategy applied to them. However, only for the reliability-centered maintenance strategy, this type of control is the principal mechanism for controlling the reliability of products.

With this maintenance strategy, the criterion for the technical condition of the set of similar aircraft system products is the reliability level expressed by the corresponding index. Such an index should carry a maximum of information on the technical condition of products, be convenient for carrying out operational comparative analysis, and also be critical to changes in the process of aircraft fleet operation (changes in operating conditions, level of recovery of functional systems). The following indexes most fully meet these requirements in the operating conditions of AE: the failure rate and the failure number of products per 1,000 flight hours.

The condition-based maintenance strategy is a set of rules for determining conditions and regulations for diagnosing products and making decisions on the need for their maintenance, replacement or repair based on information on the actual technical condition. With this maintenance strategy, aircraft products and systems are operated (used) until the pre-failure condition.

To identify the pre-failure condition of products, the principle of preemptive tolerances for diagnostic parameters can be used. Herewith, the preemptive tolerance means the set of parameter values between the limiting and pre-failure levels of the parameter. Out-of-tolerance condition means failure. Achievement of the pre-failure level means the need for scheduled maintenance or replacement of products.

2. Literature review and problem statement

In recent years, researchers have continued to develop and study models of optimum maintenance for various types of civil and military equipment [15–26]. In [15], the model of optimum condition-based maintenance of radio-electronic devices has been proposed. In [16], the introduction of the principle of preventive maintenance of aircrafts has been shown. In [17], various strategies of equipment maintenance have been considered: heuristic and based on the application of mathematical models. In [17], the problem of finding a rational maintenance strategy for complex systems, the elements of which function in different conditions, has been considered. The mathematical model of the process of adaptive condition-based maintenance of complex electronic equipment has been considered in [18]. The paper [19] deals with the operation of the atomic fleet, according to the actual technical condition of the ships. In [20], models of operational reliability of aircrafts for maintenance planning in the process of operation have been considered. The paper [21] presents the formalized mathematical model of the process of adaptive condition-based maintenance that is used in simulation. The model of maintenance optimization for one type of three-dimensional array antennas has been considered in [22]. In [23], the application of the method of group accounting of arguments for forecasting the longevity of radio-electronic systems in the implementation of the condition-based maintenance strategy has been considered. In [24], the model for calculating the indexes of the residual life of radio-electronic devices by the parameters of technical condition has been presented. In [25], the substantiation of the possibility of application of optimum strategies of maintenance and repair of complex technical systems has been presented.

In [6], the model of optimum maintenance of the PAA has been considered in detail, formulas for calculating the utilization factor and specific operating costs in the exponential distribution of time between failures of the PAA channels have been presented. Also, formulas for determining the optimization gain have been given. Illustrative examples of optimization of maintenance of two PAA structures composed of 256 channels, 12 standby channels for the first structure, and 25 channels for the second structure have been shown. The values of the optimization gains have been calculated. When optimizing the utilization factor of the PAA, the gain ranges from 13 % to 17 %, while in optimizing the specific operating costs it ranges from 86 % to 98 %.

The model of optimization of maintenance of a group of phased array antennas of radars in the diffusion nonmonotonic and exponential distributions of time between failures of the array modules has been investigated in [26]. The review of the above works showed [15–26] that the researchers from the USA, China, Ukraine and Russia pose and partially solve the theoretical problems of optimum adaptive maintenance and condition-based maintenance of various devices. However, materials on the condition-based maintenance and repair of modern radio-engineering systems have practically not been given. Also, there are no publications on the study of indexes of reliability and maintenance of marine and ground-based APAR such as Aegis, Patriot, Meads, THAAD. This is due to the specifics of the application of military APAR and confidentiality of information about these systems.

From the results of the review of early works on maintenance [1–14], it follows that a number of authors consider models of optimum maintenance of devices in a traditional statement, in which the utilization factor or specific operating costs are optimized and the optimization gains are determined. This does not take into account the use of information on device failures received from the monitoring and diagnostic system during operation. Also, device failures during operation are expected.

In later works, the authors of [15–27, 29–31] propose to determine the parameters of optimum maintenance taking into account the specification of reliability indexes of devices based on the results of operation. In doing so, they are mainly limited to the general formulation of the problem and suggestions to use simulation. The models of optimum maintenance of non-redundant devices considered in the review cannot be used as maintenance models for quasi-redundant structures with high redundancy, including the APAR.

Table 3

Interrelation of operation and maintenance strategies of the APAA

Maintenance and repair strategy	Operation (use) strategy	
	until the end of service life	until the pre-failure condition
Maintenance		
Time-based	+	–
Condition-based	+ –	+
Reliability-centered	+	+

The interrelation of operation and maintenance strategies of the APAA is presented in Table 3.

Time-based or condition-based maintenance strategies of the APAA

Each of the products can be operated (used) until the end of service life or until the pre-failure condition. The monitored reliability index is the gamma-percentile life. At the same time, there are two possible maintenance strategies of the APAA: time-based or reliability-centered.

Under the time-based maintenance strategy of the APAA, at the stage of development and testing of the prototype, the operating time of the APAA until the end of the gamma-percentile life (for a certain level of reliability of the array antenna modules) or the allowed failure number of the modules, which are reflected in the operational documentation are determined. After the end of the gamma-percentile life or failure of the allowed number of the modules, the decision is made on the corrective replacement of the modules of the distributed array structure. After the corrective replacement of the modules, the APAA is updated (the probability of failure-free operation rises to a value close to 1,000).

Under the reliability-centered maintenance strategy, after each failure of the module of the distributed array structure, the reliability indexes of the modules are refined (redefined), the time of the next module failure, the reliability and life indexes of the APAA and maintenance indexes such as the time and number of corrective replacements of the array modules are predicted. After the controlled probability of APAA failure-free operation decreases to a value of $1-\gamma$ during operation, collection of statistics on module failures is terminated and a decision is made on the corrective replacement of the modules.

Further, the reliability and maintenance indexes of one of the possible implementations of the promising APAA of the multifunctional radar of the SAM system will be investigated. Functionally, the promising APAA includes 100 power supply modules (PSM) and 100 subarrays, each consisting of:

- subarray aperture with 80 emitters;
- 16 five-channel antenna transmit-receive modules (ATRM);
- one subarray transmit-receive module (STRM).

The APAA is divided into 100 subarrays with 80 channels each. In the reception mode, the total signals from 80 channels of each subarray are fed to the subarray modules, in which double frequency signal conversion to an intermediate frequency is performed. Power supply modules of the APAA provide antenna modules with supply voltage.

The ATRM installed in the APAA after the emitters perform amplification of microwave signals, calculate and create the required phase and amplitude distributions. In the transmit channels of the modules, amplification is generated by powerful transistor amplifiers, in the receive channels – by low-noise amplifiers. Phase distribution is created by microwave digitally controlled phase shifters for setting the beam in a given direction. Amplitude distribution in the reception mode is created by microwave digitally controlled attenuators.

The ATRM are the most numerous (1,600) and powerful transistor microwave modules of the APAA. Each antenna module includes:

- five transmit-receive channels (TRC);
- microstrip divider-adder of microwave signals;
- phase and amplitude distribution computer;
- hermetic case with hermetic inserts for connecting the emitters and microwave by the coaxial connector.

Each TRC includes a 6-bit controlled phase shifter, a preamplifier of transmit-receive channels, a low-noise amplifier, a power amplifier and a secondary power supply.

The STRM is designed to amplify the transmitting outgoing pulse and transmit it to the ATRM in the transmission mode. In the reception mode, the signal coming from the transmit-receive modules is amplified in the subarray module and transmitted to the intermediate range for further processing.

The built-in control and calibration system (BCCS) of the APAR provides [27]:

- assessment of the technical condition of various elements in the APAA channels and phase distribution computers;
- determination of the location and type of failures of elements and modules;
- evaluation of integrated characteristics and technical condition of the APAA as a whole (control of technical condition at the system level);

– monitoring of changes in the amplitude-phase distribution and parameters of elements in the APAA channels during operation, APAA calibration, calculation and transmission of corrections to the beam control system to correct the APAA parameters at the system level.

In terms of structure, the APAA is a distributed system composed of a very large number of microwave modules of limited reliability (from several hundred to several tens of thousands). At the same time, the failure of up to 10 % of the modules is allowed. The APAA reliability indexes are subject to strict requirements (one APAA failure per several thousand hours is allowed). From the theory of reliability, it is known that the probability of failure-free operation of the serviced system with high redundancy approaches unity if there are a sufficient number of spare elements in the SPTA set. That is, due to timely maintenance, it is possible to create a failure-free redundant system before the end of service life. It is also known that the APAA are provided with the automated control and calibration system.

Considering the above, it is promising to build an algorithm for the individual forecasting of reliability and maintenance indexes of the APAA (algorithm of reliability-centered maintenance of the APAA), based on statistical processing of the results of the failures of the APAA subarray modules by the monitoring and calibration system.

3. The aim and objectives of the study

The aim of the work is to develop and study the algorithm of reliability-centered maintenance of the APAA during operation. This will make it possible to predict the reliability indexes of each APAA and to determine in a timely manner the time points and the number of corrective replacements of the APAA modules.

To achieve the aim, the following objectives were set:

– selection of mathematical models of reliability of the antenna subarray modules and APAA as a whole, and selection of a method for processing statistical information on the failures of the antenna subarray modules in the process of operation;

– development of a methodology for determining reliability indexes for the APAA time-based maintenance strategy;

– development of the structure and the “body” of the algorithm for individual forecasting of reliability indexes and maintenance indexes of the APAA on the basis of statistical information on reliability indexes of the antenna modules;

– determination of the gain from the introduction of the APAA reliability-centered maintenance strategy in comparison with the time-based maintenance strategy;

– implementation and comparison of reliability-centered maintenance strategies and the time-based maintenance strategy on the example of calculating the maintenance indexes when operating the receive APAA.

4. General provisions of the APAR reliability-centered maintenance strategy

The APAA reliability-centered maintenance strategy is the strategy for determining the time and volumes of corrective replacements of the antenna array modules based on the results of individual forecasting of reliability indexes of the APAA.

During the normal operation, the radar control system:

– collects and processes statistical information on the failures of the antenna subarray modules;

– predicts the reliability level of the antenna subarray modules and the APAA as a whole;

– stores information on the time points of detection of failures of the antenna subarray modules;

– calculates individual forecast estimates of the actual level of probability of failure-free operation and the gamma-percentile life of a particular APAA;

– makes recommendations on the time and volume of corrective replacements (CR) of the failed antenna subarray modules.

After each series of failures of the modules of this type, point and interval estimates should be determined based on statistical information on the time points of failure detection in these modules:

– for reliability indexes of the modules of this type;

– for reliability and longevity indexes of the APAA as a whole;

– for time intervals between failures of the modules of this type;

– for the predicted time for the next failures of the modules of this type.

Based on the results of processing of the obtained data, the time points of a subsequent series of failures of the modules of this type are predicted and a decision is made on the need and time of corrective replacements of the modules of this type. In this case, the main condition for the need for corrective replacements of the modules of this type will be a predicted reduction in the probability of the APAA failure-free operation to a level below $1-\gamma$. That is, the corrective replacement of the modules of this type will be carried out only after the end of the gamma-percentile life Tγ by a specific APAA (Fig. 1). Fig. 1 shows the corrective replacement of the modules when the probability of APAA failure-free operation reaches the value of $P_{\text{APAA}}(T_\gamma)=0.95$.

5. Development and investigation of the reliability-centered maintenance algorithm of the APAA during operation

5. 1. Selection of mathematical models of reliability of the antenna subarray modules and APAA and the method of processing of statistical information on the failures of the antenna subarray modules during operation

When choosing the module failure model, the failure rate of the semiconductor antenna subarray modules of the APAA is defined as the sum of sudden and gradual failure rates [29, 30]:

$$\lambda_{tot.fail.\text{mod.}} = \lambda_{sud.fail.\text{mod.}} + \lambda_{gr.fail.\text{mod.}} \tag{1}$$

$$\lambda_{sud.fail.\text{mod.}} = C_1 \lambda_{tot.fail.\text{mod.}}, \lambda_{gr.fail.\text{mod.}} = C_2 \lambda_{tot.fail.\text{mod.}} \tag{2}$$

$$C_1 < 1.0; C_2 < 1.0; C_1 + C_2 = 1.0. \tag{3}$$

Then the probability of failure-free operation of the semiconductor antenna array modules is defined as the product of the probabilities of failure-free operation during sudden and gradual failures of the modules:

$$P_{\text{mod.}}(t)=P_{sud.fail.\text{mod.}}(t)\times P_{gr.fail.\text{mod.}}(t). \tag{4}$$

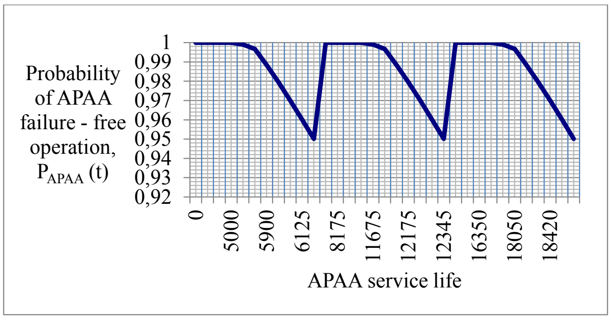

Fig. 1. Graph of the probability of failure-free operation of the serviced APAA, with control of the reliability index $P_{APAA}(t_{CR})=P_{APAA}(t_{\gamma})$

To characterize sudden failures of the semiconductor modules, exponential time distribution of failure-free operation is used:

$$P_{sud.fail.\text{mod.}}(t)=\exp(-\lambda_{sud.fail.\text{mod.}}t). \tag{5}$$

To characterize gradual failures of the semiconductor modules, the diffusion nonmonotonic (DN) time distribution [31] of failure-free operation is used:

$$P_{gr.fail.mod}(t)=1-\left[\Phi\left(\frac{t-\mu}{\nu\sqrt{t\mu}}\right)+\exp\left(\frac{2}{\nu^2}\right)\Phi\left(-\frac{t+\mu}{\nu\sqrt{t\mu}}\right)\right], \tag{6}$$

where μ is the mean time to gradual failure of the APAA semiconductor modules, v is the variation coefficient of the DN distribution.

In the formalization of the reliability model of the transmit APAA, the receive APAA and the system of secondary power modules (PM) of the APAA, the mathematical model of the APAA reliability, presented in [28, 29] is used:

$$P_C(t)=\sum_{i=0}^{n}C_N^i\left[P_0(t)\right]^{N-i}\left[1-P_0(t)\right]^i, \tag{7}$$

where $P_0(t)$ is the probability of failure-free operation of one module; C_N^i is the number of connections of N modules by i; $N=n+m$ is the total number of the modules in the array antenna; n is the number of principle modules; m is the number of standby modules.

Block diagrams of reliability of the promising APAA are shown in Fig. 2–6.

The probability of failure-free operation of the APAR is determined by the expression:

$$P_{APAA}(t)=P_{\text{RSV\_APAA}}(t)\times P_{\text{TRS\_APAA}}(t)\times P_{\text{SP\_APAA}}(t), \tag{8}$$

where $P_{\text{RCV\_APAA}}(t)$ is the probability of failure-free operation of the receive APAA (with the STRM system); $P_{\text{TRS\_APAA}}(t)$ is the probability of failure-free operation of the transmit APAA system (with the ATRM system); $P_{\text{SP\_APAA}}(t)$ is the probability of failure-free operation of the system of secondary power modules (PM) of the APAA.

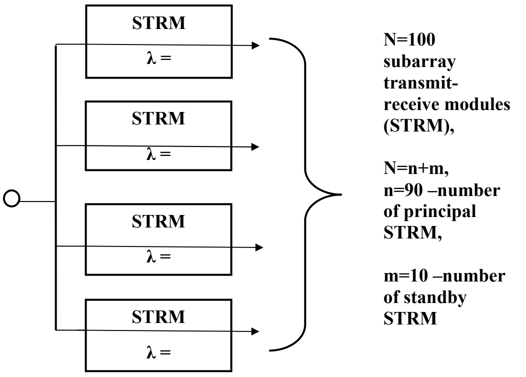

Fig. 2. Block diagram of reliability of the receive APAA (with the STRM system)

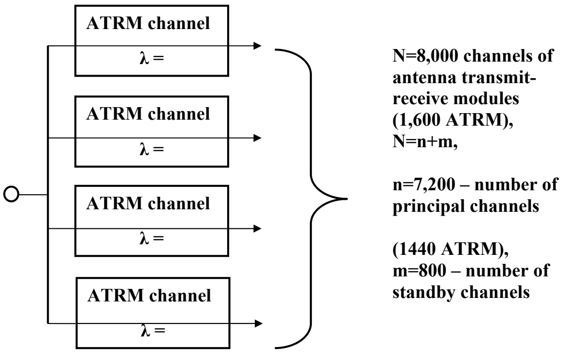

Fig. 3 Block diagram of reliability of the transmit APAA (with the STRM system)

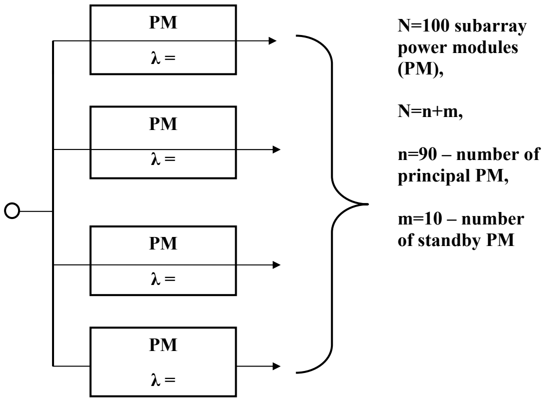

Fig. 4. Block diagram of reliability of a part of the APAA with the system of secondary power modules (PM)

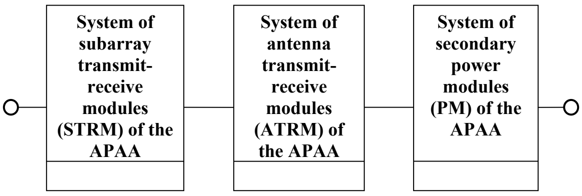

Fig. 5. Block diagram of reliability of the APAA of the multifunction radar

The mean time to failure (reliability index) of the transmit (receive) APAA is determined from the solution of the nonlinear equation [29]:

$$P_{\text{mod.}}(t=T_{0\_APAA})=1-\frac{m_0+1}{N_0}, \tag{9}$$

For the exponential distribution of time between failures of the phased array modules, the formula for the mean time to failure of the APAA has the form:

$$T_{0\_APAA}=T_{0\_\mathrm{mod.}}LN\left[1-\frac{m_0+1}{N_0}\right]^{-1}, \qquad (10)$$

where N_0 is the total number of similar modules in the APAA; m_0 is the number of quasi-redundant modules of this type (the allowable number of module failures) in the APAA.

The gamma-percentile life (longevity index) of the transmit (receive) APAA is determined from the solution of the following nonlinear equation:

$$\gamma=\sum_{i=0}^{N}C_N^i\left[P_0(T_{\gamma\_APAA})\right]^{N-i}\left[1-P_0(T_{\gamma\_APAA})\right]^i. \qquad (11)$$

For processing of statistical information on the failures of the APAA modules and determining the estimates of the sample mean, upper and lower confidence limits, the method of quantiles is used [31].

In this case, the analytical expression for determining the point (average) estimate of the mean time to failure of the APAA modules has the form:

$$\tilde{T}_{0\_\mathrm{mod}}=\frac{1}{m_0}\sum_{i=1}^{m_0}\frac{t_i}{x\left(i/N_0,\nu\right)}, \qquad (12)$$

where

$$x\left(i/N_0,\nu\right)=\frac{t_i}{T_{0\_\mathrm{mod.}\_i}}$$

is determined from the solution of the nonlinear equation:

$$1-\exp(-x)\left\{1-\left[\Phi\left(\frac{x-1}{\nu\sqrt{x}}\right)+\exp\left(\frac{2}{\nu^2}\right)\Phi\left(-\frac{x+1}{\nu\sqrt{x}}\right)\right]\right\}=q, \qquad (13)$$

for

$$q=\frac{i}{N_0}$$

and a given value of the variation coefficient – **ν**.

The formulas for determining the upper $\overline{T}_{0\_\mathrm{mod}}$ and lower $\underline{T}_{0\_\mathrm{mod.}}$ confidence limits of the mean time to failure of the APAA modules have the form:

$$\underline{T}_{0\_\mathrm{mod.}}=\tilde{T}_{0\_\mathrm{mod.}}\left[1+\frac{U_q^2}{2m_0}-\frac{U_q}{2\sqrt{m_0}}\sqrt{4+\frac{U_q^2}{m_0}}\right], \qquad (14)$$

$$\overline{T}_{0\_\mathrm{mod}}=\tilde{T}_{0\_\mathrm{mod}}\left[1+\frac{U_q^2}{2m_0}+\frac{U_q}{2\sqrt{m_0}}\sqrt{4+\frac{U_q^2}{m_0}}\right], \qquad (15)$$

where U_q is the quantile of the rated normal distribution, for q=0.90 we have U_q=1.282.

The forecasting of the moments of the implementation of corrective replacements of the APAA modules is performed by the formulas:

$$\tilde{\Delta}t_{\mathrm{ATRM}}(i)=(t_i-t_1)/i, \qquad (16)$$

$$\tilde{\Delta}t_{STRM}(j)=(t_j-t_1)/j, \qquad (17)$$

$$\tilde{\Delta}t_{PM}(l)=(t_l-t_1)/l, \qquad (18)$$

$$t_{\mathrm{ATRM}}(i+1)=t_i+\Delta t_{\mathrm{ATRM}}(i), \qquad (19)$$

$$t_{STRM}(j+1)=t_j+\Delta t_{STRM}(j), \qquad (20)$$

$$t_{PM}(l+1)=t_l+\Delta t_{PM}. \qquad (21)$$

Here t_1 is the value of the APAA sample running time before the start of operation at the facility (after preliminary and acceptance tests).

The number of the failed APAA modules, replaced with fault-free modules in the corrective replacement of $n_{\mathrm{ATRM}}(i)$, $n_{\mathrm{STRM}}(j)$, $n_{\mathrm{PM}}(l)$ is determined by the number of the failed modules, respectively: *i*, *j*, *l*.

5. 2. Development of a methodology for determining reliability indexes for the APAA time-based maintenance strategy

For the implementation of the APAA time-based maintenance strategy, the following indexes are determined:

– the probability of failure-free operation of the APAA modules according to formulas (1)–(6);

– the probability of failure-free operation of the APAA according to formulas (7), (8);

– the mean time to failure of the APAA from equation (9) or formula (10);

– the gamma-percentile life of the APAA from equation (11);

– the number of corrective replacements of the APAA modules to provide the gamma-percentile life as:

$$\tilde{n}_{1\_\mathrm{ATRM}}(i)=\tilde{T}_{\gamma\_\mathrm{APAA}}(t_i)\times n_{0\_\mathrm{ATRM}}/\tilde{T}_{0\_\mathrm{APAA}}(t_i). \qquad (22)$$

In this case, the initial data for the failure rates of electronic elements on which the APAA subarray modules are developed is information from reference books on reliability and results of accelerated tests.

5. 3. Development of the structure and the "body" of the algorithm of individual forecasting of reliability indexes and APAA maintenance indexes on the basis of statistical information on reliability indexes of the antenna modules

On the basis of the reliability-centered maintenance strategy of the APAR, the structure and the "body" of the algorithm of individual forecasting of APAA reliability indexes and maintenance indexes were developed.

This algorithm implements the following tasks:

– calculation of statistical estimates of the sample mean, upper and lower confidence limits of the mean time to failure of the antenna subarray modules;

– individual forecasting of APAA reliability indexes: the time of the next module failure; the probability of failure-free operation, the mean time to failure and the gamma-percentile life of the APAA as a whole;

– individual forecasting of APAA maintenance indexes: the time and volumes of corrective replacements of the antenna subarray modules during normal operation.

For the implementation of the mathematical model of condition-based maintenance, the algorithm is developed (Fig. 6).

In the algorithm (Fig. 6), formulas for sequential step-by-step calculation of statistical estimates of reliability indexes of the antenna subarray modules and the APAA as a whole are implemented. Also, formulas for calculating the time and the number of corrective replacements of the antenna subarray modules are implemented. The detailed description of the operations of the algorithm is presented in Table 4.

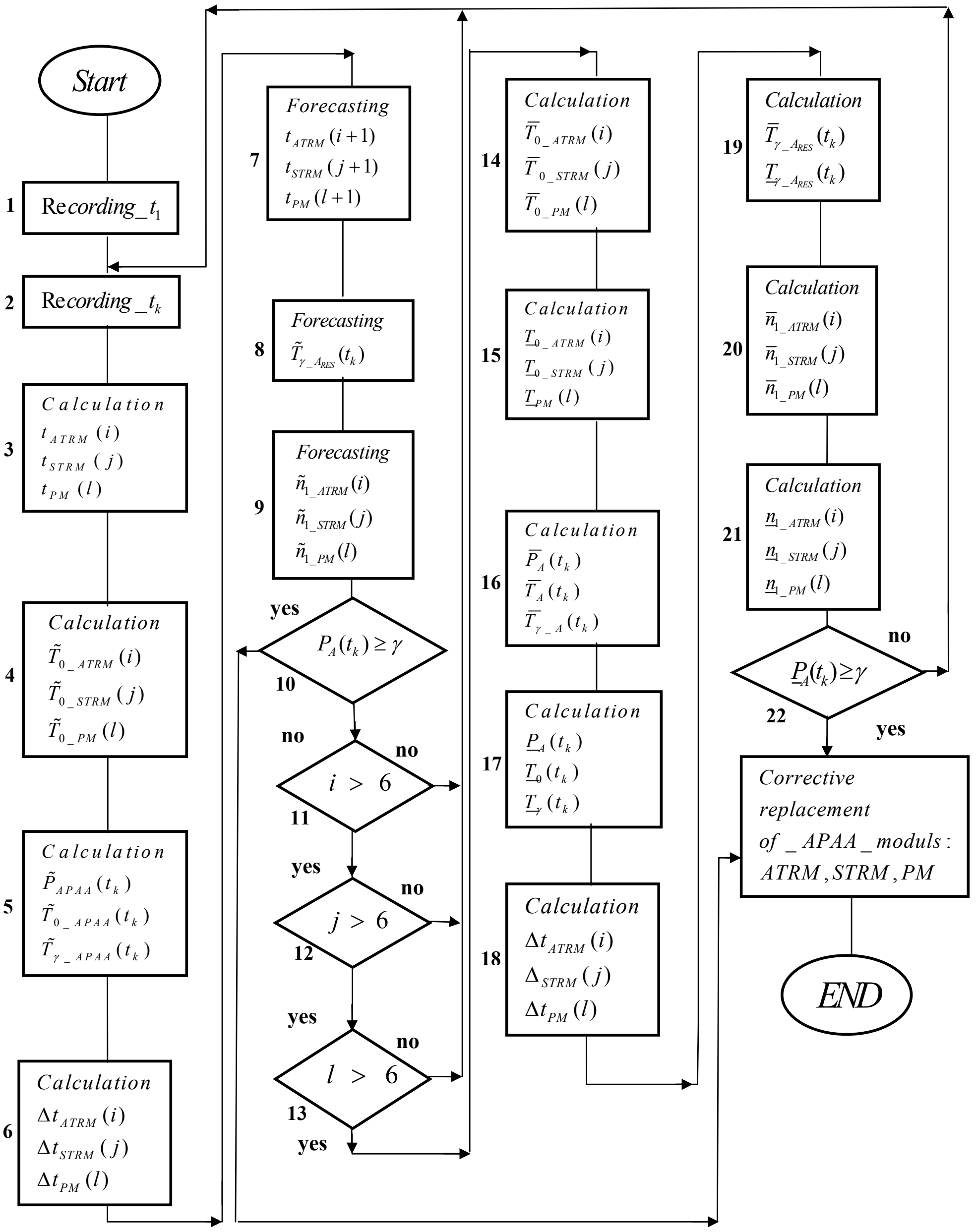

Fig. 6. APAR reliability-centered maintenance algorithm

Table 4

Characteristics of the processes presented in the APAR reliability-centered maintenance algorithm

Operation No.	Process name	Process characteristics	Models, formulas, sections
1	2	3	4
1	Recording of t_1	Recording of the moment of the first failure of the APAA module of any type by the radar AACS	k=1
2	Recording of t_k	Recording of the moment of the k-th failure of the APAA module of any type by the AACS	k=i+j+1
3	Calculation of $t_{\mathrm{ATRM}}(i)$, $t_{\mathrm{STRM}}(j)$, $t_{\mathrm{PM}}(l)$	Classification of failures by types of the APAA modules: ATRM, STRM, PM	k=i+j+1

Continuation of Table 4

1	2	3	4
4	Calculation of $T_{0\_\text{ATRM}}(i)$ $T_{0\_\text{STRM}}(j)$ $T_{0\_\text{PM}}(l)$	Determination of the estimate of the sample mean of reliability indexes of the APAA modules: ATRM, STRM, PM	Method of quantiles, see section 4.6
5	Calculation of $\tilde{P}_{\text{A}}(t_k)$ $\tilde{T}_{0\_\text{A}}(t_k)$ $\tilde{T}_{\gamma\_\text{A}}(t_k)$	Determination of the estimate of the sample mean of the probability of failure-free operation, the mean time to failure and the gamma-percentile life of the APAA	See sections 4.3, 4.4, 4.5
6	Calculation of $\tilde{\Delta}t_{\text{ATRM}}(i),\ \tilde{\Delta}t_{STRM}(i),$ $\tilde{\Delta}t_{PM}(l)$	Determination of the sample mean of time to failure of the APAA modules: ATRM, STRM, PM	$\tilde{\Delta}t_{\text{ATRM}}(i)=(t_i-t_1)/i,$ $\tilde{\Delta}t_{STRM}(j)=(t_j-t_1)/j,$ $\tilde{\Delta}t_{PM}(l)=(t_l-t_1)/l,$
7	Forecasting of $t_{\text{ATRM}}(i+1),$ $t_{STRM}(j+1),$ $t_{PM}(l+1)$	Forecasting of timepoints of subsequent failures of the APAA subarray modules: ATRM, STRM, PM	$t_{\text{ATRM}}(i+1)=t_i+\Delta t_{\text{ATRM}}(i),$ $t_{STRM}(j+1)=t_j+\Delta t_{STRM}(j),$ $t_{PM}(l+1)=t_l+\Delta t_{PM}$
8	Forecasting of $\tilde{T}_{\gamma\_RES\_A}(t_k)$	Forecasting of the sample mean of the residual gamma-percentile life of the APAA	$\tilde{T}_{\gamma\_RES\_A}(t_k)=\tilde{T}_{\gamma\_A}(t_k)-t_k$
9	Solution: comparison of $\tilde{P}_{\text{A}}(t_k)>\gamma$	Comparison of probabilities: γ with $\tilde{P}_A(t_k)$ – if $\tilde{P}_A(t_k)\leq\gamma,$ then the corrective replacement of the APAA modules is carried out (transition to process 24); – if $\tilde{P}_A(t_k)>\gamma,$ then collection of statistics on module failures during normal operation of the APAR is continued (transition to process 11)	- - -
10	Solution: comparison of *i*>6	Comparison of the failure number of the ATRM – *i* with number 6 (six): – if *i*≤6, then proceed to process 2; – if *i*>6, then proceed to process 14	- - -
11	Solution: comparison of *j*>6	Comparison of the failure number of the STRM – *j* with number 6 (six): – if *j*≤6, then proceed to process 2; – if *j*>6, then proceed to process 14	- - -
12	Solution: comparison of *l*>6	Comparison of the failure number of the PM – *l* with number 6 (six): – if *l*≤6, then proceed to process 2; – if *l*>6, then proceed to process 14	- - -
13	Calculation of: $\overline{T}_{0\_\text{ATRM}}(i),\ \overline{T}_{0\_\text{STRM}}(j),$ $\overline{T}_{0\_PM}(l)$	Calculation of the upper confidence limits of the mean time to failure of the APAA modules: ATRM, STRM, PM	Section 4.6, Formulas (1)–(4), (12)
14	Calculation of: $\underline{T}_{0\_\text{ATRM}}(i),\ \underline{T}_{0\_STRM}(j),$ $\underline{T}_{0\_PM}(l)$	Calculation of the lower confidence limits of the mean time to failure of the APAA subarray modules: ATRM, STRM, PM	Section 4.6, Formulas (1)–(4), (13)–(15)

Continuation of Table 4

1	2	3	4
15	Calculation of: $\overline{P}_A(t_k)$, $\overline{T}_{0A}(t_k)$, $\overline{T}_{\gamma A}(t_k)$	Calculation of the upper confidence limits of the probability of failure-free operation, the mean time to failure and the gamma-percentile life of the APAA	Section 4.6, Formulas (7)–(9), (11), (12)
16	Calculation of: $\underline{P}_A(t_k)$, $\underline{T}_{0\_A}(t_k)$, $\underline{T}_{\gamma\_A}(t_k)$	Calculation of the lower confidence limits of the probability of failure-free operation, the mean time to failure and the gamma-percentile life of the APAA	Section 4.6 Formulas (7)–(9), (11), (14)
17	Calculation of: $\overline{\Delta} t_{\mathrm{ATRM}}(i)$, $\overline{\Delta} t_{STRM}(j)$, $\overline{\Delta} t_{PM}(l)$	Determination of the upper confidence limits of the time between failures of the APAA subarray modules: ATRM, STRM, PM	Section 4.6, Formulas (16)–(18)
18	Calculation of: $\underline{\Delta} t_{\mathrm{ATRM}}(i)$, $\underline{\Delta} t_{STRM}(j)$, $\underline{\Delta} t_{PM}(l)$	Determination of the lower confidence limits of the time between failures of the APAA modules: ATRM, STRM, PM	Section 4.6, Formulas (16)–(18)
19	Calculation of: $\overline{T}_{\gamma\_A\_RES.}(t_k)$, $\underline{T}_{\gamma\_A\_RES.}(t_k)$	Determination of the upper and lower confidence limits of the residual gamma-percentile life of the APAA	Section 4.6, $\tilde{T}_{\gamma\_RES\_A}(t_k)=\tilde{T}_{\gamma\_A}(t_k)-t_k$ Formulas (13), (14)
20	Solution: comparison of $\underline{P}_A(t_k)>\gamma$	Comparison of the lower confidence limit of the probability of failure-free operation $\underline{P}_A(t_k)$, with γ – if $\underline{P}_A(t_k)\leq\gamma$, then the corrective replacement of the APAA modules is carried out (transition to process 24); – if $\underline{P}_A(t_k)>\gamma$, then collection of statistics about module failures during normal operation of the ATRM is continued (transition to process 2)	- - -
21	Corrective replacement of the module	Corrective replacement of the APAA modules: ATRM, STRM, PM	- - -

5. 4. Determination of the gain from the introduction of the APAA reliability-centered maintenance strategy in comparison with the time-based maintenance strategy

When implementing the condition-based maintenance strategy, in comparison with the time-based strategy, there is an increase (“gain” – $W_{T\gamma}$%) or a decrease (“loss” – $\Pi_{T\gamma}$%) of the APAA gamma-percentile life. The “gains” and “losses” in the gamma-percentile life when using the APAA maintenance strategy are defined by the formulas:

$$W_{T\gamma}\,\%=(T_\gamma(\text{condition-based})-T_\gamma(\text{time-based}))\times 100\,\%/T_\gamma\,(\text{time-based}), \tag{23}$$

$$\Pi_{T\gamma}\,\%=((T_\gamma(\text{time-based})-T_\gamma(\text{condition-based}))\times 100\,\%/\,T_\gamma\,(\text{time-based}). \tag{24}$$

5. 5. Implementation and comparison of the condition-based maintenance strategies and the time-based maintenance strategy on the example of calculation of maintenance indexes in the operation of the receive APAA

The example of implementation of the algorithm of time-based maintenance of the receive APAA is presented in Table 5.

The example of implementation of the algorithm of reliability-centered maintenance of the receive APAA is presented in Table 6 (initial data) and Table 7 (calculation results).

Table 5

Example of implementation of the algorithm of time-based maintenance of the receive APAA

Initial data		Calculation results	
Number of the receive modules in the receive PAA	100	Mean time to failure	5,826 h
Mean time to failure of the receive module	50,000 h	Gamma-percentile life	3,698 h
Failure rate of the receive module	0.00002 1/h	Number of replaced modules during corrective replacement	7.0 (6.35)
Permissible probability of decrease in the probability of failure-free operation – γ	0.100	–	–

Table 6 presents the initial data for 14 failures of the receive subarray modules (STRM) of the receive APAA including 100 STRM (failure of 10 modules is allowed). The values of timepoints of failures of the receive modules were obtained by means of the EXCEL program using the “=RAND ( )” function for the uniform distribution of random numbers (the first 14 numbers) and converted for the exponential distribution with the failure rate – $\lambda_{\text{mod.}}$=0.00002 1/h.

Table 7 presents the results of the solution of the illustrative example of implementation of the algorithm of reliability-centered maintenance of the receive APAA.

Table 6

Data on the failures of STRM of the receive APAA

Failure numbers of the receive modules	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Time of failure detection in the receive module, h	800	1400	2000	2700	3300	3900	4500	5000	5400	5800	6250	6750	7200	7700

Table 7

Results of implementation of the algorithm of reliability-centered maintenance of the receive APAA

APAA maintenance algorithm	i=1	i=2	i=3	i=4	i=5
I	1	2	3	4	5
t_i	140	371	880	1038	2179
$i/100$	0.01	0.02	0.03	0.04	0.05
t_i/m_i	0.01005	0.020202	0.030454	0.04082	0.051295
m_i	13,930	18,364	28,896	25,429	42,479
$T_{0mod.}(sr)$	13,930	16,147	20,396	21,655	25,820
$P(t_i)$	0.999999	0.999999	0.999785	0.99776	0.98852
$T_{0\_APAA}(sr)$	1,623	2,140	3,367	2,963	4,950
$T_{\gamma\_APAA}(sr)$	1,030	1,358	2,137	1,880	3,142
$\sigma t_i(sr)$	140	185	293	259	436
$t_{i+1}(prognoz)(sr)$	280	556	1,173	1,297	2,615
$\tilde{T}_{\gamma\_A\_RES.}(t_k)$	890	987	1257	842	963
Comparison of: $P(t_i)\geq\gamma$	0.9999>0.900	0.9999> 0.900	0.9998> 0.900	0.9978>0.900	0.9885>0.900
Transition to corrective replacement	NO	NO	NO	NO	NO
APAA maintenance algorithm	i=6	i=7	i=8	i=9	i=10
i	6	7	8	9	10
t_i	2360	3266	3418	3454	3531
$i/100$	0.06	0.07	0.08	0.09	0.1
t_i/m_i	0.06187	0.07258	0.08338	0.09431	0.10536
m_i	38144	44999	40933	36624	33514
$T_{0mod.}(sr)$	27874	30320	31654	32206	32337
$P(t_i)$	0.96241	0.909165	0.844	0.7118	0.58316
$T_{0\_APAA}(sr)$	4445	5244	4777	4628	3905
$T_{\gamma\_APAA}(sr)$	2821	3328	3032	2709	2478
$\sigma t_i(sr)$	393	466	427	384	353
$t_{i+1}(prognoz)(sr)$	2753	3732	3845	3838	3884
$\tilde{T}_{\gamma\_A\_RES.}(t_k)$	460	62	–386	–745	–374
Comparison of: $P(t_i)\geq\gamma$	0.9624>0.900	0.9092>0.900	0.844<0.900	0.7118<0.900	0.5832<0.900
Transition to corrective replacement	NO	NO	YES	YES	YES
APAA maintenance algorithm	i=11	i=12	i=13	i=14	–
I	11	12	13	14	–
t_i	3,620	5,286	7,645	9,584	–
$i/100$	0.11	0.12	0.13	0.14	–
t_i/m_i	0.116533	0.127833	0.139263	0.150821	–
m_i	31,064	41,351	54,896	63,546	–
$T_{0mod.}(sr)$	32,221	32,982	34,668	36,731	–
$P(t_i)$	0.45288	0.3337	0.2337	0.156	–
$T_{0\_APAA}(sr)$	3,620	4,819	6,397	7,465	–
$T_{\gamma\_APAA}(sr)$	2,297	3,058	4,060	4,700	–
$\sigma t_i(sr)$	329	440	588	685	–
$t_{i+1}(prognoz)(sr)$	3,749	5,726	8,243	10,269	–
$\tilde{T}_{\gamma\_A\_RES.}(t_k)$	–1,323	–2,228	–3,585	–4,884	–
Comparison of: $P(t_i)\geq\gamma$	0.452<0.900	0.3337<0.900	0.2337<0.900	0.156<0.900	–
Transition to corrective replacement	YES	YES	YES	YES	–

Table 7 shows the calculations of values of the sample mean for:

– the probability of failure-free operation of the APAA – $P(t_i)$;

– the mean time to failure of the receive subarray modules and the receive APAA – $T_{0mod.}(sr)$;

– the gamma-percentile life of the APAA – $T_{\gamma\_APAA}(sr)$;

– the time between failures of the receive modules – $\sigma t_i(sr)$;

– the predicted time of detection of the next failure of the receive subarray module – $t_{i+1}(prognoz)(sr)$;

The main results of implementation of the algorithm of condition-based maintenance of the APAA are obtained after the failure of the 8th receive module when it was decided to perform the corrective replacement of the failed modules:

The mean time to failure of the APAA after the 8th failure of the receive module is $T_{0\ \mathrm{APAA}}(8)$=4,777 h.

The gamma-percentile life of the APAA after the 8th failure of the receive module is $T_{\gamma\ \mathrm{APAA}}(8)$=3,032 h.

The number of replaced receive modules during corrective replacement is n_1= 8 modules.

The “gain” $W_{T\gamma}$ % (“loss” $\Pi_{T\gamma}$ %) from the use of the reliability-centered maintenance strategy in the APAA operation in comparison with the time-based maintenance strategy is determined by formulas (23) and (24):

$$W_{T\gamma}\,\%=[(3{,}032-3{,}698)\times100/3{,}698]\,\%=-18\,\%,$$

$$\Pi_{T\gamma}\,\%=[(3{,}032-3{,}698)\times100/3{,}698]\,\%=+18\,\%.$$

6. Discussion of the results of the study of the APAR reliability-centered maintenance algorithm

When using the APAA reliability-centered maintenance strategy, there is a “gain” or “loss” in the gamma-percentile life compared to the time-based maintenance strategy. This phenomenon can be explained by the following reasons.

1. Randomness of the selected numbers and small sample size in the formation of a random sample for timepoints of failures of the PAA receive modules. For different samples, there can be:

a) “loss” during the APAA condition-based maintenance (the example in Section 4 – Π_T %=18 %);

b) “gain” during the APAA condition-based maintenance;

c) approximately equal values of the gamma-percentile life during the APAA time-based maintenance and during the condition-based maintenance (no “gain” or “loss”).

2. Differences in operating conditions (ambient temperature, humidity, dust, etc.) and operating modes of the APAA liquid cooling system from the required in accordance with the APAR operating instructions.

3. Differences in the values of operational reliability indexes of the APAA modules (mean time to failure and failure rate) from the requirements of specifications for the modules (supplier plants may not provide high reliability of the APAA modules for mass delivery).

During the design process, the development company should think over and put the strategies of provision and replenishment of the APAR with spare parts (modules, units, nodes, etc.) during operation in the design and operational documentation. Volumes of SPTA may be at least 50 % of the volume of radar equipment. Therefore, it is necessary to determine the APAA time-based maintenance indexes during the radar operation. This will allow forecasting and design of the required volume of SPTA of the APAR.

In the process of APAR design, the development companies are recommended to determine the possible APAA reliability-centered maintenance indexes for the two reliability levels of the APAA modules:

– negative (reliability indexes do not meet the specifications for the modules);

– positive (reliability indexes meet the specifications for the modules).

In the design process, it is advisable for developers to implement the reliability-centered maintenance algorithm when developing software for the mathematical support of the APAR control and calibration system. This will allow the maintenance staff, in the process of radar operation, to obtain operational information about the real values of APAA reliability and maintenance indexes after each subarray module failure.

7. Conclusions

1. The strategy of reliability-centered maintenance of the APAA during operation is recommended. Its peculiarity is the determination of time and volumes of corrective replacements of the antenna array modules based on the results of individual forecasting of APAA reliability indexes.

2. The proposed mathematical models are the basis for the implementation of strategies and construction of algorithms of APAA time-based and condition-based maintenance. The use of exponential and diffusion nonmonotonic distributions makes it possible to take into account sudden and gradual failures of the modules when calculating the APAA reliability and maintenance indexes. The proposed mathematical expressions of the methodology formalize the APAA time-based maintenance strategy.

3. The proposed structure and description of the algorithm formalize the reliability-centered maintenance strategy during the APAR operation.

4. The presented “gains” and “losses” characterize the degree of differences in the APAR reliability and longevity indexes when using different maintenance strategies: condition-based and time-based.

5. The results obtained when considering the example of construction of the maintenance algorithm for the receive APAA allowed us to consider the reasons for differences in reliability and maintenance indexes obtained during the condition-based maintenance from those obtained during the time-based maintenance.

The results presented in the paper may be useful to the radio industry specialists in the development of radio-engineering systems when designing SPTA and elaborating operational documentation. They can also be used by specialists operating radio-engineering systems when developing the condition-based maintenance algorithms and regulations.

The use of the APAA reliability-centered maintenance strategy can allow:

– providing failure-safe functioning of marine and ground-based APAR in the process of operation;

– planing the timely order and delivery of spare parts (modules) in the APAR operation.

References

1. Barzilovich E. Yu., Voskoboev V. F. Ekspluataciya aviacionnyh sistem po sostoyaniyu (elementy teorii). Moscow: Transport, 1981. 198 p.
2. Ickovich A. A., Smirnov N. N. Obsluzhivanie i remont aviacionnoy tekhniki po sostoyaniyu. Moscow: Transport, 1987. 272 p.
3. Tekhnicheskaya ekspluataciya letatel'nyh apparatov sostoyaniyu / N. N. Smirnov (Ed.). Moscow: Transport, 1990. 423 p.
4. Ignatov V. A., Man'shin G. G., Traynev V. A. Statisticheskaya optimizaciya kachestva funkcionirovaniya elektronnyh sistem. Moscow: Energiya, 1974. 264 p.
5. Ignatov V. A., Man'shin G. G., Kostanovskiy V. V. Elementy teorii optimal'nogo obsluzhivaniya tekhnicheskih izdeliy. Minsk: Nauka i tekhnika, 1974. 191 p.
6. Kostanovskyi V. V. Optymizuvannia tekhnichnoho obsluhovuvannia fazovanykh antennykh reshitok // Matematychny mashyny i systemy. 2015. Issue 1. P. 164–170.
7. Barlow R. E., Proschan F. Mathematical theory of reliability. Wiley, 1965. 255 p.
8. Kececioglu D. B. Maitainability, Availability and Operational Readiness Ingineering Handbook. Vol. 1. DEStech Publications, Inc., 2003. 769 p.
9. Kececioglu D. B. Reliability Ingineering Handbook. Vol. 1. DEStech Publications, Inc., 2002. 720 p.
10. Kececioglu D. B. Reliability Ingineering Handbook. Vol. 2. DEStech Publications, Inc., 2002. 576 p.
11. Nakagawa, T. Advanced reliability models and maintenance policies. Springer, 2008. doi: 10.1007/978-1-84800-294-4
12. Nakamura S., Nakagawa T. Stochastic Reliability Modeling, Optimization and Applications. World Scientific Publishing Co., 2009. 316 p. doi: 10.1142/9789814277440
13. Nakagawa T. Stochastic Processes with Applications to Reliability Theory. Springer, 2011. doi: 10.1007/978-0-85729-274-2
14. Nachlas J. A. Reliability Engineering: Probabilistic Models and Maintenance Methods. 2nd ed. CRC Press Pages, 2016. 378 p.
15. Banzak H. V. Matematycheskaia model adaptyvnoho tekhnycheskoho obsluzhyvanyia po sostoianyiu // Informatyka ta systemni nauky (ISN-2015): materialy VI Vseukrainskoi naukovo-praktychnoi konferentsii za mizhnarodnoiu uchastiu. Poltava: PUET, 2015.
16. Orlovskiy M. N., Akimenko K. Yu., Onishchenko A. P. Vnedrenie principa uprezhdayushchego tekhnicheskogo obsluzhivaniya vozdushnyh sudov // Otkrytye informacionnye i komp'yuternye integrirovannye tekhnologii. 2014. Issue 64. P. 79–83.
17. The present status of maintenance strategies and the impact of maintenance on reliability / Endrenyi J., Aboresheid S., Allan R. N., Anders G. J., Asgarpoor S., Billinton R., Singh C. // IEEE Transactions on Power Systems. 2001. Vol. 16, Issue 4. P. 638–646. doi: 10.1109/59.962408
18. Opredelenie optimal'nyh parametrov tekhnicheskogo obsluzhivaniya po sostoyaniyu slozhnyh ob'ektov radioelektronnoy tekhniki / Lenkov S. V., Selyukov A. V., Zubarev V. V., Cycarev V. N. // Informatyka ta matematychni metody v modeliuvanni. 2013. Vol. 3, Issue 3. P. 215–224.
19. Myasnikov Yu. N. Ekspluataciya flota po fakticheskomu tekhnicheskomu sostoyaniyu korabley // Atomniy flot. ProAtom. 2014. URL: http://www.proatom.ru/modules.php?name=News&file=print&sid=5667
20. Modeling Aircrafts Operational Reliability / Tiassou K., Kanoun K., Kaaniche M., Seguin C., Papadopoulos C. // HAL. URL: https://hal.archives-ouvertes.fr/hal-01176051
21. Lenkov E. S., Zhirov G. B., Bondarenko T. V. Formalizovannaya matematicheskaya model' processa adaptivnogo tekhnicheskogo obsluzhivaniya po sostoyaniyu slozhnoy radioelektronnoy tekhniki // Informatyka ta matematychni metody v modeliuvanni. 2016. Vol. 6, Issue 4. P. 365–371.
22. Maintenance Optimization Model for One kind of Three-Dimensional Radar Antenna Array / Wang M., Yang J., Wang Y., Liu W. // IOP Conference Series: Materials Science and Engineering. 2017. Vol. 224. P. 012046. doi: 10.1088/1757-899x/224/1/012046
23. Open'ko P. V., Kobzev V. V., Fomenko D. V. Obosnovanie primeneniya gruppovogo ucheta argumentov dlya prognozirovaniya dolgovechnosti radioelektronnyh sredstv zenitnyh raketnyh kompleksov pri realizacii strategii tekhnicheskoy ekspluatacii i remonta po tekhnicheskomu sostoyaniyu // Suchasny informatsiyni tekhnolohiyi u sferi bezpeky ta oborony. 2012. Issue 1. P. 52–56.
24. Kyryliuk A. S. Modeli dlia rozrakhunku pokaznykiv zalyshkovoho resursu funktsionalnykh system radioelektronnykh zasobiv ZRK za parametrom tekhnichnoho stanu pry vidomiyi modeli yoho zminy // Systemy ozbroiennia i viyskova tekhnika. 2008. Issue 3 (15). P. 113–115.
25. Lanetskyi B. N., Lukianchuk V. V., Fomenko D. V. Obosnovanie optimal'nyh strategiy tekhnicheskogo obsluzhivaniya i remonta slozhnyh tekhnicheskih sistem // Systemy obrobky informatsiyi. 2009. Issue 6 (80). P. 72–74.
26. Kostanovskiy V. V., Kozachuk O. D. Optimizaciya tekhnicheskogo obsluzhivaniya gruppy iz neskol'kih fazirovannyh antennyh reshetok antennogo posti RLS pri diffuzionnom nemonotonnom i eksponencial'nom raspredeleniyah vremeni bezotkaznoy raboty kanalov reshetki // Matematicheskie mashiny i sistemy. 2017. Issue 1. P. 122–130.
27. Osnovnye tendencii razvitiya blizhnezonnyh metodov izmereniya harakteristik antenn. Ch. 2. Metody kontrolya, nastroyki i izmereniya parametrov FAR / Usin V. A., Markov V. I., Pomazanov S. V., Usina A. V., Filonenko A. B. // Radiotekhnika. 2010. Issue 160. P. 213–227.
28. Kostanovskyi V. V. Matematychni modeli nadiynosti typovykh apertur fazovanykh antennykh reshitok, yaki vrakhovuiut raptovi ta postupovi vidmovy moduliv nadvysokykh chastot // Matematychni mashyny i systemy. 2014. Issue 2. P. 142–150.
29. Kostanovskiy V. V., Kozachuk O. D. Veroyatnostnyy analiz bezotkaznosti i dolgovechnosti apertur fazirovannyh antennyh reshetok v processe proektirovaniya // Matematychni mashyny i systemy. 2015. Issue 3. P. 201–212.
30. Kostanovsky V. V., Kozachuk O. D. Prospects for probabilistic-physical analysis of reliability in the design of radio-electronic systems // Electronics and Control Systems. 2017. Vol. 1, Issue 51. P. 59–67. doi: 10.18372/1990-5548.51.11690
31. Azarskov V. N., Strel'nikov V. P. Nadezhnost' sistem upravleniya i avtomatiki: ucheb. pos. Kyiv: NAU, 2004. 164 p.