The problem solution of the Surface-to-air missile systems electronic equipment durability prediction when implementing the strategy of condition-based maintenance and repair using the Group Method of Data Handling

Pavlo Open'ko [1 A]; Vladyslav Kobzev [2 B]; Volodymyr Larin [3 B]; Pavlo Drannyk [4 A]; Volodymyr Tkachev [5 A]; Oleh Uhrynovych [6 A]

[A] The National Defense University of Ukraine named after Ivan Cherniakhovskyi, Kyiv, Ukraine
[B] Ivan Kozhedub Kharkiv National Air Force University, Kharkiv, Ukraine

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Abstract

The possibilities of application of known methods for estimating the life to the task of forecasting the ultimate state of radio-electronic means of the surface-to-air missile system during the operation status of the requested technical. A procedure for constructing a mathematical model of change of reliability in service with the Group Method of Data Handling, which is more fully into account the specific characteristics of radio-electronic means of the surface-to-air missile system and considers possibility of use as basic data for creation of models not uniformly precise results of estimation of an indicator of non-equal exact measuring to operational supervision.

Key words: radio-electronic means, surface-to-air missile system, strategy of condition-based maintenance and repair, Group Method of Data Handling.

Introduction

A characteristic feature of the condition-based maintenance and repair (M&R) strategy is that during operation, the condition of a particular object is monitored to make timely decisions about the need for repair and its scale. In this case surface-to-air missile systems (SAM) can be operated without inter-repair resources (service life) establishment and are subject to repair when they reach the corresponding type of limiting condition. The efficiency of condition-based M&R strategy implementation to a great extent is defined by timely detection of radio-electronic means (REM) of surface-to-air missile systems (SAM) transition to a limiting condition. In the process of operation, the reliability of REM of specific SAM deteriorates, because by the nature of the main degradation processes that lead the equipment to the limit state, REM of SAM belongs to the aging equipment. That is why the value of the monitored reliability indicator being out of the established limits is one of the indications of REM of SAM limiting state.

In the absence of design changes in the REM

[1] **Corresponding author:** Candidate of Technical Science, Senior Reseacher, Head of the Scientific-research Department of the Aviation and Air Defence Institute, e-mail: pavel.openko@ukr.net, ORCID: 0000-0001-7777-5101

[2] Candidate of Technical Science, Senior Reseacher, Senior Researcher of the Scientific-research Department, e-mail: vladiskob@ukr.net, ORCID:0000-0002-0954-8887

[3] Candidate of Technical Science, Associate Professor, Associate Professor of Mathematical and Software ACS Department, e-mail: volodymyr_larin@gmail.com, ORCID:0000-0003-0771-2660

[4] Candidate of Military Sciences, Senior Researcher, Associate Professor of the Department, e-mail: pavchyc@ukr.net, ORCID: 0000-0002-6073-2962

[5] Candidate of Military Sciences, Professor, Leading Researcher of the Scientific-research Department, e-mail: vsk@vsk.com.ua, ORCID: 0000-0001-8957-2733

[6] Candidate of Military Sciences, Associate Professor, Associate Professor of the Department, e-mail: olegenya999@gmail.com, ORCID: 0000-0001-6644-7620

of SAM and the established system of M&R, the indicators of maintainability can be considered independent of the operation duration. Consequently, when predicting the REM of SAM limit state, it is necessary to investigate the change of REM of SAM reliability, and assessments of durability indicators of specific REM of SAM should be determined using the established patterns of individual changes in the values of reliability indicators (RI).

Material and methods

The known in scientific and technical literature methods of durability indicators estimation can be divided into parametric and nonparametric. Parametric methods (Gaskarov D. V., 1976; GOST 27.302-86; Reliability and efficiency…,1989; RD 50-490-84; Sadykhov G. S., 1985; Zubarev V. V., Kovtunenko A. P., Raskin L. G., 2005; Raskin L. G., Kirichenko I. O., 1977) are applied in the assumption that the type of the distribution function (operating time) of objects up to resource failure (limiting state) is known in advance, and its parameters are established by a sufficiently large volume of the homogeneous objects samples operation results. Nonparametric methods can be applied under the assumption of unknown type of the operating time distribution function to the moment of failure. Distribution function of operating time (duration of operation) up to the resource failure moment can be determined by calculation-experimental methods of before-repair and between-repairs resources estimation (service life), which are reduced to one of the options:

- experimental estimation of probability density distribution to the moment of the same type component parts groups failures in the form of superposition of different probability density of their failure rates;
- empiric function formulation of the REM of SAM lifetime (operating time) distribution to resource failures.

The REM of SAM methods of lifetime indicators estimation are developed in relation to regulated strategy of operation and planned repair and are applied for the same type park of SAM; do not fully take into account the individual characteristics of the conditions and operation modes of the specific air defense systems' REM. Besides, in practice the REM of SAM durability indicators estimation based on results of organization and carrying out resource tests or operational observations is difficult due to the fact that there are no statistics on transition moments of SAM and their REM to limiting states and, as a consequence, there are no values of their resources and service life samples, which does not allow establishing distribution laws of these random quantities; distribution laws of resources and service life of SAM and their REM establishment by calculation-experimental method according to known laws of the distribution of resources and the service life of component parts, determined from the results of operational observations, leads to large errors due to the impossibility of taking into account the conditions and operating modes of specific components in the SAM electronic equipment, its REM and its components.

The purpose of the article is to create a mathematical model of change of an indicator of non-equal exact operation is presented in article on the basis of use of a Group Method of Data Handling in use REM of SAM which considers possibility of use as basic data for creation of models not uniformally precise results of estimation of an indicator of non-equal exact measuring to operational supervision and allows to carry out creation of multiple regressive-temporal model at fuller accounting of specific features of REM of SAM.

Results and discussion

For individual solution of the durability assessment indicators of certain SAM and their REMs problem, taking into account their actual technical condition and reliability, it is necessary to assess durability indicators of SAM with regard to specific modes and conditions of their operation, the degree of influence of these modes and operating conditions on the REM. It is reasonable to carry out this assessment with the use of dependence of RI changes on parameters, characterizing operating modes, for example, duration of operation, cumulative operating time, etc. At the same time, the results of operational observations, accumulated on a set of operation intervals of fixed duration, in the form of a set of RI estimates are considered as initial data for formulation of their values change dependence of RI during operation for prediction of values on forthcoming operation interval and, respectively, the REM of SAM durability indicators evaluation. The most elaborated mathematical apparatus, which can be used to solve this problem, are methods of regression analysis (Aivazyan S. A., Enyukov I. S., Meshalkin L. D., 1985; Vuchkov, I., Boyadzhieva, L., Solakov, E., 1987; Demidenko E. Z., 1981; Draper N., Smith G., 1986; Seber, J., 1980). At the same time, for the application of this mathematical apparatus it is advisable to take the following assumptions:

The change in the value of controlled (estimated) RI for a fixed duration of operation interval can be neglected, since this duration is incommensurately small compared to the value of the assigned resource (service life) of the object. At the same time, the REM of SAM recovery of reliability after failures is assumed to be minimal, i.e. the REM of SAM reliability as a result of recovery of serviceability within the operation interval of a fixed duration practically does not change; the values of monitored (estimated) RI change significantly on a set of operation intervals of fixed duration, and the nature of this change is unknown in advance and must be established in the form of models of their change depending on the duration of operation and other factors according to the accumulated values of RI estimates.

A set of parameters, characterizing the REM of SAM operation modes, taking into account forms and mechanisms of operational observations registration results, it is advisable to choose the following: duration of operation, total operating time, total number of switching on. Dependence of RI value on parameters values, characterizing operation modes, with reference to a specific REM of SAM, can be determined by a mathematical model, describing the process of change of REM of SAM reliability.

Mathematical model formulation of REM of SAM change of RI with the help of paired regression-time dependence of RI (only on duration of operation or on total operating time) significantly simplifies actual dependence of these RI from other various parameters, characterizing the REM of SAM operation modes, and their correlations; observed values, used as factors at formulation of multiple regression models, are assumed independent, which is not performed for the selected set of parameters, characterizing the REM of SAM operation modes. This can lead to errors in evaluation of lifetime indicators and, as a consequence, to making wrong decisions about the premature repair or about possibility (expediency) of the REM of SAM operation, which is in the limiting condition.

It is proposed to formulate a pattern of RI change using methods of multiple regression analysis in the following way. Duration of operation is divided into intervals of operation, during which the reliability characteristics are considered to be constant. The duration of this interval of operation is determined on the basis that it must be:

- not exceeding a value sufficient to accumulate an acceptable amount of operational observations and a subsequent point estimate of the RI;
- such that the REM of SAM operation reliability during the interval in question could not change significantly;
- coordinated with the frequency of technical maintenance and the mechanism of in-service observation results accounting.

For the REM of SAM in the intended use

mode it is advisable to take it equal to one quarter. According to the operation data, the following is determined: data on the number of failures for the operation intervals; values of the total operating time and total number of the REM of SAM turnovers, corresponding to each *i*-th operation interval. The results of the REM of SAM operation for each interval, recorded in the operational documentation, are used to obtain corresponding quantitative evaluations of RI and dispersions of these evaluations. Calculation relations for RI calculation estimates and dispersions are given in (Reliability and efficiency…, 1989). Values of point assessments of the REM of SAM operated and dispersions of these assessments are further used at formulation of dependence of these indicators on parameters, characterizing operating modes. The grouped information can be represented as a set of k points in four-dimensional space $\{\hat{R}_i, T_{(i)}, T_{op(i)}, N_{(i)}\}$, where $\hat{R}_i$ – estimate of reliability index R at the *i*-th operating interval. Further the RI dependence of the REM of SAM estimations on parameters, characterizing its operation modes are formulated $\{R = f(T, T_{op,} N)\}$.

In general, these regression-time models can be represented as (Aivazyan S. A., Enyukov I. S., Meshalkin L. D., 1985; Vuchkov, I., Boyadzhieva, L., Solakov, E., 1987; Demidenko E. Z. 1981; Draper N., Smith G., 1986; Seber, J., 1980):

$$R = BX + e; \quad (1)$$

where $R = (\hat{R}_1, \dots, \hat{R}_i, \dots, \hat{R}_k)^m$ — is a vector of dimension, whose elements are the calculated point estimates of R_l (k— total number of evaluations calculated);

B — is a vector of dimension m, which elements are the unknown coefficients of the multiple regression-time model;

X — is a matrix of dimension $m \times k$, the elements of which are factors (the total number of which in the model is m), representing the functions of the parameters that characterize the modes of a particular object operation (duration of operation T_{op}, total operating time T , total number of switching operations *N*);

e — are vectors of dimension k, the elements of which are random deviations (residuals).

Factors in the model (1) are parameters, characterizing modes of operation of particular object (T_{op}, T, N), and their various combinations

$$\begin{pmatrix} T_{op}, T, N, T_{op}^2, T^2, N^2, T_{op} \times T, T_{op} \times N, T \times \\ \times N, T_{op} \times T \times N, \dots \end{pmatrix}.$$

Total number of factors m and unknown regression coefficients depends on the number of selected parameters, characterizing operation modes of the REM of SAM system, and the order of regression model. So, the total number of factors m (unknown regression coefficients), when using three parameters, characterizing the operation modes of the REM of SAM system, for linear regression of the first order is 4 (m = 4); for linear regression of the second order – m = 10; for linear regression of the third order – m = 20, etc.

Obviously, the accuracy and reliability of the assessments of durability indicators will be determined by the REM of SAM accuracy of the reliability change model formulation, which, in its turn, is characterized by the accuracy of assessments of the unknown regression coefficients. The increase of the number of unknown regression coefficients at the limited volume of operational observations leads to their estimation's accuracy decrease (Aivazyan S. A., Enyukov I. S., Meshalkin L. D., 1985; Vuchkov, I., Boyadzhieva, L., Solakov, E., 1987; Demidenko E. Z. 1981; Draper N., Smith G., 1986; Seber, J., 1980; Adler Y. P., Markova E. V., Granovsky Y. V., 1976). In (Vuchkov, I., Boyadzhieva, L., Solakov, E., 1987; Demidenko E. Z. 1981; Draper N., Smith G., 1986) the analysis of the "overshooting" and "undershooting" quantity of initial factors consequences is carried out. Also, it is necessary to note, that initially parameters, characterizing the REM of SAM operation modes, are dependent (positive interdependence), that breaks the preconditions of classical linear regression analysis. In this case the situation is possible, when some of the initial factors insignificantly influence the value of RI (i.e. are redundant) or turn out to be linearly dependent. The processing of data using the entire number of input factors (including redundant and linearly dependent) leads to unreasonable costs. The degree of representativeness of a sample of the same volume is inversely proportional to the dimensionality of the factor space. The large dimensionality of the factor space does not allow a clear representation of the data, and also complicates the interpretation of the results obtained.

There are various ways of excluding redundant initial factors on the basis of checking the significance of their coefficients, calculating the coefficients of all possible regression models, consecutive inclusion (exclusion) of initial factors in the multiple linear regression model under consideration, taking into account their mutual influence, transition to a different factor space (Aivazyan S. A., Enyukov I. S., Meshalkin L. D., 1985; Vuchkov, I., Boyadzhieva, L., Solakov, E., 1987; Demidenko E. Z. 1981; Draper N., Smith G., 1986; Seber, J., 1980; Adler Y. P., Markova E. V., Granovsky Y. V., 1976; Aleksandrov V. V., Gorsky N. D., 1983; Lawley D., Maxwell A., 1967), etc. The application of most of these methods is complicated by the fact that reducing the dimensionality of the factor space can often lead to difficulties in the interpretation of modeling results.

In addition, according to the results of predicting, it is necessary to establish the values of assigned resources and service lives, which are directly related to such parameters, characterizing the modes of operation, as total operating time and duration of operation.

In other words, after defining the model structure in the new factor space, it may be necessary to return to the original factor space. This can lead to new errors, connected with transitions from one factor space to another and back, which, in its turn, can decrease accuracy and credibility of the REM of SAM reliability prediction.

Promising in deciding the choice of significant factors and, consequently, the exclusion of redundant factors, is the use of the group arguments consideration method (Ivakhnenko A. G., 1982). As applied to prediction of the REM of SAM safety factor change, the algorithm of finding the model of optimal structure will consist of the following main steps.

Aggregate of the REM of SAM RI values of assessments at different fixed operation intervals is divided into training and testing ones (if there are enough observations, aggregate of assessments can be divided into three groups – training, testing and examining). Index sets ℓ and c in the aggregate W, which satisfy the conditions $\ell \cup c = W$, $\ell \cap c = \emptyset$, denote the estimates belonging to the training and test samples, respectively.

The partitioning of the sample is represented as

$$X_W = \binom{X_\ell}{X_c}, R_W = \binom{R_\ell}{R_c}, \qquad (2)$$

where X_W – the entire set of factors that are functions of the parameters that characterize the modes of operation of a particular object;

X_ℓ, X_c – the set of factors belonging to the training and test samples, respectively;

R_W – the whole totality of RI assessments of a particular REM of SAM;

R_ℓ, R_c – is a set of estimates of RI of a particular REM of SAM, belonging to the training and test samples, respectively.

Polynom (1) is assigned as a base model, which describes RI value dependence of specific REM of SAM estimation on parameters, characterizing modes of its operation. Expert method can decide on the need to increase the number of elements of factor vector by adding non-linear transformations of individual parameters. The basic model is linear with respect to model coefficients and non-linear with respect to factors.

Also, by the expert method the target function is selected – an external criterion describing the quality of the model (Ivakhnenko A. G., Stepashko V. S., 1985).

Candidate models are generated taking into account the pre-established restriction on the length of the polynomial of the basic model. For example, the degree of the polynomial of the basic model must not exceed a given number.

The unknown coefficients of competing models are calculated according to the internal criterion, i.e. the criterion calculated using the training sample.

It should be noted that at each operation interval the values of total operating time and number of switchings may differ significantly. This, in its turn, leads to different accuracy of obtained estimations of RI of REM and violation of one of basic assumptions of classical linear regression analysis about observation dispersion equality. Therefore, considering the results of operational observations for different operating intervals and reliability tests as equal in terms of their information value will lead to inaccurate formulation of a mathematical model of REM of SAM reliability changes, and as a consequence, to errors in predicting RI values at the forthcoming stage of operation.

In this connection when calculating the unknown coefficients of regression dependence, it is necessary to apply the weighted method of least squares, which implies the transition to new variables, satisfying the classical assumptions (Aivazyan S. A., Enyukov I. S., Meshalkin L. D., 1985; Vuchkov, I., Boyadzhieva, L., Solakov, E., 1987; Demidenko E. Z. 1981; Draper N., Smith G., 1986; Adler Y. P., Markova E. V., Granovsky Y. V., 1976). Then the residuals covariance matrix in the model based on the training sample is written as $cov(e_\ell) = \Omega_\ell$, where Ω_ℓ — matrix, the elements of which are the mutual covariances of the residuals between the observations within the training sample.

Given the assumption of independence of the factors, the matrix Ω_ℓ takes a diagonal form, and the values of the elements of the main diagonal are equal to the dispersions of the REM of SAM RI estimates, which belong to the training sample and are calculated directly from the results of its operation for the corresponding operating intervals. Then the matrix Ω_ℓ is considered to be known, and to calculate the values of the matrix elements B_ℓ, according to the generalized method of least squares, we can use the well-known Eitken estimate

$$B_\ell = \left[X_\ell^m \Omega_\ell^{-1} X_\ell\right]^{-1} X_\ell^m \Omega_\ell^{-1} R_\ell, \qquad (3)$$

which, as shown in (Demidenko E. Z., 1981), is unbiased and linearly effective. The aggregate of obtained values of elements of the above matrix represents the estimates of coefficients of the regression-time model, calculated on the training sample, which describes the dependence of specific REM of SAM RI values on parameters characterizing the modes of its operation. When complicating the model, the internal criterion does not give a minimum for models of optimal complexity, so it is not suitable for selecting the final model.

To select a model with an optimal structure, the quality of competing models is calculated. At the same time, using the coefficients calculated on the training sample in accordance with the assigned external criterion, an error is calculated on the test sample. The regularity criterion is proposed to be used when predicting the REM of SAM RI. In accordance with this criterion, the optimal model is the one $\Delta^2(c)$that provides a minimum of the root-mean-square error

$$\Delta^2(c) = \left(\Omega_c^{-1} R_c - B_\ell \Omega_c^{-1} X_c\right)^m \left(\Omega_c^{-1} R_c - B_\ell \Omega_c^{-1} X_c\right) \qquad (4)$$

where Ω_c — diagonal matrix, the elements of which are dispersions of the REM of SAM RI evaluations, which belong to the test sample and are calculated directly by the results of its operation for the corresponding intervals of operation.

As one of variants of external criterion it is possible to use modification of regularity criterion – criterion of predictive ability. In this case the initial aggregation is divided not into two, but into three samples – training, testing and examining. The criterion calculates the root-mean-square error on the test sample, which was not used when calculating coefficients or when selecting models (Ivakhnenko A. G., Yurachkovsky Y. P., 1987).

When the regression model is specified and its parameters are estimated, it can be applied for prediction of the REM of SAM reliability and, as a consequence, the moment of its transition to the limiting state of the REM of SAM.

Висновки

Thus, the proposed mathematical model formulation procedure of RI change during REM of SAM operation extends the known similar procedures (Gaskarov D. V., Golinkevich T. A., Mozgalevsky A. V., 1974; GOST 27.302-86; RD 50-490-84; Zubarev V. V., Kovtunenko A. P., Raskin L. G., 2005; Raskin L. G., Kirichenko I. O., 1977), and in contrast to them:

firstly – takes into account that unequal results of RI estimation according to operation data can be used as input data for model creation;

secondly – proposes to create a multiple regression-time model, describing dependence of change in RI on a set of parameters, characterizing objects operation modes, which provides more complete account of specific features of the REM of SAM instead of previously used pair linear regression-time models of change in reliability index on duration of operation (total operating time).

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