ESTIMATION OF FUNCTIONAL USABILITY OF RADIO ELECTRONIC CIRCUITS BY APPLYING THE METHOD OF CONFIDENCE ELLIPSOIDS

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Abstract: The problem of estimation of functional usability of radio electronic circuits (REC) by applying the confidence ellipsoid method is considered in this article. The index of probability of the functional usability is chosen as that of the functional usability. A method which is based on the comparison of the domain of functional usability with the confidence domain of dispersion in the course of operation (such a method enables us to obtain an analytical relation for calculation of the probability of functional usability of REC) is suggested and substantiated. This method is implemented in the example of evaluation of functional usability of a band filter.

Key words: probability of functional usability, permissible domain, confidence ellipsoid, radio electronic circuit.

1. Introduction

Functional usability of REC is their capability of performing certain functions during a certain time interval, as well as, resuming regular work in the case of certain failures of REC or uncontrollable influence from outside. On the other hand, REC is considered to be functionally usable if their characteristics necessary for performing certain functions are within permissible limits. In general, the functional usability of the whole REC depends both on the functional usability of each separate component of the circuit and on their interaction with other components. In the course of production and operation, actual output values of REC characteristics differ from the rated ones, that in turn leads to the fact that some characteristics take their values beyond the permissible limits, and, correspondingly, to the reduction of the functional usability of REC. Therefore, in the course of production and operation of REC, there arises the necessity to estimate the functional usability taking into account random deviations of the values of radio element parameters from their rated ones. One of the indexes of the functional usability estimation is the one which determines the probability of functional usability. The issue of estimation of the aforesaid index is considered in the works [2, 4, 5]. Approaches which are based on the calculation of functional usability on the basis of a multi-dimensional integral whose dimensionality depends on the number of the characteristics of

REC are suggested. Taking into account the complexity of the aforesaid problem, approximate methods of evaluation of the probability of functional usability are used in the works [4, 5], in particular, the Monte Carlo methods. However, this method is a very time-taking one, because of errors caused by approximations; losses of calculation accuracy are possible in this method, which also causes a change in distribution of random deviations of REC characteristics from their rated values [1, 3].

Under these conditions, the problem of reduction of computational expenditures and improvement of the evaluation accuracy of REC functional usability is considered urgent. This can be done on the basis of the analysis of random deviations of REC parameters from their rated values; in the case of normal or logarithmic-normal density distribution, these deviations can be described by confidence ellipsoids.

2. Statement of the problem

The requirements as to the functional usability of REC can be written with the help of the following system:

$$y_i^- \le g_i(\vec{b}) \le y_i^+ , \qquad (1)$$

where $[y_i^-, y_i^+]$ are the intervals of the values of the output REC characteristics y_i which are permissible for the functional usability of REC. In general case, REC characteristics $g_i(\vec{b})$ are non-linear. As the functional usability of REC is to be determined in a neighborhood of the rated values of its parameters, it is expedient to apply linearization of the characteristics of REC and, thus, to pass to the following system of linear inequalities:

$$\delta y_i^- \le \sum_{j=1}^{m} S_{ij} \cdot \delta b_j \le \delta y_i^+ , \; i = 1,..,N , \qquad (2)$$

where $\delta b_j = \ln(b_j) - \ln(b_{0j})$, $\delta y_i^- = y_i^- - y_{i0}$,

$\delta y_i^+ = y_i^+ - y_{i0}$, $S_{ij} = b_j \cdot \dfrac{\delta y_i(\vec{b})}{\delta(b_j)}\Big|_{\vec{b}=\vec{b}_0}$ – is the sensitivity

of the ith characteristics of REC to variation of the parameter of the jth element.

The solution of the linear inequalities system (2) in the space $\vec{b} \in R^m$ is the domain of the REC functional usability and, at the same time, it is its permissible domain $\tilde{\Omega}$.

Let us consider the peculiarities of the domain of REC functional usability stated in the work [6].

1. In m-dimensional space of the parameters $b_1,...,b_m$, the domain $\tilde{\Omega}$ is a convex polyhedron; this means that any point of the permissible domain is a solution of the system (2).

2. The domain $\tilde{\Omega}$ is a domain of permissible deviations δb_j of the elements parameters from their rated values. Any deviation $\vec{\delta b}$ of a vector which belongs to the domain ensures perfect functional usability of REC with the probability $P_d = 1$.

3. The greater sizes of the permissible domain $\tilde{\Omega}$, the longer the permissible parameters intervals $[\delta b_i^-, \delta b_i^+]$.

Estimation of the functional usability of REC means evaluation of the probability of the functional usability P_d as that of belonging the random vector $\vec{\delta b} = (\delta b_1,...,\delta b_m)^T$ to the permissible domain $\tilde{\Omega}$. A traditional approach to the estimation of the probability of functional usability of REC is based on the following relation [1]:

$$P_d = \int ... \iint_{\tilde{\Omega}} W_\delta(y_1,...,y_N) dy_1 ... dy_N \qquad (3)$$

where $W_\delta(y_1,...,y_N)$ is the density of the distribution of the random deviation $\delta y_i(\vec{b})$ of REC characteristics from their rated values.

The problem (3) in the form of calculation of a multidimensional integral is rather a complicated one, because the values of $\delta y_i(\vec{b})$ are inter-dependable. The application of the Monte Carlo method does not ensure sufficient accuracy of the multidimensional integral calculation (3) because of errors caused by the approximation as well as because of change of density distribution of random deviations of REC characteristics due to the approximation errors. Therefore, in this paper, for the estimation of functional usability P_d, another approach is used instead of the formula (3); this approach is based on the comparison of the permissible domain with the technological domain of dispersion. The aforesaid approach is based on a set-theoretical approach, in particular, on the method of interval data analysis [1, 3].

3. Method for evaluation of functional usability of REC by applying confidence ellipsoids

Let us write the inequality system (2) in matrix form [6]:

$$\vec{\delta Y^-} \le S \cdot \vec{\delta b} \le \vec{\delta Y^+} \qquad (4)$$

where $S = \{S_{ij}, i = 1,...,m, j = 1,...,N\}$ is the matrix of sensitivities of ith characteristics to the jth parameters; $\vec{\delta Y^-}, \vec{\delta Y^+}$ are the vectors of lower and upper limits of deviations of the characteristics values from their rated ones, these vectors consist of the components $\delta y_i^- = y_i^- - y_{i0}$, $\delta y_i^+ = y_i^+ - y_{i0}$, respectively.

Let us consider a case when in a radio electronic circuit the number of characteristics is equal to the number of radio elements' parameters, i.e. N=m. In this case, in the system (4), the sensitivity matrix S is of $(m \times m)$ – dimensions; and the permissible domain $\tilde{\Omega}$, which is the solution to this system, is a paralleletop [2]. Let us designate the permissible domain in this case by $\tilde{\Omega}_m$. Relying upon the work [2], for this case, the permissible domain is estimated with the help of a permissible ellipsoid:

$$Q_m = \{\vec{\delta b} \in R \mid (\vec{\delta b} - \vec{\bar{\delta b}})^T \cdot S^T \cdot E^{-2} \cdot S \cdot (\vec{\delta b} - \vec{\bar{\delta b}}) \le 1\} \quad (5)$$

where $E = diag\{0,5 \cdot (\delta y_1^+ - \delta y_1^-),...,0,5 \cdot (\delta y_m^+ - \delta y_m^-)\}$ is the diagonal matrix of the REC characteristics tolerance; $\vec{\bar{\delta b}} = \tilde{S}^{-1} \cdot (0,5 \cdot (\delta y_1^+ + \delta y_1^-),...,0,5 \cdot (\delta y_m^+ + \delta y_m^-))^T$ is the centre of ellipsoid gravity.

In Fig. 1, the domain of functional usability $\tilde{\Omega}_{m=2}$ and the permissible ellipsoid domain $Q_{m=2}$ are schematically compared for the case when $m = 2$.
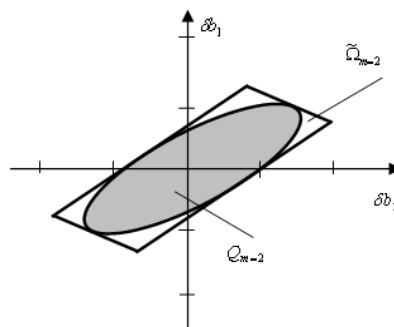

Fig. 1. Domain of functional usability and that
in the form of a permissible ellipsoid for m=2.

As we can see from Fig.1, the permissible ellipsoid "covers", to a great extent, the actual parallelogram-shaped permissible domain, with the ellipsoid having analytical representation in the form of the formula (5), which is obtained in the work [2].

Relying upon the analytical representation of the permissible domain in the form of ellipsoid (5), we derive a relation for estimating the functional usability in the case discrete technology of REC production. As it is known, in this case, the permissible values of deviations

of REC parameters from their rated ones are set by confidence intervals [6]:

$$-\vec{\sigma} \cdot u(\alpha) \le \vec{\delta b} \le \vec{\sigma} \cdot u(\alpha), \qquad (6)$$

where $u(\alpha)$ is the function which determines the standard normal distribution; α is the confidence probability; $\vec{\sigma} = (\sigma_1,...,\sigma_m)^T$ is the known vector of standard deviations of parameters values from their rated ones.

Relying on the formula (6), let us represent the deviations of REC parameters from their rated ones in the following interval form:

$$[\vec{\delta b}] = [-\vec{\sigma} \cdot u(\alpha); \vec{\sigma} \cdot u(\alpha)] \qquad (7)$$

Let us put an equality sign instead of an inequality one in the formula (5), implying the shell of the ellipsoid, and then, on substituting the interval values calculated by the formula (7) for the vector of deviations of REC parameters from the rated ones, we obtain:

$$([-\vec{\sigma} \cdot u(\alpha); \vec{\sigma} \cdot u(\alpha)] - \vec{\bar{\delta b}})^T \cdot S^T \cdot E^{-2} \times$$
$$\times S \cdot ([-\vec{\sigma} \cdot u(\alpha); \vec{\sigma} \cdot u(\alpha)] - \vec{\bar{\delta b}}) = 1 \qquad (8)$$

Taking into account the fact that, in practice, intervals of output REC characteristics are rather often symmetric about their rated value, i.e. $\delta y_i^+ = -\delta y_i^-$, the centre of a permissible ellipsoid is assumed to coincide with the zero point. In this case, the expression (8) takes the form:

$$u^2(\alpha) \cdot [\vec{\sigma}^T] \cdot S^T \cdot \tilde{E}^{-2} \cdot S \cdot [\vec{\sigma}] = 1 \qquad (9)$$

Taking into account the fact that the normal distribution of random deviations of REC characteristics from their rated values is symmetric, we obtain from the expression (9) the following;

$$u(\alpha) = 1/(\vec{\sigma}^T \cdot S^T \cdot \tilde{E}^{-2} \cdot S \cdot \vec{\sigma})^{\frac{1}{2}} \qquad (10)$$

Having calculated the table value of $u(\alpha)$ according to the formula (10), we obtain the value of the confidence probability α from the table. Then, the lower estimation of the probability of functional usability we obtain according to the formula:

$$P_d^- > 1 - \alpha. \qquad (11)$$

Note that the formula (11) does not provide an exact evaluation of probable effectiveness: it provides its lower limit because the permissible ellipsoid does not cover the real permissible domain $\tilde{\Omega}_m$ completely.

The obtained estimation of the probability of functional usability does not take into account random changes of REC parameters in the course of operation, and in this sense it is set too high. Therefore, it is expedient to determine it more exactly taking into account the action of different kinds of factors of the external medium.

Let us assume that the integrated action of the external medium leads to random deviations of parameters which follow the normal distribution. Then, the result of such an action can be described by the confidence ellipsoid:

$$Q(\alpha,m) = \{\vec{\delta b} \in R \,|\, \vec{\delta b}^T \cdot D(\vec{\delta b}) \cdot \vec{\delta b} \le \chi^2(\alpha,m)\} \quad (12)$$

where $D^{-1}(\vec{\delta b})$ is the covariance matrix of probable deviations of parameters due to the action of factors of external medium; $\chi^2(\alpha,m)$ – is the table value of χ^2 – distribution.

Under the conditions of a pre-set covariance matrix of deviations of element parameters related to the action of external medium factors and the absence of technological deviations of radio elements parameters from their rated values, i.e. $\vec{\sigma} = (\sigma_1,...,\sigma_m)^T = (0,...,0)^T$, the evaluation of the probability P_d^+ of functional usability can be obtained from the solution of the following problem:

$$\chi^2(\alpha,m) \xrightarrow{\alpha \in [0,1]} \max, \ Q(\alpha,m) \subseteq \tilde{\Omega}_m. \qquad (13)$$

The problem (13) is a problem of finding such value of α under which the ellipsoid $\tilde{\Omega}_m$ inscribed in the permissible domain has the greatest volume. When the centre of the confidence ellipsoid (12) coincides with its zero point, its centre also coincides with the centre of the permissible domain $\tilde{\Omega}_m$. Then, to solve the problem (13), let us use the lemma from [6] on the possibility of inscription of *m*-dimensional maximum volume ellipsoid which touches the centers of all the faces of the domain in their centers, the center of the ellipsoid coincides with that of the domain.

Relying upon this lemma, in the work [], it is shown that the solution of the problem (13) is the following:

$$\chi^2(\alpha,m) = 1 \Big/ \max_{i=1,...,m} \{\Lambda'_{ii}\} \qquad (14)$$

where Λ'_{ii} are the diagonal elements of the following matrix:

$$\Lambda' = E^{-1} \cdot S \cdot D^{-1}(\vec{\delta b}) \cdot S^T \cdot E^{-1} \qquad (15)$$

Based on the formula (14), let us find the value of the confidence probability α in the table, and then determine the evaluation of the probability of functional usability of REC which is related to the action of the factors of the external medium in the following form:

$$P_d^+ = 1 - \alpha. \qquad (16)$$

Note that the result of estimation of the probability of functional usability due to the action of the factors of the external medium is obtained by the formulae (14-16) without taking into account technological factors. Under the condition that the independence between functional usability of REC which is determined by technological factors and that determined by factors of external medium, the general estimation of the probability of

functional usability of REC, in the final analysis, we obtain by the following formula:

$$P_d > P_d^- \cdot P_d^+ . \qquad (17)$$

4. An example of evaluation of functional usability of a radio electronic circuit

Let us take the band filter shown in Fig. 2 as an example to illustrate the implementation of the method of evaluation of REC functional usability using confidence ellipsoids. In this case, while evaluating the functional usability, let us take into account the deviations of random REC parameters from their rated ones both at the stage of their manufacturing and during their operation, their random change under the action of external factors being also taken into account.
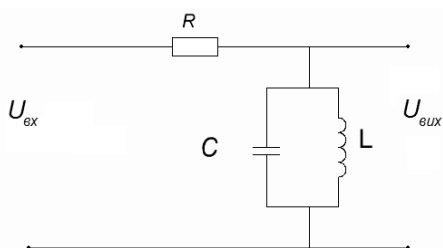

Fig. 2.Circuit diagram of the band filter.

Let us choose the amplitude-frequency characteristic of the band filter at the fixed frequency values as REC characteristics. Let us set the rated values of the elements parameters: $R_0 = 10$ kΩ, $C_o = 1 \cdot 10^{-6}$ F, $L_0 = 10$ mH. The amplitude-frequency characteristic for the rated values of radio elements parameters of the band filter is the following:

$$y_{0i} = K_o(f_i) = \frac{1}{\sqrt{R_0^2 \cdot (\frac{1}{2\pi \cdot f_i \cdot L_0} - 2\pi \cdot f_i \cdot C_0)^2 + 1}} \qquad (18)$$

Let us calculate the rated values of the modulus of gain factor for the following three values of frequency: $f_1 = 1000$ Hz, $f_2 = 2000$ Hz, $f_3 = 3000$ Hz.

The requirements to the functional usability of the band filter (Fig. 2) are stated as follows: at these values of frequency, the deviation of the modulus of gain factor should be within 20 %.

The output data for estimation of the probability of functional usability are given in Table 1.

Table 1

Table of output data for estimation of the probability of functional usability of REC

i	f_i	K_{0i}	K_{0i}^-	K_{0i}^+	δK_i^-	δK_i^+
1	1000	0,0103	0,0082	0,0124	-0,0021	0,0021
2	2000	0,0217	0,0173	0,026	-0,0043	0,0043
3	3000	0,0073	0,0059	0,0088	-0,0015	0,0015

The amplitude-frequency characteristic which is set by the expression (18) is to be linearized in a neighborhood of the rated values; the sensitive of this characteristic to changes of parameters of radio elements is to be determined at different values of frequency:

$$S_{i1} = \frac{-R_0^2 \cdot (\frac{1}{2\pi \cdot f_i \cdot L_0} - 2\pi \cdot f_i \cdot C_0)^2}{(R_0^2 \cdot (\frac{1}{2\pi \cdot f_i \cdot L_0} - 2\pi \cdot f_i \cdot C_0)^2 + 1)^{\frac{3}{2}}} \qquad (19)$$

$$S_{i2} = \frac{-R_0^2 \cdot 2\pi \cdot f_i \cdot C_0 (\frac{1}{2\pi \cdot f_i \cdot L_0} - 2\pi \cdot f_i \cdot C_0)}{(R_0^2 \cdot (\frac{1}{2\pi \cdot f_i \cdot L_0} - 2\pi \cdot f_i \cdot C_0)^2 + 1)^{\frac{3}{2}}} \qquad (20)$$

$$S_{i3} = -\frac{\frac{R_0^2}{2\pi \cdot f_i \cdot L_0} \cdot (\frac{1}{2\pi \cdot f_i \cdot L_0} - 2\pi \cdot f_i \cdot C_0)}{(R_0^2 \cdot (\frac{1}{2\pi \cdot f_i \cdot L_0} - 2\pi \cdot f_i \cdot C_0)^2 + 1)^{\frac{3}{2}}} \qquad (21)$$

where $\vec{b}_0 = (R_0, C_0, L_0)$ is the vector of rated components of REC. In the course of the linearization, we obtain the system (4) of interval equations. The solution of this system is the permissible domain $\tilde{\Omega}_m$; the corresponding confidence ellipsoid inscribed into this domain is of the form (5) where the sensitivity matrix S and the diagonal matrix E of permissible deviations are the following:

$$S = \begin{pmatrix} -0,0104 & 0,0068 & 0,0171 \\ -0,0217 & -0,0594 & -0,0376 \\ -0,0074 & -0,0103 & -0,0029 \end{pmatrix}$$

$$E = \begin{pmatrix} 0,0021 & 0 & 0 \\ 0 & 0,0043 & 0 \\ 0 & 0 & 0,0015 \end{pmatrix}$$

Let us consider a case of discrete technology of REC production. In this case, the permissible values of deviations of REC parameters from their rated ones are set by confidence intervals (6). In such case, the confidence intervals of deviations are given in relative units at the 2 % level of the deviation from the rated values, i.e.

$$-0,02 \cdot u(\alpha) \le \delta\vec{b} \le 0,02 \cdot u(\alpha)$$

Hence, according to the expression (10), we calculate the table value: $u(\alpha) = 1,6$.

Then, using the table of standard normal distribution and using the formula (11), we obtain the probability of functional usability of REC which is related to technological dispersion of the parameters $P_d^- > 0,89$.

The next step is the calculation of the probability of functional usability related to the dispersion of parameters

of radio elements of the band filter during its operation. For this purpose, let us set the predicted domain of dispersion in the form of confidence ellipsoid according to the expression (12), where $D^{-1}(\vec{\delta b})$ is the covariance matrix of probable deviations of parameters, which is the following:

$$D^{-1}(\vec{\delta b}) = \begin{pmatrix} 0,004 & 0,001 & 0,0025 \\ 0,001 & 0,004 & 0,001 \\ 0,0025 & 0,001 & 0,004 \end{pmatrix}$$

The elements Λ'_{ij} of the matrix Λ' are calculated by the formula (20). We obtain the following result:

$$\Lambda' = \begin{pmatrix} 0,023 & -0,0447 & -0,0179 \\ -0,0447 & 0,1734 & 0,0871 \\ -0,0179 & 0,0871 & 0,0455 \end{pmatrix}$$

The greatest value of a diagonal element of the matrix Λ' is the value of the element $\Lambda'_{22} = 0,1734$. Then, with the help of the formula (14), we calculate the table value of χ^2 – distribution function: $\chi^2(\alpha, m = 3) = 5,768$. Using the values from χ^2-distribution table and the formula (16), we find the probability of functional usability of REC in the course of operation: $P_d^+ = 0,825$.

The general estimation of effectiveness of the aforesaid band filter, taking into account the technological domain of radio elements parameters deviations caused by the processes of manufacturing and operation, is $P_d > 0,73$.

From the considered example, it can be seen that for estimation of functional usability of REC it is necessary to take into account both technological dispersion of parameters of REC radio elements and the dispersion related to the action of the external factors.

5. Conclusions

The problem of estimation of functional usability of REC taking into account the influence of technological and external factors during its operation is considered. The method of estimation of functional usability of REC which is based on the comparison of the domain of functional usability with the confidence domain of dispersion in the course of operation and which enables us to obtain an analytical relation for calculation of the probability of functional usability of REC is proposed..

Estimation of functional usability of a band filter showed low calculation complexity of the method and proved the necessity of taking into consideration an influence of both technological and external operational factors on the REC functional usability at the design stage.

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ОЦІНЮВАННЯ ФУНКЦІОНАЛЬНОЇ ПРИДАТНОСТІ РАДІОЕЛЕКТРОННИХ КІЛ ІЗ ЗАСТОСУВАННЯМ МЕТОДУ ДОВІРЧИХ ЕЛІПСОЇДІВ

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У статті розглянуто задачу оцінювання функціональної придатності радіоелектронних кіл. За показник функціональної придатності обрано показник імовірності функціональної придатності. Запропоновано та обґрунтовано метод оцінювання функціональної придатності РЕК, який ґрунтується на співставленні області функціональної придатності та довірчої області розсіювання в процесі експлуатації і уможливлює отримання аналітичного співвідношення для обчислення імовірності функціональної придатності РЕК. Запропонований метод реалізовано на прикладі оцінювання функціональної придатності смугового фільтра.

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