Software for Tolerance Design of Electronic Devices

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Abstract: **The algorithms of tolerance design which are based on the geometric representation of the tolerable domain are proposed. The shape of the domain is defined by law of distributions and optimization criterion. Software for tolerance design is developed. The software can be used as a separate system for mathematical modelling of electronic devices and can be integrated as a component in different electronic design automation systems or computer-aided design systems, for example in SPICE or HFSS.**

Keywords – **tolerable domain, tolerance design, optimization criterion, electronic devices, computer-aided design.**

I. INTRODUCTION

The assignment of tolerances is one of the most important stages in the design of various devices, because standard deviations values of the elements parameters set the accuracy of the output functions and affect the equipment cost. The problem of ensuring the accuracy of output characteristics and parameters of the electronic equipment is solved at the stage of circuit design by tolerance design. Two aspects are to be considered. The deviations of the output functions are to be obtained if the deviations of components parameters are given (tolerance analysis). The deviations of parameters are to be defined if the boundary deviations of the output functions are given (tolerance synthesis).

In modern systems of computer-aided design of electronic devices the procedures of the analysis of tolerances are implemented. These procedures enable to calculate the relative sensitivity of the characteristics of the circuit to change the parameters of the selected element, to perform the Monte Carlo statistical analysis, the simulation of the worst case, to research the circuits taking into account the technological parameters spread of the electronic elements, and temperature dependences. Unfortunately, these systems do not include tools for solving the problems of the tolerances synthesis.

The purpose of the work is to develop software for the tolerance design of electronic devices and integrate it with EDA or ECAD systems.

II. ALGORITHMS OF THE TOLERANCE DESIGN FOR THE ELECTRONIC EQUIPMENT

Knowledge in the field of tolerance design has been accumulated for many years [1-4]. During this time, it has been established that the value of the tolerances assignment greatly depends on the law of distribution of parameters, which is formed in the process of manufacturing components for different devices. It has led to the widespread using the method of moments, statistical tests of Monte Carlo in tolerances assignment [5].

However, to ensure sufficient accuracy in the synthesis of tolerances, the Monte Carlo method requires a large number of tests. The method of moments is used only in the normal law of the parameters distribution and does not provide sufficient accuracy due to the limited number of parameters of the distribution law (mathematical expectation and dispersion).

The accuracy of the procedure for assigning tolerances was increased when the method of tangent [6] was introduced. In this method, standard deviations of the parameters are formed at the tangent point of tolerance domain and domain of operational capability of device. The interval models of output functions are also used. This approach is successfully used in the procedures for assigning tolerances with a uniform [7], normal law of the parameters distribution [8] or if such a distribution law is given by statistical series [9]. There is a need to implement these approaches in modern computer-aided design systems.

When dealing with issues, the peculiarities of the manufacturing and operation of electronic equipment should be taken into account. It is necessary to provide the possibility to consider the law of distribution of parameters, the correlation between the parameters of the components, and possible compensation of the external factors.

The tolerance synthesis is the inverse problem and therefore it is inaccurate and resolved ambiguously. Thereby, it is necessary to apply methods of optimization according to different criteria for solving this problem. In this case it is convenient to use different algorithms for each design strategy: strategy for equal tolerances (δ-strategy), maximum volume tolerance domain (*V*- strategy), the minimum cost (*P*-strategy), optimal price / quality ratio (*P/V*- strategy). Thus, for the software implementation, the following algorithms were developed:

- algorithms for the synthesis of interval tolerances using 4 design strategies;
- algorithms for the synthesis of tolerances on component parameters, taking into account the normal distribution law for 4 design strategies;
- algorithms for the synthesis of tolerances on component parameters taking into account the distribution law given by statistical series for 4 design strategies;
- algorithms for the synthesis of tolerances on the parameters of components, taking into account the correlation between the parameters;
- algorithms for the synthesis of tolerances, taking into account the coefficients of external influences, which are given in the form of interval structures.

The algorithm that enables to assign the same symmetric interval tolerances to the component parameters is following:

Step 1. The coefficients of the model of the output function are determined at the point of the parameters nominal values and the initial values of the parameters deviations of the elements are assigned:

$$\underline{\delta}_i^{(0)} = \begin{cases} \dfrac{\underline{\delta}_y}{n}, & a_{ri} > 0 \\ -\dfrac{\underline{\delta}_y}{n} & \text{otherwise} \end{cases}, \qquad (1)$$

where δ_i is the relative deviation of component parameters; $\underline{\delta}_y = (\underline{y} - y_r)/y_r$ is the lower standard deviation of the output function; y_r is the rating value of the output function; $\underline{y}$ is the lower value of output function.

Step 2. The initial coordinates of the point of tangency between the top of the tolerance domain and the domain boundaries of working operation are determined:

$$\underline{x}_i^{(0)} = x_{ri}(1 + \underline{\delta}_i^{(0)}) . \qquad (2)$$

Step 3. The coefficients of the model of the output function are determined at the point of tangency between the top of the tolerance domain and the boundaries of the capability region. Standard deviations are assigned by the formula

$$\delta = b_w / \sum_{i=1}^{n} \left| \overline{a}_i + \underline{a}_i \right| x_{ri} , \qquad (3)$$

where $b_w = \overline{b} - \underline{b}$; x_{ri} are the rating values of components parameters; a_i are the model coefficients of the output function at the point of the rating values of parameters.

Step 4. The coordinates of the point of tangency between the top of the tolerance domain and the boundaries of the area of working operation are determined:

$$\underline{x}_i^{(k)} = x_{ri}\left(1 + \underline{\delta}_i^{(k)}\right), \qquad (4)$$

where $\underline{\delta}_i^{(k)}$ is the standard deviation of parameters on k iteration.

Step 5. The value of the output function is determined at the tangency point of the top of the tolerance domain and the boundaries of the operational capability region. The completion condition of the algorithm is checked:

$$\left| \frac{y^{(k)} - \underline{y}}{\underline{y}} \right| \le \varepsilon , \qquad (5)$$

where ε is accuracy of calculations.

When the condition is satisfied, the algorithm is over, otherwise, step 3 follows.

The algorithms for *V*-, *P*- and *P/V*- strategies include the same steps but deviations of parameters are defined by formulae given in [7]-[10].

In order to take into account external influences on electronic devices, interval structures are used in tolerance synthesis [11]. It allows to store information about a range of changes in external factors and to estimate compensation for their effect. The algorithm for taking into account external factors is based on the mapping method and has the following form:

Step 1. $\underline{x}_{di}^{(0)}$ boundary values of the parameters of the elements are determined based on $\underline{y}_e$ boundary operating value of the output function and x_{ri} rating values of elements parameters. The algorithm for assigning interval tolerances with a given optimization criterion is used.

Step 2. In the vicinity of $\underline{B}_d^{(0)}$ boundary point $\underline{d}_i$ relative changes in the elements parameters are determined regarding the most unfavorable combination of external factors.

Step 3. The coordinates of $\underline{x}_{di}^{(0)}$ boundary points are mapped onto normal environmental conditions, and the nominal boundary value of the output function is determined in the first approximation:

$$\underline{x}_{ri}^{(0)} = \underline{x}_{di}^{(0)} / \underline{d}_i ; \qquad \underline{y}_r^{(1)} = y(\underline{X}_r^{(0)}) , \qquad (6)$$

where $\underline{X}_r^{(0)} = \{\underline{x}_{r1}^{(0)}, \ldots, \underline{x}_{rn}^{(0)}\}$ is the set of coordinates of $\underline{B}_r^{(0)}$ boundary point.

Step 4. The possibility of implementing the algorithm for a given boundary operational value of the output function and given coefficients of external influences is tested. To do this, the condition is checked:

$$\underline{y}_r^{(1)} < y_r , \qquad (7)$$

where $y_r = y(X_r)$ is the rating value of the output function.

If the condition is satisfied, the algorithm ends and the message about the impossibility of implementation is displayed.

Step 5. Nominal interval tolerances are assigned at the boundary values of $\underline{y}_r^{(k)}$ output function and $\underline{x}_{ri}^{(k)}$ rating boundary values of the elements parameters are determined. The algorithm for assigning interval tolerances is used.

Step 6. The boundary values of the elements parameters and the output function are determined by the effect of external factors:

$$\underline{x}_{di}^{(k)} = \underline{x}_{ri}^{(k)} \underline{d}_i ; \qquad \underline{y}_d^{(k)} = y(\underline{X}_d^{(k)}) . \qquad (8)$$

Step 7. The relative change in the boundary value of the output function is determined and its boundary nominal value is specified:

$$\underline{d}_y^{(k)} = \underline{y}_d^{(k)} / \underline{y}_r^{(k)} ;$$
$$\underline{y}_r^{(k)} = \underline{y}_r^{(k-1)} - (\underline{y}_d^{(k)} - \underline{y}_e) / \underline{d}_y^{(k)} . \qquad (9)$$

Step 8. The condition for the completion of the algorithm is checked:

$$\left| \frac{\underline{y}_d^{(k)} - \underline{y}_e}{\underline{y}_e} \right| \le \varepsilon , \qquad (10)$$

where ε is the accuracy of calculation.

If the condition is satisfied, the algorithm ends, otherwise, go to step 5.

These algorithms are used to develop the software for tolerance design.

III. TOLERANCE DESIGN SOFTWARE

Tolerance design software are allowed to analyze and synthesize deviations of geometric and electric parameters of electronic devices and select components. The main features are

- analysis of deviations of output function by given standard deviation of parameters of components;
- synthesis of equal deviations of the parameters;
- synthesis of deviations of the parameters for case of maximal volume of tolerance domain;
- selection of components by optimal price/quality ratio.

Software consists of the modules. They are the forming of the models of output characteristics, tolerance analysis, tolerance synthesis, component selection, report generation.

The structure of the software is shown in Fig. 1.

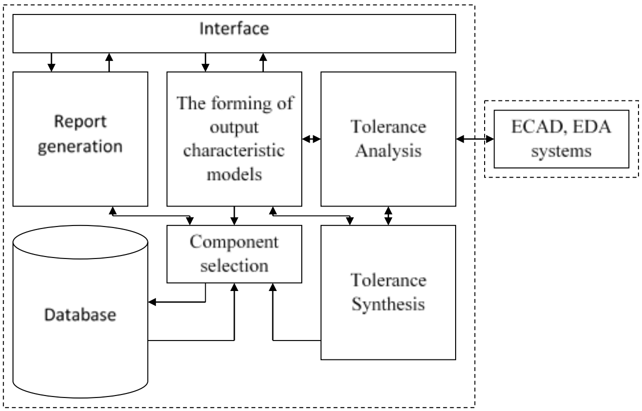

Fig. 1. The structure of the software for the tolerance design

The Database is used for component selection. Tolerance synthesis module includes

- selection of optimality criterion;
- procedures for synthesis of the tolerances of electronic device parameters for the uniform law of parameter distribution, the normal law, and distribution given by statistical series;
- procedures for synthesis of the tolerances taking account correlation between parameters;
- procedures for synthesis of the operating tolerances;

Input data are deviations of output function, the law of parameter distribution, rating values of parameters, coefficients of external factors, accuracy of calculation. As a result, the tolerances of parameters are defined. In the software it is necessary to choose the mode of output function forming in the program system. There are the symbolic form mode and the mode of forming models by external ECAD system.

The module for the formation of output characteristics enables to describe the mathematical models in a symbolic form. The formulae are created in two modes: command mode and visual ones. MathML library is used for visualization.

An example of the application of tolerance design software for synthesize the deviations of the parameters of the power pulse generator is given below. Pulse duration is defined by

$$e^{\frac{\tau}{R_3C_1}} = 1 - e^{\frac{\tau}{R_2C_2}} .$$

The rating values of parameters are the following $R_2 = 110$ kOhm; $R_3 = 110$ kOhm; $C_1 = 0{,}47$ mkF; $C_2 = 0{,}47$ mkF. The rating value of pulse duration is $\tau_r = 35{,}84$ ms.

If the deviation of pulse duration is $\Delta\tau = \pm 1$ ms, then standard deviations for the elements parameters are $\delta_R = \delta_C = \pm 1{,}43$. If the deviation of the pulse duration is $\Delta\tau = \pm 2$ ms, then standard deviations for the parameters are $\delta_R = \delta_C = \pm 2.86$ %. For the boundary values of the delay time, the values of tolerances on the parameters of the scheme components are given in Table 1 and Table 2.

TABLE 1. BOUNDARY VALUES OF DELAY TIME FOR THE DEVIATION OF $\Delta\tau = \pm 1$ MS PULSE DURATION.

Delay time	Boundary deviations of parameters, %				Deviations of delay time, ms
	δ_{C1}	δ_{R3}	δ_{R2}	δ_{C2}	
$\bar{\tau}$	1,43	1,43	1,43	1,43	1,031
$\underline{\tau}$	–1,43	–1,43	–1,43	–1,43	–1,017

TABLE 2. BOUNDARY VALUES OF DELAY TIME FOR THE DEVIATION OF $\Delta\tau = \pm 2$ MS PULSE DURATION.

Delay time	Boundary deviations of parameters, %				Deviations of delay time, ms
	δ_{C1}	δ_{R3}	δ_{R2}	δ_{C2}	
$\bar{\tau}$	2,86	2,86	2,86	2,86	2,077
$\underline{\tau}$	–2,86	–2,86	–2,86	–2,86	–2,019

If the component parameters are distributed according to the normal distribution law, then for the case $\Delta\tau = \pm 1$ ms; tolerances are $\delta_R = \delta_C = \pm 2.74$ %. Delay time values are $\bar{\tau} = 1{,}031$ ms; $\underline{\tau} = -1{,}017$ ms. If $\Delta\tau = \pm 2$ ms, then $\delta_R = \delta_C = \pm 5.47$ % and boundary values of delay time are $\bar{\tau} = 2{,}077$ ms; $\underline{\tau} = -2{,}019$ ms.

Integration of the developed automated system with modern CAD is possible in three ways:

- by developing the interface software module, which uses specialized macros to calculate the output characteristics of the radio electronic device in CAD environment;
- by developing an internal application in CAD, which implements the calculation of output characteristics of radio-electronic devices using API functions;
- by inputing the value of the output characteristic, calculated using a special CAD system in a dialogue mode.

The first integration method is implemented in the ANSYS HFSS system for the low frequency coaxial filter. The example of program interface is shown in Fig. 2. LPF is designed to reduce the level of side-effects in the spectrum of probe signals and suppression of off-band radiation in the spectrum of output signals of amplifier modules of a distributed transmitting device in the antenna.

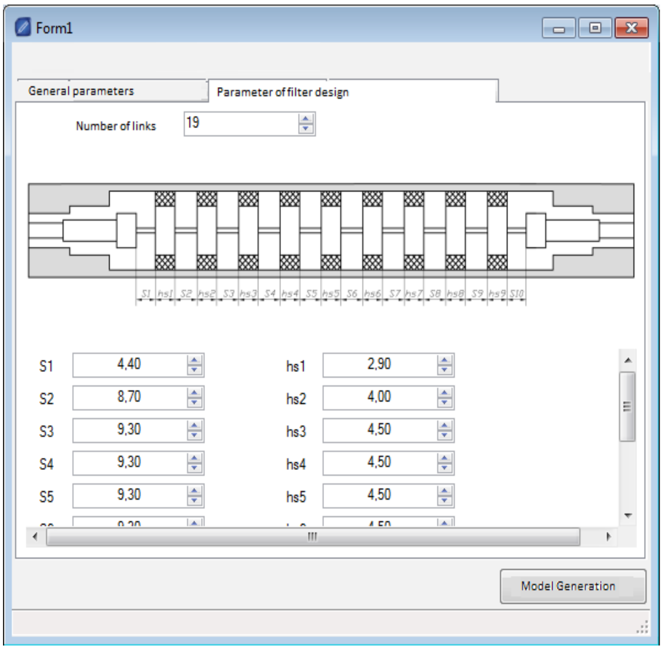

Fig. 2. Program interface of tolerance design software

For an example of the applying of the tolerance assignment system, a coaxial low pass filter (LPF) with following parameters was designed:

- number of links -19, cut-off frequency of the LPF ~ 3300 MHz;
- bandwidth from 2800 to 3100 MHz;
- maximum losses in the bandwidth are not more than 0,3 dB;
- the static wave constant at the voltage in the bandwidth K ≤ 1,2;
- effective attenuation in the barrier band (for the 2nd and 3rd harmonics band) - not less than 60 dB: from 5600 to 6200 MHz; from 8400 to 9300 MHz.

As result the three-dimensional model of filter is generated. This model is shown in Fig.3.

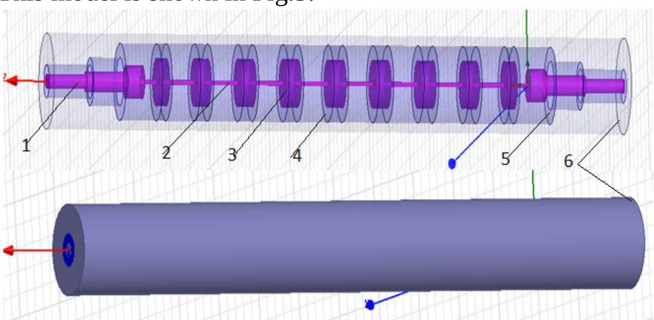

Fig.3. The three-dimensional model of coaxial low pass filter.

Analysis of the influence of the parameters tolerances of the step transition to the standing wave coefficient by the interval methods was carried out.

IV. Conclusion

The software of tolerance design has been developed. It provides an opportunity to analyze and synthesize tolerances if the tolerance domain is represented by various geometric objects (boxes, ellipsoids, and their combination). Individual procedures are implemented to assign tolerances of parameters taking into account the correlation between the parameters, the effect of external factors during the operation stage. The possibility to calculate tolerances for different design strategies is provided. These strategies ensure either the best quality or minimum cost, or taking into account the features of the technological process (strategy of equal tolerances).

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