

The optimization of diffraction structures based on the principle selection of the main criterion

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Abstract. The possibilities of optimizing the characteristics of diffractive structures are analysed. A functional block diagram of a subsystem of diffractive structure optimization is shown. Next, a description of the method for the multicriterion optimization of diffractive structures is given. We then consider an algorithm for selecting the main criterion in the process of optimization. The algorithm efficiency is confirmed by an example of optimization of the diffractive structure.

1. Introduction

The lenses of radar signals and the energy converters of electromagnetic waves are, as a rule, characterized by large electrical dimensions, complex geometries, and the presence of absorbing and non-linear elements. The analysis and synthesis of the above-mentioned electrodynamic objects are based on ideas, whereby the physical processes carry the risk of significant and barely controllable error evaluation of their main characteristics, which themselves usually change very quickly when you adjust the frequency, polarization and angle of incidence of electromagnetic waves [1-5]. The measurement of the main characteristics of objects in a wide frequency band and wide angular sector requires a certified or specially equipped polygonal antenna, or a certified anechoic chamber (the cost of which can amount to several million dollars), as well as time-consuming and material resources.

The development of computer-aided design (CAD) for electrodynamic systems allows us to solve completely new problems in the field of antenna-feeder equipment and in the diffraction theory of electromagnetic waves in structures with complex shapes, which requires substantial computing resources, and also to implement research and development, the high degree of difficulty of which has hampered its practical implementation.

In this paper we present a functional diagram showing a subsystem of diffractive structure optimization. Following this, a method of multi-criteria optimization of diffractive structures is described. Then the algorithm for selecting the main criterion is discussed. At the end of the article an example of optimization of a diffractive structure is shown.

2. The functional diagram of the subsystem of optimization of diffractive structures



We have developed a functional diagram showing a subsystem of diffractive structure optimization and this is presented in Figure 1.

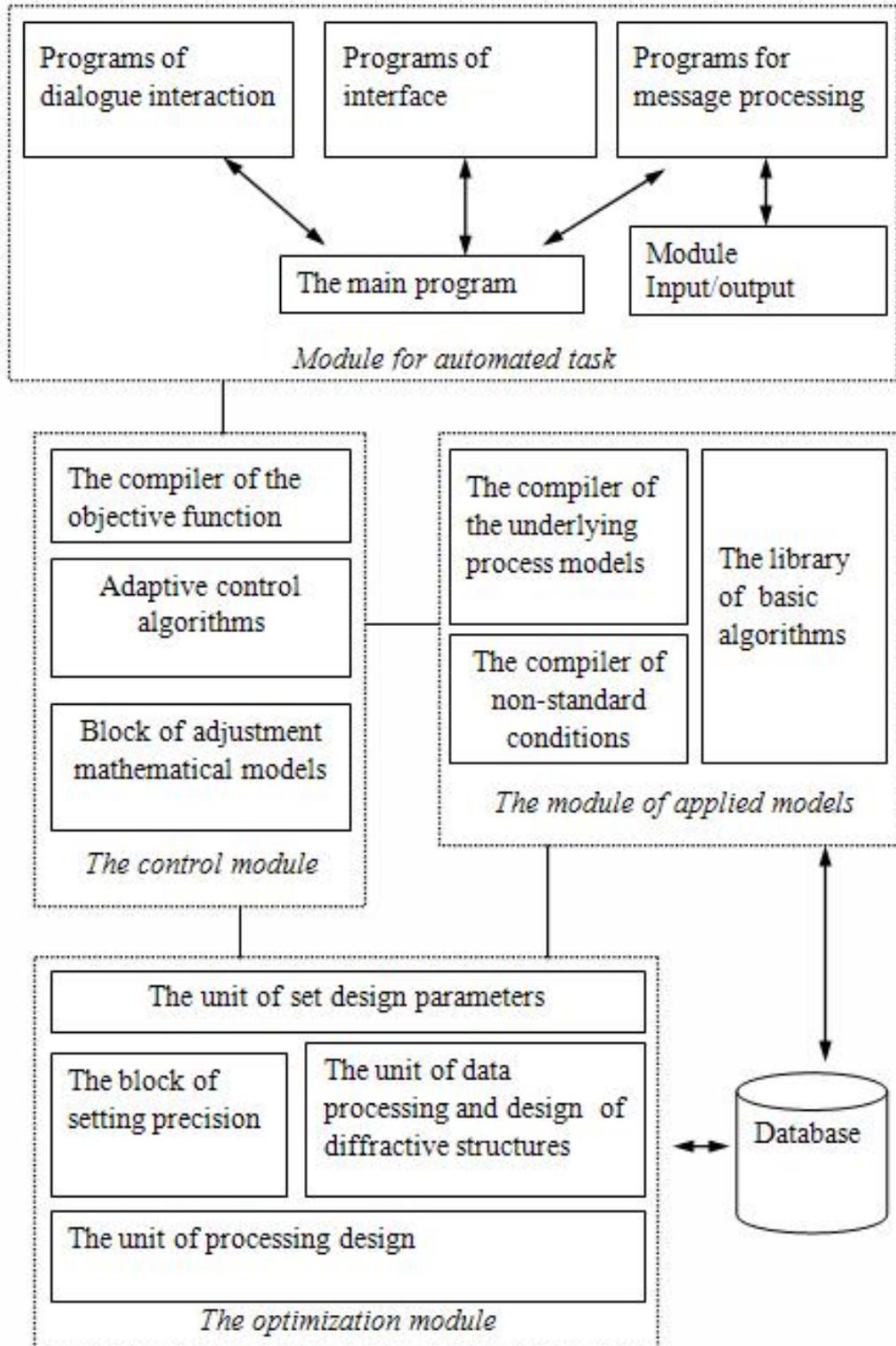


Figure 1. A functional diagram showing a subsystem of optimization of diffractive structure characteristics

The basis of the module of the automated task is the main program transmitting the preferences and settings and creating diffractive structures with a view to adjusting their parameters. To be able to adjust the parameters of the diffraction structures in manual mode, a program processing messages and program dialogue interaction are used. By using the module input and output, the operator can unload from the database the current settings, or set them in manual mode (through manual input or download from the file history settings that were used in the production of diffractive structures).

In the optimization module, a list of operations received from the system top-level management for this particular implementation of the diffractive structure and analysis is given: they set the precision of the optimization and the parameters that characterize the scattering properties of the object. The obtained information is transmitted to the module of applied models characterized by the presence of analytical and numerical models. Input and output parameters for each of the diffraction structures are defined and the target function of optimization is formed. A key feature of the proposed subsystem for the optimization of object parameters is a control module. It uses control algorithms (adjustable model) [6]. This module is responsible for the process of forming the diffraction object, generating and clarifying a mathematical model derived from the applied model module, and transmitting it to the module of the automated tasks: striving for the maximization of the objective function of a number of discrete arguments in imposing functional, topological restrictions. The obtained object parameters and control expressions are logged into a database for the analysis of scattering characteristics of diffractive structures and downloaded in further analyses.

Thus, in the developed subsystem of optimization, the requirements of possible applications for different diffractive structures, the possibility of changing their parameters in the analysis of scattering characteristics of the operator and the loading (restoring) from the database of corresponding parameters in the previous calculations are taken into account.

3. The method of multicriterion optimization of the diffraction structures

Obtainment of the diffractive structures with the desired scattering characteristics is a multi-criteria (multi-factor) challenge [7, 8]. Therefore, optimization of the diffraction structure needs to be multi-criteria –so that it can be carried out in such a way that the operation of the multivariable system [9] will match several criteria, which depend on the output parameters of the diffraction structure.

The method for the main criterion is to be as follows. Depending on the purpose of designing the diffractive structure, as the objective function is selected, the only criterion $f_m(X)$ and the rest of the parameters $f_l(X)$ are taken into account by introducing additional constraints Δ_l :

$$\begin{aligned} f_m(X) &\rightarrow \min \\ f_l(X) &\leq \Delta_l \end{aligned}$$

where $l=1\dots n, l \neq m$.

The main problem in applying this method is the necessity to correctly choose the main criterion and specify the ranges for the remaining criteria. If there are several main criteria, in the case of their mutual contradictions (conflicting criteria), the use of this method is difficult. In addition, an incorrect setting range – for example, placing overly stringent requirements for $f_l(X)$, can lead to an empty set D when manufacturing the diffractive structure with the specified requirements.

On the contrary, with excessively weak restrictions, it is possible to obtain the solution, satisfying some criteria $f_l(X)$ (not meeting the technical specification of the diffraction structure). This can be avoided by using an algorithm, in which each of the quality parameters $f_l(X)$ is designated as the master, and after that the obtained results are compared [10].

In the general case, the main task of optimizing the characteristics of the diffractive structure is by introducing some optimized function $F(X)$, its optimal value:

$$F(X) \rightarrow opt \tag{1}$$

For multi-objective optimization [11]:

$$\mathbf{X} = \{x_1, x_2 \dots x_n\}, X \in D, F = \{f_1, f_2 \dots f_n\}, D \subseteq S \quad (2)$$

where X is the vector of independent variables in some feasible region D (i.e., many possible values of variables), x_i is an unknown, which represents the managed objects (input characteristics) to an optimization problem of the diffraction structures S – space optimization (e.g. – the set of real numbers, R_n).

That is, (1) is the problem of the optimal selection of controlled parameters for a certain class of diffractive structures, which for given n criterion functions $f_k, k=1\dots n$ there are some restrictions ($X \in D$), (for example, the dimensions of the diffractive structures, etc.).

An additional challenge faced during the optimization of diffraction structures is the interaction of these different criteria among themselves, in addition to independent and (or) neutral criteria, there are conflicting ones (mutually contradictory) [11].

One of the most commonly used methods to solve this problem for multi-objective optimization is the use of some model of trade-off (averaging) on the basis of the construction of the Pareto set in the space of criterion functions):

$$H = D_p = \{(f_1(X), f_1(X), \dots, f_n(X)) \in R, X \in D_p\} \quad (3)$$

where D_p is the set of all Pareto points. Thus, from the definition of the Pareto set, there is no point outside of this set for which the values for all criteria $f_i(X)$ are not worse than for the points in the Pareto set [10].

The multi-objective optimization problem is the task of finding Pareto optimal sets of decisions, but the decision "in a forehead" would entail significant time costs, and in some cases would be impossible.

It is possible in the design of diffractive structures to make a decision with less effective parameters, but it provides the best resistance to deviations that arise during the design.

Simplifying the construction of a Pareto-optimal solution for a particular class of diffraction structures is one of the most important tasks to reduce time spent on a search and one to a reasonable level [10].

Let's consider the algorithm for selection the main criterion in the design of the specified class of diffraction structures.

4. The algorithm for selection the main criterion

Let the processes of designing diffractive structures be determined by k parameters (that is, there are k criteria (output parameters) for the specified class of diffractive structures), then we write:

$$F(X) = [f_1(X), f_2(X) \dots f_k(X)] \quad (4)$$

by virtue of (1) and (2), $F(X)$ must strive to the maximum for X in some space optimization S . In the space S must be a number (and even constrained) allowable solutions – A_d .

However, as noted previously, there are contradictory settings in the design of diffractive structures.

Based on the analysis of optimization methods, it is rational to use a discriminatory method of allocating the main criterion [12].

A mathematical model for this case consists in defining a possible option, which provides a maximum for the target function:

$$K(v_i) = \max \left\{ \sum_{k=0}^{n-1} g_k(v_i) \right\} \quad (5)$$

$$g_k(v_i) \geq g_k'$$

where:

$$g_k(v_i) = \sum_{l=0}^{l-1} g_k(p_l) \quad (6)$$

this value specifies parameters, $k=0,1,\dots,m-1$; $g_k(p_l)$ – the values of parameters p_l and v_i – options and the option of a diffraction structure (a set of kinds of parameters); g_k' – limits values of the parameters (approximate); $K(v_i)$ is a generalized criterion (the objective function).

Figure 2 presents an algorithm to detect a major parameter that consists of the following:

in step 1 is the ordering of the elements: that is, for each of the n available options of diffractive structures according to the values of the current (reporting) criterion, the items of different types are sorted in ascending (or descending).

It is proposed to introduce the parameter Σ as the sum of values ordered by element types (or, conversely, the sum of the first values is sorted in ascending order).

Σ is a perfect solution for this diffraction structure (that is, the minimum value of the scattered field, the minimum amount of material for forming the diffraction structures, etc.) [13].

In step 2 is the calculation of range parameters for each of the diffraction structures: e is the number of options:

$$\Delta = y_i^e - \Sigma$$

In step 3 the elements e of the second option, which surpass the value of the parameter Δ are discarded.

In the case of there not being at least one element in any embodiment (a feasible solution does not exist), it is necessary to expand the restrictions and return to step 1.

Step 4 proceeds to the next criterion, as has happened until now, until you have considered all of the criteria.

Next, steps 5 and 6 consist in calculating the value of the object function and the job range of its change. The solver uses elements of different options of diffractive structures. The range of change of the object function is as follows:

$$f(v_i) \geq f_i^{\min} = \frac{f_{\max} + f_{i-1}^{\min}}{2}$$

where $f_{i-1}^{\min} = f^{\min}$ and f^{\min} is the sum of the minimum values of the objective function of each option.

In step 7, the final step, the control of elements in each of the options is carried out (a necessary condition for the existence of the decision) and the decision to expand the restrictions on the fits in the absence of elements of at least one option is to be taken.

The result of the algorithm's work is the decision which is the main criterion for the design of diffraction structures obtained in the last iteration.

5. The use a hierarchy analysis method

After making a list of criteria for further use in the algorithm for selecting the main criterion, it is necessary to determine the relative importance of each of them. The most common method is the formation of evaluation in which the relative importance of each criterion is determined by comparing the criteria that can be assessed by comparing the rated points.

It is proposed to use a method of forming the coefficients of criteria importance, based on Thomas Saaty's [14] method of hierarchy analysis. In the method of hierarchy analysis, the pairwise comparison of the criteria will use the following scale for their evaluation: a scale value of 1:9 represents the nine degrees of superiority of one criterion over the other: five values (1, 3, 5, 7, 9) are the main values, and four (2, 4, 6, 8) are the intermediate ones. In this case, if the quality criterion is less important, inverse values are used for its evaluation: 1, 1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9.

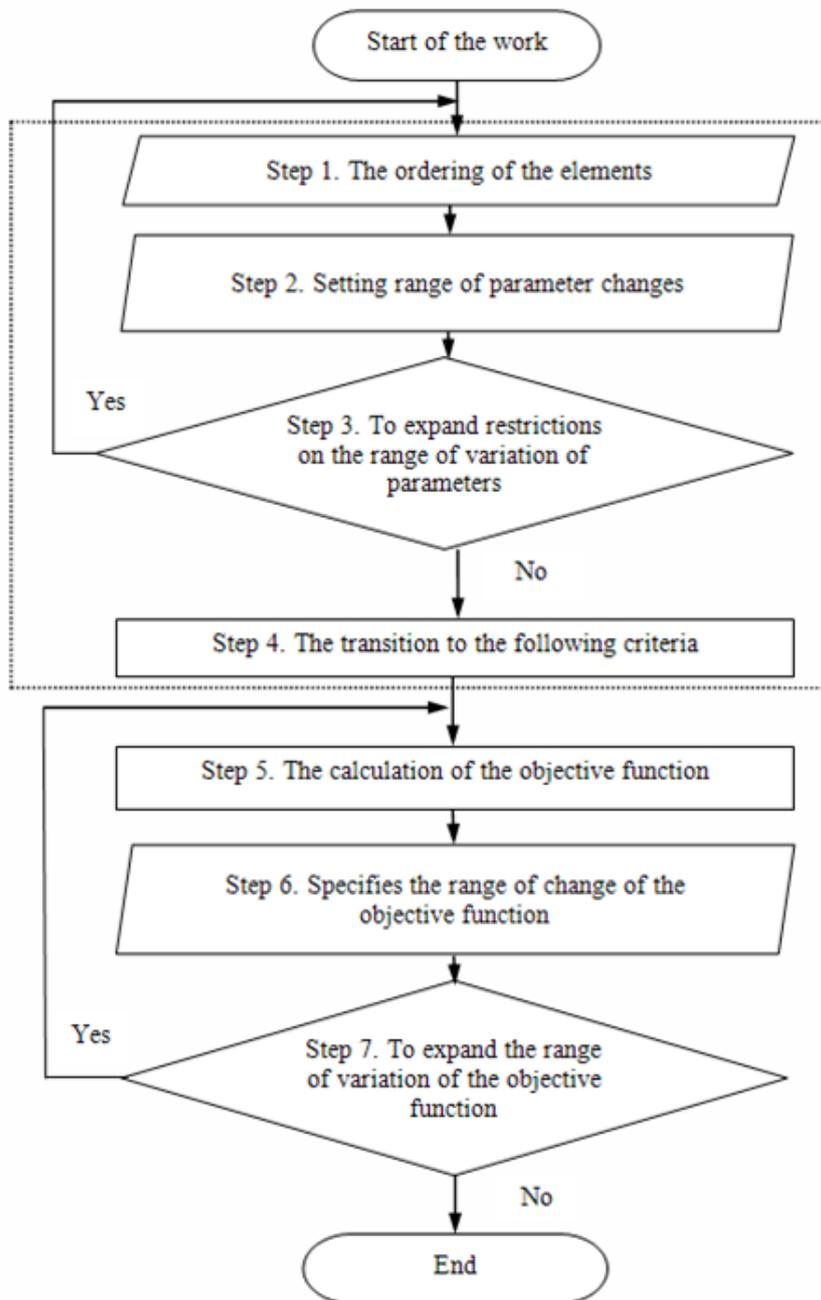


Figure 2. Algorithm for selecting the main criterion for the multi-objective optimization design of diffractive structures.

Below is the matrix of pairwise comparisons of the criteria (Table 1) and the matrix of coordination importance of the criteria (Table 2)

Table 1. The matrix of pairwise comparisons of the criteria.

	Criterion №1	Criterion №2	...	Criterion №n
Criterion №1	1	k_{12}	...	k_{1n}
Criterion №2	k_{21}	1	...	k_{2n}
...				
Criterion №n	k_{n1}	k_{n2}	...	1

Table 2. The matrix of matching the criteria importance.

	Criterion №1	Criterion №2	...	Criterion №n
Criterion №1	1	k_{12}	...	$k_{2n} \times k_{12}$
Criterion №2	$1/k_{12}$	1	...	$1/k_{2n}$
...				
Criterion №n	$1/(k_{2n} \times k_{12})$	k_{n2}	...	1

After filling in the matrix, it is necessary to control the index of consistency of a matrix [14]. To check the correctness of its contents, you must define the index of consistency I:

$$I = \frac{K_{\max} - n}{n - 1} \quad (7)$$

where n is the number of quality criteria, K_{\max} is the maximum eigenvalue. For a consistent matrix, the index of a match is equal to 0. Using the formula (7) the index of consistency of the matrix is calculated and compared to the average index of consistency for random matrices of the same order.

To apply the proposed algorithms to the optimization of production, the 6 estimated parameters are introduced; prior to filling in the table an expert is exposed to one of the most important quality parameters in the optimization [14] (table 3). We performed a simulation in which the artificial increase (deviation) of the weights (factor of importance) of one of the quality parameters in a fully aligned matrix (for dimensions 3, 4 and 5 quality criteria), the threshold [14] requirement, is set out, and proposed to be used to assess the consistency of the matrix after filling of the coefficients of importance by an expert (table 4).

The method of the main criterion from the point of view of the possibility of using it to develop new types of diffractive structures has advantages related to the fact that when using it, you must not specify the exact values of parameters influencing the characteristics of the object being created, but only the ranges of their change. The scattering characteristics were determined on the basis of the method of integral equations [15].

The main input data is: the possible sector of angles, the ranges of the sizes of the structure and angles of the walls, the required minimum possible level of average radar cross section (RCS) in the given sector of angles. The optimization criterion is defined thus: to define the dimensions of the analysed diffractive structure in which in a given angle sector or several sectors of the viewing angles, the average value of RCS is not lower than a predetermined desired minimum possible level.

The limitations of the method are associated with the size of the required memory, which is required for the elements of the matrix that we get after using the method of moments in solving integral equations. The desirable number of input parameters must not exceed 10 and the number of criteria 3 or 4, as with their subsequent increase, the calculations on modern personal computers require not a few minutes, but several tens of minutes.

Table 3. The rate scale of the quality criteria influence.

Rating	The degree of influence	Comment
1	the equivalence of parameters	
3	some advantage (not essential)	
5	strong superiority (important)	
2,4	intermediate values	2 – the criterion of weak (minimal) advantage 4 – a distinct advantage
6	important criterion	the most important criterion
0	incomparable criteria	Difficult for an Expert to estimate

Table 4. Indices of matrices coherence for the proposed rate scale.

The number of parameters	1	2	3	4	5	6
The value of a random index of consistency	0	0	0,31	0,46	0,49	0,53

6. The results of the optimization of the diffraction structure

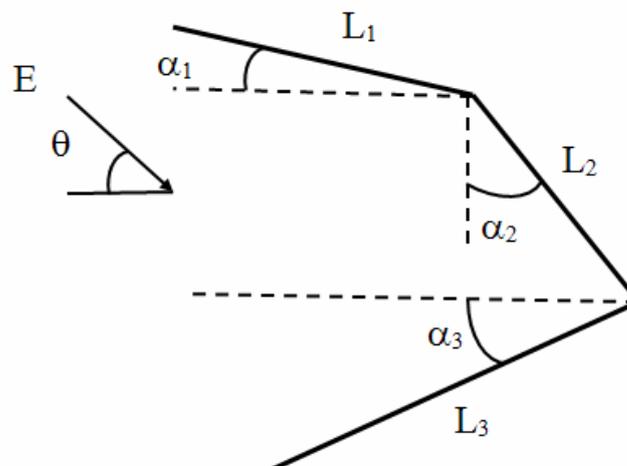


Figure 3. An example of the diffraction structure which is being investigated. Here: L_1 , L_2 , L_3 are the typical dimensions of the structure, α_1 , α_2 , α_3 are the angles of inclination of the walls of the hollow structure, E is the vector of the incident electromagnetic wave; θ is the angle of flat electromagnetic wave.

The following limitations for parameters were set: $0^\circ \leq \alpha_1 \leq 30^\circ$, $0^\circ \leq \alpha_2 \leq 25^\circ$, $0^\circ \leq \alpha_3 \leq 31^\circ$, $4.5\lambda \leq L_1 \leq 6.4\lambda$, $5.1\lambda \leq L_2 \leq 7.2\lambda$, $4.7\lambda \leq L_3 \leq 6.8\lambda$, $L = L_1 + L_2 + L_3 \leq 19.5\lambda$, where λ is the length of the incident electromagnetic wave.

It was necessary to design a diffraction structure, which has the value of the average RCS in the range of $10^\circ \leq \theta \leq 26^\circ$ not exceeding 20 dB.

As a result of using this approach the following structure parameters were determined: $\alpha_1 = 5^\circ$, $\alpha_2 = 6^\circ$, $\alpha_3 = 3^\circ$, $L_1 = 5.1\lambda$, $L_2 = 5.7\lambda$, $L_3 = 4.9\lambda$.

7. Conclusion

As can be seen from the above, this paper introduces an efficient method of designing diffractive structures with the desired characteristics, based on the selection of the main criterion. The obtained results can be used to solve problems related to the management of the scattered electromagnetic field.

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