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DESIGN OF CONTROL SYSTEMS BY A METHOD OF STRUCTURAL FUNCTIONS

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Abstract. An approach to purpose-oriented design of the complex dynamic systems based on presentation of the system as a structural oriented graph is considered. The arcs of this graph are described by a pair of structural functions, which reflect an internal structure of a system based on its decomposition with use of amplifiers and integrators. The method of design is based on the use of structural criteria formulated in the form of structural functions.

Key Words. Structural design, modal control, control systems, oriented graph, structural functions

1. INTRODUCTION

An important stage in development of complex dynamic systems, determining their functioning efficiency, is the design of the structure and parameters of controllers. In practice, the most popular approach to the structural design of control systems, is based on experience accumulated by developers, designing similar systems. However, this approach is justified only for such dynamic systems, the controlling elements of which have rather simple structure, and which in the process of their development do not undergo any significant modifications.

At present, it is possible to point out two main approaches of describing the problems and methods of analysis and design of complex dynamic systems [1]:
1) based on the use of classical operator-frequency methods;
2) based on the use of equations in state space.

Each of these methods in the theory of graphs corresponds to graphic representation of the system in the form of oriented graph of signals, as well as oriented graph of signals and states.

The advantage of the first approach is its simplicity and obviousness, as well as the possibility of description of multivariable control systems both at the level of subsystems, elements and links between them, and at the level of the system as a whole, what has caused its broad application in engineering practice. The second approach reflects most completely the internal structure of a dynamic system.

It is topical to develop a formalised approach to the choice of structures of complex dynamic systems that would unite advantages of both forms of description of the systems and would allow to form a structure of the system in compliance with selected criteria. In order to solve this problem, a method of presentation of the structures of dynamic systems in the form of structural functions is proposed. They include information about the internal structure of dynamic system which can be represented as some composition of amplifiers and integrators. The corresponding criteria of structural design for modal control systems are considered.

2. PROBLEM STATEMENT OF MODAL CONTROL WITH USE OF GRAPH THEORY

Suppose that the dynamic properties of a system are described by linear differential equations and can be represented by appropriate oriented graph of signals and states. It is supposed also that required dynamic properties of the system are ensured by the given distribution of roots of characteristic polynomial of the closed–loop system $D(s)$ on a complex plane, that means a fulfilment of condition:

$$D(s) = D^*(s), \qquad (1)$$

where $D(s) = s^n + d_{n-1} s^{n-1} + ... + d_0$;
$D^*(s) = s^n + d_{n-1}^* s^{n-1} + ... + d_0^*$.

In accordance with [2], let us consider a structure of controlling part of a system as acceptable if it provides the fulfilment of the following conditions of design:
1) mathematical correctness of design problem;
2) structural stability of a system;
3) the given order of astatism;
4) physical feasibility of controller.

Then, it is possible to formulate a problem of structural design. Let us suppose that the structure of invariable part of a system, satisfying the condition of full controllability, the set of correcting elements of controlling part, and the restrictions imposed on the means of connection of the mentioned parts are specified. This all allows to construct the algebra of structures which inductively describes a set of possible structures S of controller for investigated problem.

It is necessary to organise a choice of possible structures from a set S_d, where $S_d \in S$, in order to satisfy to the given conditions of quality, formulated by equation (1).

In order to obtain the solution of (1), i.e. to provide the equality of coefficients $d_i = d_i^*$ for identical degrees s^i of polynomials $D(s)$ and $D^*(s)$, a set of non-linear algebraic equations can be written:

$$d_i^* = f_i(\alpha_1, \alpha_2, \ldots, \alpha_r), \quad i = 0,1,2..., n-1, \qquad (2)$$

where $\alpha_1, \alpha_2, \ldots, \alpha_r$ are the varied parameters of controlling part. As a result of solving the equations (2) at the stage of parametrical design, the unknown parameters $\alpha_1, \alpha_2, \ldots, \alpha_r$ of the controller can be determined. An exact form of the equations of design is a priori unknown and determined by selected structure.

The correct design also supposes, that the designed structure should correspond to a criterion of minimum complexity of controlling part of a system. Taking into account (2), this criterion can be written as follows:

$$r = min, \qquad r \geq n. \qquad (3)$$

Let us introduce the following definitions. Let W and V be finite sets, elements of which are called as arcs and nodes, accordingly. The directed pseudo-graph is a function $j : W \to V^2 = V \times V$, that maps a set of arcs to Dekart product of the set of nodes. Let $l : W \to \{0,1\}$ be a mapping, indicating weights of the arcs. It is assigned in correspondence with a type of dynamic element. If w is an amplifier, then $l(w) = 0$; if w is an integrator, then $l(w) = 1$. Let k: $W \to R \setminus \{0\}$ be a mapping in a group of real numbers by multiplication. The meaning of the mapping on an arc $w \in W$ is called as an amplification factor of an arc.

Let $v_i \in V, w_j \in W$. A sequence $v_1 \cdot w_1 \cdot v_2 \cdot w_2 \cdot ...$ $... \cdot v_n \cdot w_{n+1} \cdot v_{n+1}$ is called as directed path from node v_1 to node v_{n+2}, if for every i = 1,2..., n, $j(w_i) = (v_i, v_{i+1})$. If all nodes of directed path are pairwise different, it is a path. A path, which begins and finishes in the same node, is a loop. A set of the loops that do not cross themselves in any nodes,. are called as a factor.

Then, in correspondence with [3], the characteristic polynomial D(s) can be calculated according to oriented graph of signals and states as follows:

$$D(s) = s^{m^*} + \sum_{m_*}^{m^*} \left[\sum_{l(F)=i} k(F) \right] s^{(i-m^*)}, \qquad (4)$$

where $k(F) = \prod_{\theta \in F} k(\theta)$ - gain of the factor F;

$k(\theta) = \prod_{w \in \theta} k(w)$ - gain of the loop θ,

$l(F) = \sum_{\theta \in F} l(\theta)$ - weight of the factor F;

$l(\theta) = \sum_{w \in \theta} l(w)$ weight of the loop θ,

m_* and m^* are minimum and maximum weights of the factor in oriented graph of a system, accordingly.

Transforming (4), in general case (when $m_* = n$, and $m^* = 0$) we will get:

$$D(s) = (1 + z_0) s^n + z_1 s^{n-1} + ... + z_j s^{n-j} + ... + z_n, \qquad (5)$$

where z_j is a sum of values of all factors whose weight is equal to j.

It follows from the last expression that the order of characteristic polynomial $D(s)$ of closed-loop system is determined by maximum weight m^* of the factors of oriented graph of signals and states. Here the value of the coefficient d_i of polynomial $D(s)$ is determined by values of factors, whose weights are equal to $(i\text{-}n)$.

Let us pass from such abstract concept, as a factor, to its concrete formation – the loops of oriented graph. For this purpose let us consider the following definitions. A loop will be called constant loop, if it does not contain arcs with varied coefficients, i.e. the loop is formed only by arcs of invariable part of a system. A loop is called as varied loop, if it contains at least one arc with varied coefficients of the controlling part of the system from a set of parameters $\{a_1, a_2, ..., a_r\}$.

Taking into account the last statement and equations (4) and (5) the necessary condition of solvability of a set of equations (2) can be formulated as follows. For solvability of a set of equations (2) it is necessary that the indicated oriented graph of a system should contain at least one varied loop q^{var} of weight $l(q^{\text{var}}) = i$ for all i = 1,2..., n.

It is obvious that for correct solving the set of equations (2) it is necessary that oriented graph of signals and states of a system should not contain the loops whose weight is equal to zero (that form factors whose weight is equal to zero), otherwise the number of equations of design grows up to $(n+1)$.

It is obvious that for the structural stability of a system concerning absence of lacunas (zero coefficients by some degrees of s) in a characteristic polynomial of closed-loop system $D(s)$ it is necessary that oriented graph of a system contains at least one loop θ, weight which is equal to $l(\grave{e}) = i$ for all i=1,2,…,n, because it follows from (4) that availability of at least one weight loop of i leads to existence of weight factor i in the initial graph.

Another important requirement to the structure of multivariable controller is connected with required accuracy of a system at stable operation modes. As it is known, multivariable control system has the àstatism of order h with regard to the vector of reference actions $g(t) = \|g_i(t)\|_{n\times 1}$ if its transfer matrix by error $\Phi_e(s)$ is as follows [4]:

$$\Phi_e(s) = \mathrm{I} - \Phi(s) = s^n \tilde{\Phi}_e(s), \tag{6}$$

where the value s=0 is not a pole for the elements of matrix $\Phi_e(s)$. And, besides, $lim \tilde{\Phi}_\varepsilon \neq 0$. A structural criterion of astatic system supposes the presence of integrators between a point of error measurement and a point of disturbance action.

Thus, the required order of astatism $\boldsymbol{n}$ (in a sense of (6)) is ensured, if all the elements $W_{ij}(s)$ $(i,j$=1,2,…, $n)$ of transfer matrix $W(s)$ of open-loop system have $\boldsymbol{n}$ zeros, i.e. $\boldsymbol{n}$ last coefficients of polynomials $B_{ij}(s)$ (denominators of $W_{ij}(s)$) are equal to zero.

So, taking into account (6), the necessary and sufficient condition of astatism of a system can be formulated as follows: n-order system has an astatism of $\boldsymbol{n}$ -order with respect to a vector of reference actions $g(t) = \|g_i(t)\|_{n\times 1}$, if and only if the subgraph of open-loop system does not contain any factor with weights from $(n - \boldsymbol{n} + 1)$ up to n.

An additional restriction at design of a system imposes a requirement of physical feasibility [3], which means, that realisation of controlling part of a system must not use the operations of "pure" differentiation. This condition is executed automatically, if design of controller structure is carried out at the oriented graph of signals and states on the base of arcs - integrators and arcs - amplifiers, because in this case the realisation of transfer functions of correcting elements does not use ope differentiating elements.

3. STRUCTURAL GRAPH ON THE BASIS OF STRUCTURAL FUNCTIONS

Let's introduce a structural oriented graph $[C_p, E_p]$. Here C_p is a set of nodes, defining the set of controlling actions $\{u_1^0(t),..., u_n^0(t)\}$, the set of reference actions $\{g_1^0(t),..., g_n^0(t)\}$, the set of controlled variables $\{y_1^0(t),..., y_n^0(t)\}$ or coordinates of state $\{x_1^0(t),..., x_n^0(t)\}$ of a system. The arc belonging to the set of arcs E_p and directed from the node i to the node j corresponds to the pair of structural functions (L_{ij}, Q_{ij}) which are determined as follows:

$$L_{ij} = l_{ij,n}\, l_{ij,n-1} \ldots l_{ij,k} \ldots l_{ij,l}\, l_{ij,0}; \tag{7}$$

$$Q_{ij} = q_{ij,n}\, q_{ij,n-1} \ldots q_{ij,k} \ldots q_{ij,l}\, q_{ij,0}. \tag{8}$$

Here the numbers $l_{ij,k}$ in position number k of the structural function L_{ij} ($l_{ij,k} \in N$ - subset of integer positive numbers), are equal to the number of direct paths whose weight is equal to k and that are contained in the initial oriented graph of signals and states between the node by number i and the node by number j. A path of weight k is a path which passes through k consequently connected integrators. The number $q_{ij,k}$ in position number k of the structural function Q_{ij} ($q_{ij,k} \in N$) is equal to the number of loops whose weight is equal to k (these loops are formed by means of arcs that pass through k consequently connected integrators) and that are contained in the initial oriented graph of signals and states between the node by number i and the node by number j.

It was shown in [5] that the structure of any physically feasible link can be described by the pair of structural functions (L,Q) according to the form of its transfer function. Thus, in general case, the structural functions (L,Q) of the arc of structural oriented graph for the link with transfer function:

$$W(s)=\frac{a_m s^m + a_{m-1}s^{m-1} + ... + a_1 s + a_0}{b_n s^n + b_{n-1}s^{n-1} + ... + b_1 s + b_0}, \quad (m \le n), \qquad (9)$$

will look like:

$$L = 11...10...0; \quad Q = 11...10, \qquad (10)$$

where (n-m) lower-order digits of structural function L and the least-order digit of structural function Q contain zeroes.

It is possible to show, that if a coefficient b_i in a denominator of a transfer function (9) is equal to zero, it means that its oriented graph of signals and states does not contain a loop with a weight (n-i). Similarly, if a coefficient a_j in a numerator of a transfer function of (9) is equal to zero, it means that its oriented graph of signals and states does not contain a direct path with a weight (n-j).

The advantage of the offered method of description of the structures of linear systems is that the transformations on a structural oriented graph can be carried out with use of rather simple mathematical operations. According to [5], for parallel connection of n dynamic links with transfer functions $W_i(s)$, which can be described by structural functions (L_i,Q_j), the equivalent structural functions (L,Q) are determined as follows:

$$L = L_1 + L_2 +... + L_n; \quad Q = Q_1 + Q_2 +... + Q_n. \qquad (11)$$

The structural functions (L,Q) for consequent connection of n dynamic links can be determined as follows:

$$L = L_1 \times L_2 \times_{...} \times L_n; \quad Q = Q_1 + Q_2 +... + Q_n. \qquad (12)$$

If we have a reverse connection of a dynamic link, having transfer function $W_1(s)$ and structural function (L_1,Q_1), with a dynamic link, having transfer function $W_2(s)$ and structural function (L_2,Q_2), then structural functions (L,Q) of the equivalent arc of the structural oriented graph are determined as follows:

$$L = L_1; \quad Q = Q_1 + Q_2 + L_1 \times L_2. \qquad (13)$$

The offered operations of transformation of the structure of the system with the aid of structural functions can be used while analysing structural properties of the system on the appropriate structural oriented graph for determination of equivalent structural functions of the closed loop system as a whole.

4. REQUIREMENTS TO THE MODAL CONTROL PRESENTED BY STRUCTURAL FUNCTIONS

Let a set of structural functions correspond to a structure of controlling part of a system:

$$\{(L^j_{ce}, Q^j_{ce}) \mid j = 1, 2, \ldots, N_{ce}\}$$

where $L^j_{ce} = l_{j,n} l_{j,n-1} .. l_{j,k} .. l_{j,0}$;
$Q^j_{ce} = q_{j,n} q_{j,n-1} ... q_{j,k} ... q_{j,0}$;

and N_{ce} is a quantity of correcting elements. Then the problem of the structural design of controlling part of a system can be reduced to a search in the framework of the given set of tolerable nodes of variable part of a system using a set of structural functions $\{(L^j_{ce}, Q^j_{ce})\}$ that satisfy some sets of tolerable values L^* and Q^*, which ensure the fulfilment of the given requirements to tolerable structure of the system.

The solution of the problem of structural design in considered statement because of the properties of structural oriented graph is guaranteed in a class of physically realised correcting elements. Taking into consideration, that the structural oriented graph completely reveals the internal structure of the system described by initial oriented graph of signals and states, the requirements to the accepted structure of modal controller concerning structural oriented graph, taking into account the earlier obtained results to oriented graph of signals and states can be formulated as certain restrictions to the type of appropriate structural functions.

4.1. Structural Stability

In order to secure structural stability of a system, it is necessary that in all positions, except the lowest of equivalent structural function Q^{closed} of a closed-loop system, there must be non-zero values, i.e the following condition must be fulfilled:

$$q_i^{closed} \neq 0, \quad for\ all\ i = 2,..., (n+1) \qquad (14)$$

The equivalent structural function Q^{closed} is calculated on the structural oriented graph of closed-loop system as a sum of equivalent structural functions Q^{loops} for all its loops, i.e.

$$Q^{closed} = \sum_{j=1}^{N_{loops}} Q_j^{loops} \ , \qquad (15)$$

where N_{loops} is total number of loops of a structural oriented graph.

4.2. The required order of astatism

The required order of astatism in multivariable control system can also be determined with the aid of structural functions Q. The closed-loop system of order n has astatism of order $\boldsymbol{n}$, if in all the equivalent structural functions Q_{ij}^{open} between the i-th input nodes and the j-th output nodes of structural subgraph of open-loop system, the higher order positions, beginning with position number (n -$\boldsymbol{n}$+2) up to position number (n + 1) are equal to zero, and the position number (n-$\boldsymbol{n}$ +1) is not equal to zero, that is the following condition should be provided:

$$q_{ij,k}^{open} = \begin{cases} = 0, & for\ \ all\ \ k = \overline{(n - \boldsymbol{n} + 2), n+1}; \\ \neq 0, & for\ \ all\ k = (n - \boldsymbol{n} + 1), where\ \ k \neq 0. \end{cases} \qquad (16)$$

4.3. The condition of mathematical correctness

The necessary condition of mathematical correctness of the problem of design can be taken into account directly according to the form of equivalent structural function Q^{var}, that contains information about variable loops of a system and can be calculated similarly to (15) as the sum of all equivalent structural functions Q_j^{var} of variable loops of a structural oriented graph, that is

$$Q^{var} = \sum_{j=1}^{M_{var}} Q_j^{var}, \qquad (17)$$

where M_{var} is a total quantity of variable loops.

It is obvious, that in this case a condition, similar to (14), should be fulfilled for Q^{var} that means the necessity of the presence of non-zero elements in all the positions except the lower-order one. Here the total quantity of varied loops, determined as a sum of values of all positions q_i^{var}, should not be less than the order of characteristic equation of the closed-loop system. Therefore, the necessary condition of mathematical correctness of a design problem of a structure of modal controller with use of a structural oriented graph can be presented as follows

$$q_i^{var} \neq 0,\ for\ \ all\ \ i = 2,..., (n+1); \sum q_i^{var} \geq 0. \qquad (18)$$

Let us unite a set of numbers $l_{j,k}$ and $q_{j,k}$ that form a set of structural functions of the controlling part $\{(L_{ce}^j, Q_{ce}^j) | j = 1,2,..., N_{ce}\}$, to the vector of variable parameters $g = (g_1, g_2,...,g_r)^T$. Then, taking into account the above mentioned, the design of the structure of modal control system by the method of structural functions can be solved with relation to the variable parameters $g_1, g_2,..., g_r$ of the following set of equations of structural design:

$$q_i^{var^*} = v_i(g_1, g_2,..., g_r),\ i = 1,..., (n+1), \qquad (19)$$

where $q_i^{var^*}$ is the value of i-th position of a desirable structural function Q^{var^*}, that is formed with account of expressions (15), (16) and (18). Solving the set of equations (19) in order to ensure the criterion of minimum complexity, it is also necessary to take into account the fulfilment of the condition (3).

5. EXAMPLE

Let's consider an example of structure design of astatic modal controller for gas-turbine engine. The controlled plant is described by the following system of linear differential equations:

$$\begin{cases} \dfrac{dx_1}{dt} + a_{11}x_1 - a_{12}x_2 = b_2u_2; \\ \qquad x_2 + a_{21}x_1 = b_1u_1, \end{cases}$$

where x_1 - a frequency of rotation of turbo-compressor; x_2 - a temperature of gas before the turbine; u_1 - a square area of a cut of the jet nozzle; u_2 - fuel flow rate in the combustion chamber.

In correspondence with above-stated, design of a structure of the correcting part of a system can be realised as a search for values of a set of the structural functions between a set of input possible nodes $\{\varepsilon_1, \varepsilon_2\}$ and a set of output possible nodes $\{u_1, u_2\}$ (fig.1), that is to determine the values of structural functions: $(L_{u_1e_1}^{ce}, Q_{u_1e_1}^{ce})$; $(L_{u_1e_2}^{ce}, Q_{u_1e_2}^{ce})$; $(L_{u_2e_1}^{ce}, Q_{u_2e_1}^{ce})$; $(L_{u_2e_2}^{ce}, Q_{u_2e_2}^{ce})$.

Taking into account the requirement of astatism $(n = 1)$, the structure of a controller will correspond to a criterion of minimum complexity, if the order of transfer functions $W^{ce}_{u_i e_j}(s)$ of correcting elements is not more than one, that is their search is limited to a following set $\left\{0,\ r^0_{u_i\varepsilon_j}\big/ s,\ r^1_{u_i\varepsilon_j}s + r^0_{u_i\varepsilon_j}\big/ s;\ i, j = 1{,}2\right\}$. Hence, it follows, that all the equivalent structural functions look like $Q^{ce}_{u_i e_j} = 00$, and a set of possible values for all the structural numbers $L^{ce}_{u_i e_j} = l_{ij,2}l_{ij,1}$ (where i,j = 1,2) will have the following form: {00, 10, 11}, because in the case, if $L^{ce}_{u_i e_j} = 01$ the condition of astatism in the system is violated.

With account of (18), Q^{var} can be calculated from the following expression:

$$Q^{\mathrm{var}} = 10\times L^{ce}_{u_1e_1} + 10\times L^{ce}_{u_2e_2} + L^{ce}_{u_1e_2} + \\ + 10\times L^{ce}_{u_2e_1} + 10\times L^{ce}_{u_1e_1}\times L^{ce}_{u_2e_2}. \tag{20}$$

As a result of solution of a system (20), it is possible to obtain three variants of a structure of the modal controller meeting the requirements to possible structure, which with respect to the input vector $\varepsilon = (\varepsilon_1, \varepsilon_2)^T$ and output vector $u = (u_1, u_2)^T$ can be described by the following matrix numbers:

$$L^I_{ce} = \begin{Vmatrix} 11 & 00 \\ 00 & 10 \end{Vmatrix};\ L^{II}_{ce} = \begin{Vmatrix} 10 & 00 \\ 00 & 11 \end{Vmatrix};\ L^{III}_{ce} = \begin{Vmatrix} 10 & 10 \\ 00 & 10 \end{Vmatrix},$$

to which the following transfer functions correspond:

$$W^I_{ce}(s) = \begin{Vmatrix} W^{ce}_{u_1e_1}(s) = \dfrac{r^1_{u_1e_1}s + r^0_{u_1e_1}}{s} & 0 \\ 0 & W^{ce}_{u_2e_2}(s) = \dfrac{r^0_{u_2e_2}}{s} \end{Vmatrix};$$

$$W^{II}_{ce}(s) = \begin{Vmatrix} W^{ce}_{u_1e_1}(s) = \dfrac{r^0_{u_1e_1}}{s} & 0 \\ 0 & W^{ce}_{u_2e_2}(s) = \dfrac{r^1_{u_2e_2}s + r^0_{u_2e_2}}{s} \end{Vmatrix};$$

$$W^{III}_{ce}(s) = \begin{Vmatrix} W^{ce}_{u_1e_1}(s) = \dfrac{r^0_{u_1e_1}}{s} & W^{ce}_{u_1e_1}(s) = \dfrac{r^0_{u_1e_2}}{s} \\ 0 & W^{ce}_{u_2e_2}(s) = \dfrac{r^0_{u_2e_2}}{s} \end{Vmatrix}.$$

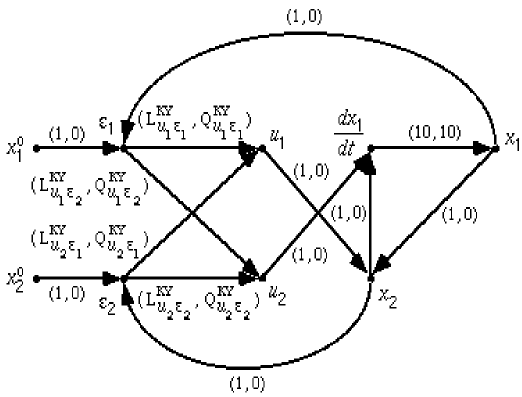

Fig.1. Structural graph of control system

6. CONCLUSIONS

In this paper a formalised method of describing the structures of complex dynamic systems, based on representation of a structure of system as a structural oriented graph is offered. The arcs of oriented graph are described by a pair of structural functions, which reflect an internal structure of a system based on its decomposition with use of amplifiers and integrators. It is shown that the requirements to the structure of designed system can be formulated as the requirements to appropriate structural functions. On the base of using such approach, it is possible to develop high-effective procedures of purpose-oriented, formalised design and analysis of the structure of complex dynamic systems. In the future, in order to solve this task, an evolutionary approach based on use of genetic algorithms is planned to develop.

7. REFERENCES

[1] Krasovsky A.A. Hand-book of the theory of automatic control, Nauka, Moscow, 1987 (in Russian).

[2] Vasilyev V.I. and Shaimardanov F.A. Design of multivariable automatic systems by method of ordinal map, Nauka, Moscow, 1983 (in Russian).

[3] Babak S.F., Ilyasov B.G., Rutkovskij V.Yu. Method of Analytical Calculation of Coefficients of Transfer Functions of Multivariable Systems. – Proceedings of Academy of Sciences of the USSR, vol.290, Num.3, 1986 (in Russian).

[4] Babak S.F., Vasilyev V.I., Ilyasov, B.G. et. al. *Fundamentals of the Theory of Multivariable* Systems of Automatic Control of Flighying Vehicles. – Moscow Aviation Institute, Moscow, 1995 (in Russian).

[5] Ilyasov B.G., Munasypov R.A. and Munasypova E.S. Design of Structures of Control Systems of Rocket Power Plants by Method of Functional Structural Numbers. – Proceedings of IV Scientific-Technical Workshop “Problems of Design and Experimental Exploration of Controlled Energetic Plants of Special Use”, Miass, 1996 (in Russian).