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SYNTHESIS METHOD OF THE OPTIMUM STRUCTURE OF THE PROCEDURE FOR THE CONTROL OF THE TECHNICAL STATUS OF COMPLEX SYSTEMS AND COMPLEXES

Synthesis method of the optimal structure of the procedure for controlling the technical state of complex systems and complexes is developed, which allows obtaining the optimal range of control parameters. It allows timely to detect failures, that is, to increase the reliability of the use of working complex systems and complexes. The problem of optimal parametric adaptation is considered, that is, determination of the ability of complex systems and complexes to reconfigure according to the change of operating conditions. The LaGrange method is proposed to solve this problem.

Keywords: *Control of technical condition, synthesis, adaptation, Complex systems and complexes.*

Formulation of the problem

In the practice of controlling the technical condition of complex systems and complexes, there are problems of ensuring the maximum efficiency of its use during operation due to the timely detection of failures, which achieved by choosing the optimal range of control parameters [1]. These tasks in a general statement can be described as follows.

The given operator $G(q)$, which depends on the vector of control parameters of the technical state of complex systems and complexes, $q=\{q_1, q_2, ..., q_n\}$, where n – the number of control parameters. Permissible values of parameters are imposed by restrictions in the form of functions

$$\varphi_i(q)=0, \quad i=\overline{1,m}, \qquad (1)$$

where m – number of restrictions.

Set function of the object, which depends on the operator of the system $G(q)$ and "vector of the situation" ξ: $\Phi\{\xi, G(q)\}$.

It is necessary to determine the vector of parameters q, which satisfies the relation (1) and provides the extremum (maximum or minimum) of the function Φ.

In some simple cases, the operator may be known in an analytical form, for example, a transient or transferable system function may be known, depending on the value of the parameters q_j, $j=\overline{1,n}$. In other cases, the structure of the operator may not be known in the analytical form and information about the technical state of a complex system is obtained only by the results of measurements of its initial reaction.

The results of measurements can be used also in those cases where the analytical form of the operator of complex systems and complexes can be calculated but due to the considerable complexity of the system and the presence of its significant nonlinearity, such calculation is labour-intensive.

The vector of the situation ξ can have both finite and infinite number of components. In the latter case, its components may be, for example, the value of the function of time or frequency.

The goal function may either be deterministic fully known or represent a mathematical termination by a possible set of situations. Thus, the function of the purpose (efficiency of the intended use) depends on the conditions of operation from the nomenclature of the parameters of the control of the technical state of complex systems and complexes.

Literature route

In the literature on the choice of the nomenclature of the parameters of the control object are considered some individual generalized cases [2–7].

1. Control parameters of complex systems and complexes. The situation vector in this case is either the output signal of the system as an object of control (with time methods), or amplitude and phase-frequency characteristics (with frequency methods) [2]. The objective function depending on the method of processing the output signal – either the magnitude of the signal of agreement or when using the Bayesian criteria for evaluation, the average risk.

2. The identification task. There are various options for setting up an identification task. For example, in identifying the initial reaction by the functional of the goal, there is a discrepancy between the vector of the initial reaction of complex systems and complexes and the initial reactions of standard models. Identification is reduced while minimizing the function of the target by the set of models.

3. The control task using a controlled object model is to choose a vector of model parameters that minimize the function of the target Φ for example, the magnitude of the discrepancy between the output signal of the system and its model.

4. The problem of optimal adaptation of complex systems and complexes in the changing environment vector ξ. The situation vector in this case may be those or other parameters of the transient, amplitude or phase-frequency characteristics of complex systems and complexes. For example, for a stabilization controller it can be the magnitude and phase reserves, gain, cut-off frequency etc. The objective function in this case is an assessment of the quality of adaptation, which characterizes the degree of proximity of the desired (necessary) and actual parameters of the complex system.

The given task is recently relevant in connection with the need to use systems of stabilization of a permanent structure for the management of objects, different in their characteristics [3]. It is necessary in the transition from one structure of a complex system to another to carry out the minimum necessary reconfiguration (to make the minimum necessary change of parameters q_j).

The purpose of this article is to develop a method for synthesizing the optimal structure of the procedure for controlling the technical condition of complex systems and complexes by solving the problem of optimal parametric adaptation.

Main part

When solving the task of reconfiguring the structure of the procedure for controlling the technical condition of complex systems and complexes, there is a question of determining its ability to adapt.

The ability to adapt a complex system will be higher, the greater the growth of the target function at a given value of system parameters change. The ability of the system to adapt will be called lability ("mobility") (lability – functional mobility. Lability characterizes the time during which the system (object) restores its characteristics after reconfiguring the constituent elements) [4].

We introduce a quantitative estimate L of the integrity of the complex system.

Let the parameters of a complex system Δq_j have allowable deviations of the growth Δq_j that satisfy the conditions of communication (1), then the corresponding increase in the function of the goal is:

$$\Delta\Phi = \Phi(q_1 + \Delta q_1, ..., q_j + \Delta q_j, ..., q_n + \Delta q_n) - \Phi(q_1, ..., q_j, ..., q_n).$$

Let's denote δq_j $j = \overline{1, n}$ as the relative increment of parameters (assigned to nominal values): $\delta q_j = \Delta q_j / q_{nom\,j}$. Fix the "length" of the vector $\|\delta q\| = \sqrt{\sum_{j=1}^{n} \delta q_j^{\,2}}$. For different directions, that is for different ratios between components δq_j, the magnitude of the increment $\Delta\Phi$ will be different. The ratio $\delta\Phi / \|\delta q\|$, where $\delta\Phi = \Delta\Phi / \Phi_{nom}$ characterizes the lability of a complex system in this direction that is, at a given ratio between the values δq_j, $j = \overline{1, n}$ For some direction, the value $\delta\Phi$ (for a fixed value $\|\delta q\|$) will be maximal. Then, for the evaluation of the lability of the system, use the value

$$L = \lim_{\|\delta q\| \to 0} = \frac{\delta\Phi_{max}}{\|\delta q\|}. \qquad (1)$$

The value L has the following physical meaning. Because $\|\delta q\|$ is a quantitative measure of the "rebuilding" of the system, then L is the maximum possible relative increase in the function of the target, which involves the individual reconfiguration of the control parameters of the complex system The value of L allows to estimate the potential capacity of a complex system for adaptation, for example, from several systems choose the one for which the required degree of adaptation is obtained by minimizing the reconfiguration; or reject the system for which adaptation is achieved at a very significant reconfiguration.

Lets note that the L estimate is useful in the alternative adaptation task, when requirements are submitted to the system for the accuracy of its initial characteristics. In this case, the advantage must be given to "hard" systems, systems with low L lability.

The L value can be determined by the parameters of the control of a complex system. So, the calculation of the $\delta\Phi$ maximum value with additional restrictions (1) and $\|\delta q\| = \text{const}$ is proposed to be carried out with the help of the Lagrange method [5]. Let's sum up the Lagrange function Ψ:

$$\Psi = \Phi - \sum_{i=1}^{m} \lambda_i \varphi_i - \frac{1}{2}\mu \sum_{j=1}^{n} \delta q_j^{\,2}, \qquad (2)$$

where μ – matching factor.

Value δq_j we can find from $\partial\Psi / \partial \delta q_j = 0$:

$$\delta q_j = \frac{1}{\mu}\left(\frac{\partial\Phi}{\partial \delta q_j} - \sum_{i=1}^{m} \lambda_i \frac{\partial \varphi_i}{\partial \delta q_j}\right).$$

Denote

$$\frac{\partial\Phi}{\partial \delta q_j} = q_{nom\,j}\frac{\partial\Phi}{\partial q_j} = a_j; \quad \frac{\partial \varphi_i}{\partial \delta q_j} = q_{nom\,j}\frac{\partial \varphi_i}{\partial q_j} = b_j^i.$$

The a_j i b_j^i values are the coefficients of sensitivity Φ i φ_i for the control parameters of a complex system. At this rate,

$$\delta q_j = \frac{1}{\mu}\left(a_j - \sum_{i=1}^{m} \lambda_i b_j^i\right), \quad j = \overline{1, n}. \qquad (3)$$

Values λ_i are determined by additional conditions (1). For small (minor) increments we get:

$$\sum_{j=1}^{n} b_j^i \delta q_j = 0, \quad i = \overline{1,m}. \qquad (4)$$

We substitute (3) in (4) and obtain a system of equations for λ_i:

$$\sum_{k=1}^{m} \lambda_k \left(\sum_{j=1}^{n} b_j^i b_j^k \right) = \sum_{j=1}^{n} b_j^i a_j, \quad i = \overline{1,m}. \qquad (5)$$

When using the reduced vector notation, we will write:

$$\vec{a} = (a_1, a_2, ..., a_n); \quad \vec{b}^i = \left(b_1^i, b_2^i, ..., b_n^i\right).$$

Denote the "scalar product" of vectors $\vec{x}$ and $\vec{y}$ through

$$(\vec{x} \cdot \vec{y}) = \sum_{j=1}^{n} x_j y_j,$$

Then the system of equations (5) takes the form:

$$\sum_{k=1}^{m} \lambda_k \left(\sum_{j=1}^{n} \vec{b}^i \vec{b}^k \right) = \left(\vec{a} \cdot \vec{b}^i\right), \quad i = \overline{1,m}. \qquad (6)$$

The determinant of the resulting system of equations (6) $\Delta = \det \left\| \left(\vec{b}^i \vec{b}^k\right) \right\|, k, i = \overline{1,m}$ is a Gram determinant. Its geometric content is the square of the volume of the m-dimensional parallelepiped constructed on the $\vec{b}^i$ vectors. Since conditions (1) should be considered as independent (otherwise, some of the conditions must be eliminated), then the $\vec{b}^i$ vector is linearly independent. For linearly independent vectors, the Gram determinant is positive, derived from its geometric content. Therefore, the system of equations (6) has a single solution [5].

Lets write (3) in the vector notation:

$$\delta\vec{q} = \frac{1}{\mu} \left(\vec{a} - \sum_{i=1}^{m} \lambda_i \vec{b}^i \right) = \frac{1}{\mu} (\vec{a} - \vec{a}_s), \qquad (7)$$

where
$$\vec{a}_s = \sum_{i=1}^{m} \lambda_i \vec{b}^i. \qquad (8)$$

On the other hand, according to (4) and (6), the vector $\delta\vec{q}$, so $\vec{a} - \vec{a}_s \equiv \vec{a}_p$, orthogonal to all vectors $\vec{b}^i$ $\left(\vec{a}_p \vec{b}^i\right) = 0$. Thus, vector $\vec{a}_p$ is the orthogonal projection of a vector in the normal to the space of vectors $\vec{a}$ to the space of vectors $\vec{b}^i$.

Denote the angle between the vector $\vec{a}$ and the subspace in which the vectors $\vec{b}^i$ are located through θ. Then the value of vector $\vec{a}_p$ will be equal to:

$$\|\vec{a}_p\| = \sqrt{\sum_{j=1}^{n} \vec{a}_{pj}^{\,2}} = a \sin\theta, \qquad (9)$$

where
$$a = \|\vec{a}\| = \sqrt{\sum_{j=1}^{n} a_j^{\,2}}. \qquad (10)$$

The *a* magnitude according to (10) is the mean square value of the sensitivity of a complex system to change its control parameters:

$$a = \left[\sum_{j=1}^{n} \left(\frac{\partial\Phi}{\partial\delta q_j} \right)^2 \right]^{1/2}.$$

As follows from (3) and (9), the projection of a vector $\delta\vec{q}$ equals

$$\delta q = \|\delta\vec{q}\| = \frac{1}{\mu} a \sin\theta.$$

Calculate the $\Delta\Phi$ value. For small (minor) increments.

$$\Delta\Phi = \sum_{j=1}^{n} \delta q_j \left(\frac{\partial\Phi}{\partial\delta q_j} \right) = \sum_{j=1}^{n} a_j \delta q_j \equiv (\vec{a} \cdot \delta\vec{q}).$$

Usage (7) allows to get

$$\Delta\Phi_{max} \frac{1}{\mu} (\vec{a} \cdot \vec{a}_p) = \frac{1}{\mu} a^2 \sin^2\theta,$$

where $(\vec{a} \cdot \vec{a}_p) = (\vec{a}_s + \vec{a}_p, \vec{a}_n) = \vec{a}_p{}^2 + (\vec{a}_p \cdot \vec{a}_s)$; $(\vec{a}_p \cdot \vec{a}_s) = 0$.

So, for the L lability we will finally write down:

$$L = \frac{\Delta\Phi_{max}}{\delta q} = a \sin\theta. \qquad (11)$$

Let's notice the physical content of the terms in (11). The value *a* takes into account the sensitivity of a complex system when its parameters are changed without taking into account the conditions (1). The value $\sin\theta$ takes into account the limitations of the lability of the system when taking into account the constraints.

The L value can be determined by the components of the vectors $\vec{a}$ and $\vec{b}^i$. Indeed, geometrically L is a perpendicular from the end of the vector $\vec{a}$ to the $\vec{b}^i$ vector's subspace . Therefore, L is the ratio of volumes of two parallelepipeds, one of which is constructed on vectors $\left(\vec{b}^1, \vec{b}^2, ..., \vec{b}^m, \vec{a}\right)$, and the second one – on vectors $\left(\vec{b}^1, \vec{b}^2, ..., \vec{b}^m\right)$. If we denote the Gram determinant of the first system of vectors through $G\left(\vec{b}^1, \vec{b}^2, ..., \vec{b}^m, \vec{a}\right)$ and the second through $G\left(\vec{b}^1, \vec{b}^2, ..., \vec{b}^m, \vec{a}\right)$ then we get

$$L = \left[\frac{G\left(\vec{b}^1, \vec{b}^2, ..., \vec{b}^m, \vec{a}\right)}{G\left(\vec{b}^1, \vec{b}^2, ..., \vec{b}^m\right)} \right]^{1/2}. \qquad (12)$$

For example, when there is only one restriction, there and

$$G\left(\vec{b}\vec{a}\right) = \begin{vmatrix} b^2 & \left(\vec{a}\vec{b}\right) \\ \left(\vec{a}\vec{b}\right) & a^2 \end{vmatrix} = a^2 b^2 - \left(\vec{a}\vec{b}\right)^2; \quad G\left(\vec{b}\right) = b^2.$$

then $L = \left[a^2 - \frac{\left(\vec{a}\vec{b}\right)^2}{b^2} \right]^{1/2} = a \left[1 - \frac{\left(\vec{a}\vec{b}\right)^2}{a^2 b^2} \right]^{1/2}.$

Lets show that the introduction of new restrictions can only reduce the value of L and calculate the loss in the lability, which occurs in this case.

Lets consider the value

$$\vec{C}_m = \vec{a} - \sum_{i=1}^{m} \lambda_i \vec{b}^i .$$

Vector $\vec{C}_m$ is operational margin in the approximation of the vector $\vec{a}$ of the linear combination of vectors $\vec{b}^i$. Lets determine quantities λ_i which provide a minimum $C_m{}^2$. Calculation of the derivative can be written for one system of equations for λ_i:

$$\sum_{k=1}^{m} \lambda_k \left(\vec{b}^i \vec{b}^k\right) = \left(\vec{a} \cdot \vec{b}^i\right), \quad i = \overline{1, m} . \qquad (13)$$

The resulting system of equations identically coincides with the system (6). After substituting the solution of system (13) into (12), we obtain a vector $\vec{a}_p = \vec{a} - \vec{a}_s$.

Thus, we write the vector $\vec{a}_p = \vec{a} - \vec{a}_s$ and equal to it value L we should write down as:

$$L = a_p = \min_{\{\lambda_i\}} \left| \vec{a} - \sum_{i=1}^{m} \lambda_i \vec{b}^i \right| .$$

Lets compare now magnitude L_m i L_{m+1}

$$L_m^2 = \min_{\{\lambda_i\}} \left(\vec{a} - \sum_{i=1}^{m} \lambda_i \vec{b}^i \right)^2 ; \; L_{m+1}^2 = \min_{\{\lambda_i\}} \left(\vec{a} - \sum_{i=1}^{m+1} \lambda_i \vec{b}^i \right)^2$$

and find the difference:

$$L_{m+1}^2 - L_m^2 = -\frac{\left(\vec{a}, \vec{b}_s^{m+1}\right)^2}{\left(\vec{b}_s^{m+1}\right)^2} . \qquad (14)$$

The resulting formula shows that $L_{m+1} < L_m$, and determines the difference. This difference can be calculated through vectors $\vec{a}$ and $\vec{b}$.

To do this, lets use the formula for the orthogonal projection vector $\vec{b}^{m+1}$ on the subterror of vectors $\left\{\vec{b}^1, ..., \vec{b}^m\right\}$ and find $\left(\vec{a}, \vec{b}_s^{m+1}\right) \equiv \frac{\Delta}{G_m}$:

$$\Delta = \begin{vmatrix} \left(\vec{b}^1\vec{b}^1\right) & \left(\vec{b}^1\vec{b}^2\right) & ... & \left(\vec{b}^1\vec{b}^m\right) & \left(\vec{b}^1\vec{a}\right) \\ \left(\vec{b}^1\vec{b}^2\right) & \left(\vec{b}^2\vec{b}^2\right) & ... & \left(\vec{b}^2\vec{b}^m\right) & \left(\vec{b}^2\vec{a}\right) \\ ... & ... & ... & ... & ... \\ \left(\vec{b}^1\vec{b}^m\right) & \left(\vec{b}^2\vec{b}^m\right) & ... & \left(\vec{b}^m\vec{b}^m\right) & \left(\vec{b}^m\vec{a}\right) \\ \left(\vec{b}^1\vec{b}^{m+1}\right) & \left(\vec{b}^2\vec{b}^{m+1}\right) & ... & \left(\vec{b}^m\vec{b}^{m+1}\right) & \left(\vec{b}^{m+1}\vec{a}\right) \end{vmatrix} . \qquad (15)$$

Value $\left(\vec{b}_s^{m+1}\right)^2 = \left(\vec{b}_s^{m+1}\, \vec{b}^{m+1}\right)$ equals:

$$\left(\vec{b}_s^{m+1}\right)^2 = \frac{G_{m+1}}{G_m} ,$$

where $G_{m+1} = G_{m+1}\left(\vec{b}^1, ..., \vec{b}^{m+1}\right)$ – is Gram determinant of vector system $\left\{\vec{b}^1, ..., \vec{b}^{m+1}\right\}$.

So, we come out with:

$$L_m^2 - L_{m+1}^2 = \frac{\Delta^2}{G_m G_{m+1}} . \qquad (16)$$

The resulting ratio allows you to calculate the loss in lability, which arises when adding new restrictions and to conduct a preliminary analysis of the influence of a limitation on the lability of a complex system, that is, to determine the ways to increase (decrease) the lability. The answer to the last question is important when designing (constructing) the structure of the procedure for controlling the technical state of complex systems and complexes with high requirements for the stability of the output characteristics.

At the same time formula (16) allows to determine the loss in lability, provided that some parameters of control of complex systems and complexes are tightly fixed, that is, to evaluate the effect of the variation of each of the parameters on lability. Indeed, the fixation of any parameter, for example q_1 reduces to the additional condition. $\delta q_1 = 0$. This condition can be written as a condition of communication:

$$\left(\vec{b}^{m+1}\, \delta\vec{q}\right) = 0 ,$$

where $\vec{b}^{m+1} = (1, 0, 0, ..., 0)$.

Let's consider as an example the case when there is one limitation and we will calculate the loss when fixing the parameter q_1.

The value Δ of (15) in this case is equal to:

$$\Delta = \begin{vmatrix} \vec{b}^2 & \left(\vec{a}\,\vec{b}\right) \\ b_1 & a_1 \end{vmatrix} = a_1 \vec{b}^2 - b_1 \left(\vec{a}\,\vec{b}\right);$$

so $$G_m = \vec{b}^2 ; \; G_{m+1} = \begin{vmatrix} \vec{b}^2 & b_1 \\ b_1 & 1 \end{vmatrix} = \vec{b}^2 - b_1 ;$$

$$L_m^2 - L_{m+1}^2 = \frac{\left[a_1 \vec{b}^2 - b_1 \left(\vec{a}\,\vec{b}\right)\right]^2}{\vec{b}^2 \left(\vec{b}^2 - b_1{}^2\right)} .$$

If we denote $\alpha = a_1/a$, $\beta = b_1/b$, $\beta = b_1/b$, $\cos\theta = \left(\vec{a} \cdot \vec{b}\right) / (a \cdot b)$ we will write for the relative loss amount:

$$\frac{L_m^2 - L_{m+1}^2}{L_m^2} = \frac{(\alpha - \beta\cos\theta)^2}{\sin^2\theta \left(1 - \beta^2\right)} .$$

Lets make a note that the Δ value can be calculated from vector $\vec{a}_p$ and vector $\vec{a}_p$ can be found similar to vector $\vec{b}_s{}^{m+1}$.

Then the Δ value (15), taking into account that the value of the determinant changes when the row is replaced by columns, is equal to:

$$\Delta = G_m \left(\vec{a}_p \vec{b}^{m+1}\right).$$

The expression obtained is simplier for calculations than formula (15), as determining $\Delta\Phi_{max}$ it is necessary to determine the vector $\vec{a}_p$, due to $\delta\vec{q} = \vec{a}_p / \mu$ according to (7). Then we will find the amount of losses:

$$L_m^2 - L_{m+1}^2 = \frac{\left(\vec{a}_p \vec{b}^{m+1}\right)^2 G_m}{G_{m+1}}. \qquad (17)$$

For $\left(\vec{a}_p \vec{b}^{m+1}\right) = \left(\vec{a}_p \vec{b}_s^{m+1}\right) = \left(\vec{a}\,\vec{b}_s^{m+1}\right)$, we obtain the relation (17) with regard to (14) and write down as:

$$L_m{}^2 - L_{m+1}{}^2 = \frac{\left(\vec{a}_p \vec{b}^{m+1}\right)^2}{\left(\vec{b}_s{}^{m+1}\right)^2} = a_p{}^2 \cos^2 \psi,$$

where ψ – "angle" between vectors $\vec{a}_p$ і $\vec{b}_s{}^{m+1}$.

The physical content of the obtained ratio is that the loss is the greater, the closer the direction determined by the vector $\vec{b}_s{}^{m+1}$ to the direction of the vector $\vec{a}$ – the direction of the gradient of the functional F. Relative loss at the same time equals:

$$\frac{L_m{}^2 - L_{m+1}{}^2}{L_m{}^2} = \cos^2 \psi. \qquad (18)$$

Summaries

So, the obtained relations (1–18) represent a method structure of the procedure for controlling the technical condition of complex systems and complexes and allow obtaining an optimal range of control parameters for determining the technical state of the system during operation. The ratio (18) shows a loss in the efficiency of the use of complex systems and complexes that are synthesized, depending on changes in parameters and operating conditions.

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МЕТОД СИНТЕЗУ ОПТИМАЛЬНОЇ СТРУКТУРИ ПРОЦЕДУРИ КОНТРОЛЮ ТЕХНІЧНОГО СТАНУ СКЛАДНИХ СИСТЕМ І КОМПЛЕКСІВ

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Розроблений метод синтезу оптимальної структури процедури контролю технічного стану складних систем і комплексів, який дозволяє отримати оптимальну номенклатуру параметрів контролю. Це дозволяє своєчасно визначати відмови, тобто підвищити достовірність використання справних складних систем і комплексів. Розглянута задача оптимальної параметричної адаптації, тобто визначення спроможності складних систем і комплексів до перенастроювання залежно від зміни умов експлуатації. Для розв'язання поставленої задачі запропонований метод Лагранжа.

Ключові слова: *контроль технічного стану, синтез, адаптація, складні системи і комплекси.*

МЕТОД СИНТЕЗА ОПТИМАЛЬНОЙ СТРУКТУРЫ ПРОЦЕДУРЫ КОНТРОЛЯ ТЕХНИЧЕСКОГО СОСТОЯНИЯ СЛОЖНЫХ СИСТЕМ И КОМПЛЕКСОВ

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Разработан метод синтеза оптимальной структуры процедуры контроля технического состояния сложных систем и комплексов, который позволяет получить оптимальную номенклатуру параметров контроля. Это позволяет своевременно определять отказ, то есть повысить достоверность использования исправных сложных систем и комплексов. Рассмотрена задача оптимальной параметрической адаптации, то есть определения способности сложных систем и комплексов к перенастройке в зависимости от изменения условий эксплуатации. Для решения поставленной задачи предложен метод Лагранжа.

Ключевые слова: *контроль технического состояния, синтез, адаптация, сложные системы и комплексы.*