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ADAPTIVE STABILIZATION SYSTEMS OF DYNAMIC OBJECTS

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***Abstract*—*There are a large number of dynamic objects, for the management of which it is advisable to apply the principles of adaptation. The reasons for applying the principles of adaptation can be combined into two main groups: the variability and complexity of the characteristics of objects and the environment; growing requirements for accuracy and technical and economic characteristics of systems. The difference between adaptive systems and optimal ones is that while in optimal systems the quality indicator is provided for certain parameters of the object, in adaptive systems - for various parameters due to the action of additional elements of adaptation. The choice of one or another approach is determined by preliminary information about the object (process) or the accepted quality criterion. The article presents the main approaches to the selection of possible variants of adaptive systems with stabilization and optimization of the quality of control of systems for stabilizing dynamic objects, based on the type of extremal characteristic of the criterion for assessing their quality.*

Index Terms—Stabilization system; block diagram; extreme characteristic; adaptation contour; reference model; extreme control; operating point; extremum search.

I. INTRODUCTION

Stabilization systems are special automatic control systems designed to guide and maintain a given spatial position of the control object during vibrations of its base.

Despite the fact that stabilization systems differ significantly in design, they are carried out according to the same type of functional diagrams. At the same time, the control processes occurring in stabilization systems are described by similar linear differential equations. As a result, their block diagrams are identical, which makes it possible to obtain a typical block diagram of a dynamic object stabilization system.

In most modern systems for stabilizing dynamic objects, control is carried out by the deviation of the controlled variable from its value specified by the setting or from the specified law of its change. A typical block diagram of such a system is shown in Fig. 1.

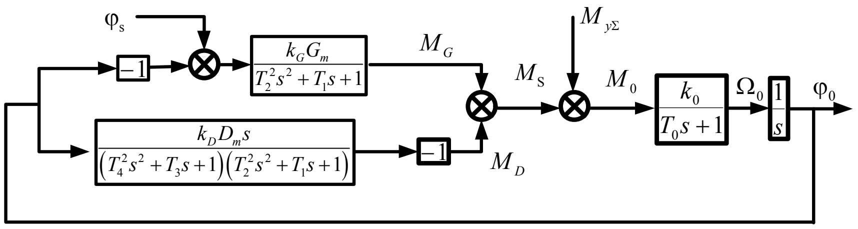

Fig. 1. Typical block diagram of a continuous stabilization system: $G_m = k_{\text{ds}} k_{\text{reg}}$ is the structural stiffness of the system; $D_m = k_{\text{sds}} k_{\text{reg}}$ is the constructive damping of the system; k_{ds} is the transfer coefficient of the deviation sensor of the control object; k_{sds} is the transfer coefficient of the sensor of the speed of deviations of the control object; k_G, k_D are stiffness and damping adjustment coefficients; k_{reg} is the transfer coefficient of the regulator

The moment of stabilization M_{S} is formed on the channels of the sensor of angular deviation and the sensor of speed of angular deviation of the control object:

$$\overline{M}_{\text{S}} = \overline{M}_G + \overline{M}_D \equiv k_G G_m + k_D D_m .$$

Simultaneous and automatic compensation of the effect on the controlled value of all disturbances acting on the system is the most important advantage of the deviation control principle.

http://jrnl.nau.edu.ua/index.php/ESU, http://ecs.in.ua

II. Problem Statement

The presence of a block diagram of the stabilization system allows its analysis and synthesis during design or modernization. Stabilization systems operating on the principle of deviation control are static systems that have an absolute error $\Delta\varphi$ that depends on the value of an external disturbance $M_{y\Sigma}$. The load characteristic of such systems is shown in Fig. 2.

Such systems are considered on the basis of the assumptions that the nature of the disturbing effects on the control object is known, and the structure and parameters of the control object itself and the stabilization system as a whole are unchanged.

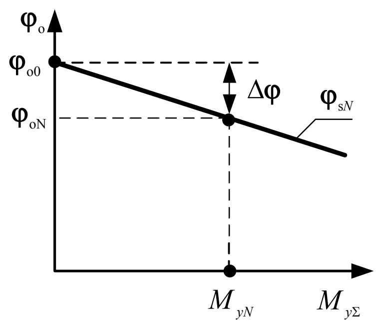

Fig. 2. The load characteristic

At the same time, in practice, there are systems for stabilizing dynamic objects, the properties of which change under the influence of external and internal factors, and the characteristics of external and internal influences themselves can differ significantly from the nominal ones taken in the calculation.

An example of a change in external conditions during operation can be non-stationary random disturbances, the probabilistic characteristics of which change in fairly wide ranges. The object of control with variable parameters is an aircraft, the mass of which changes with the consumption of fuel during the flight.

Automatic control systems capable of adapting to changing external conditions and properties of the control object by changing the structure and parameters of the controller, in order to ensure the required quality of control, are commonly called adaptive.

The tasks of analysis and synthesis of adaptive automatic systems are much more difficult than similar tasks for linear continuous systems.

In this regard, the development of possible variants of adaptive stabilization systems for dynamic objects is of particular interest. Note that the introduction of adaptation elements complicates the system and, consequently, reduces its reliability, which means that the application of adaptation principles requires their analysis and evaluation of effectiveness.

III. Problem Solution

According to the nature of setting the main automatic control system, adaptive systems are divided into three groups: self-adjusting, self-organizing and self-learning.

The fundamental difference between self-adjusting systems and self-organizing systems is that adaptation in them is achieved only by changing the parameters of the controller of the main system, while in self-organizing systems, adaptation is carried out by changing both the parameters and the structure of the controller.

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Self-learning systems accumulate and analyze information about the behavior of the main system, adjust control algorithms in order to improve its quality. Such systems are built using several levels (loops) of adaptation, each of which improves the operation algorithm of the lower level.

In this regard, the advantage of self-tuning passive adaptation for stabilization systems of dynamic objects is quite obvious. It consists in choosing a rigid structure and constant parameters of the controller. The complication and rise in the cost of the system in this case are minimal, and in addition, there is no need to control parametric multiplicative perturbations due to changes in the physical characteristics of the stabilization system.

Based on the task of adaptation, systems with stabilization of the quality of control and systems with optimization of the quality of control are distinguished. The task of systems with stabilization of control quality is to maintain the required quality level of the main ACS in accordance with the selected criterion. The task of systems with control quality optimization is more complex and consists in finding and subsequently maintaining the optimal quality level of the main ACS in accordance with the selected criterion.

Apparently, it is expedient to consider the possibility and conditions for using both stabilization and optimization of the quality of control in stabilization systems of dynamic objects.

The level of control quality of stabilization systems is determined by the maximum (minimum) of the selected criterion J for their evaluation. The latter can be put in accordance with the input actions $f(t)$ of the control object, controller settings a_j, time *t*.

Let us introduce a generalized notation $\mu \equiv f, a_j, t$ for the variable parameter of the stabilization system. Possible extreme characteristics $J = f(\mu)$ are presented in Fig. 3.

If the extremum of the quality criterion (Fig. 3a) is constant $J = \text{const}$ and corresponds to the same value of the variable parameter $\mu_m = \text{const}$ when the disturbing influences $M_y \geq 0$ change over the entire possible range, then it is hardly advisable to use adaptive systems. In this case, the problem of maintaining the required quality J_m of control of a dynamic object with a certain accuracy can be solved using the stabilization system shown in Fig. 1, while providing the initial setting μ_m.

If the extremum of the quality criterion (Fig. 3b) corresponds to the same value $\mu_m = \text{Const}$ of the variable parameter, but changes its levels $J_3 < J_2 < J_1$ when the disturbing influences change $M_{y3}(t) > M_{y2}(t) > M_{y1}(t)$, then the use of adaptive systems with stabilization of the control quality will be quite justified. In this case, based on the accepted criterion for assessing the quality, for example J_1, operating points 2, 3 will tend to operating point 1, which determines the extremum of the stabilized quality.

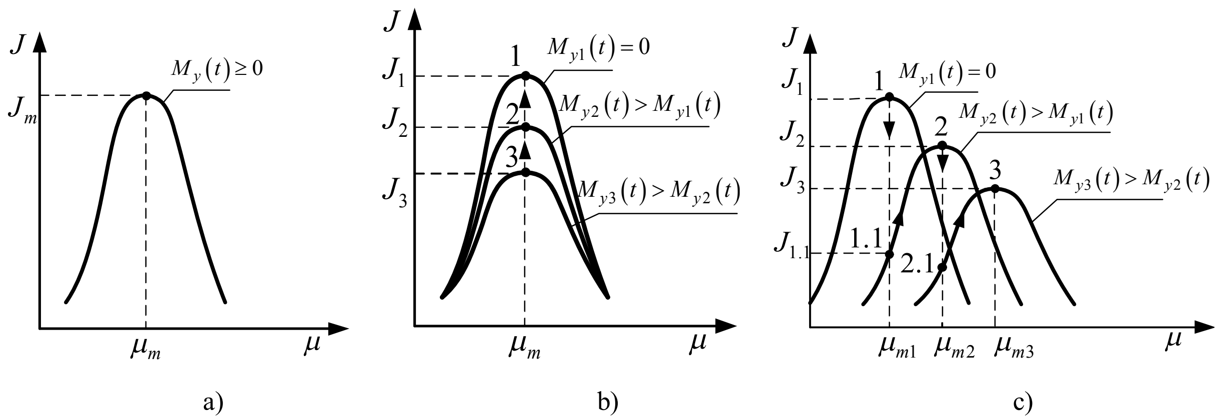

Fig. 3. Extreme performance: (a) is the no offset; (b) is the vertical displacement; (c) is the horizontal offset

The problem is completely solved by using an adaptive system with an open adaptation loop (AL) by disturbing influences. The block diagram of such a system is shown in Fig. 4.

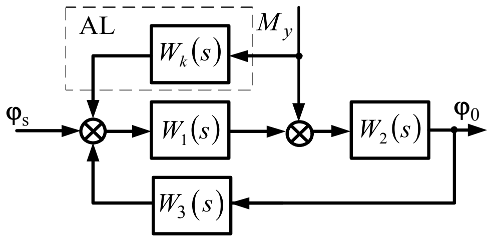

Fig. 4. Structural diagram of a system with an open adaptation loop

The block diagram of the adaptive stabilization system was obtained on the basis of a typical (see Fig. 1) one. In this case, the following values of transfer functions are introduced

$$W_1(s) = \frac{k_G G_m}{T_2^2 s^2 + T_1 s + 1}, \quad W_2(s) = \frac{k_0}{(T_0 s + 1)s},$$

$$W_3(s) = 1 + \frac{k_D D_m s}{k_G G_m} = \frac{k_G G_m + k_D D_m s}{k_G G_m}.$$

The transfer function of the amplifying device of the adaptation loop is generally defined as

$$W_k(s) = \frac{k}{T_6^2 s^2 + T_5 s + 1}.$$

Based on the block diagram, we obtain the equation of motion of the system

$$\varphi_0 = \frac{W_1(s) W_2(s)}{1 + W_1(s) W_2(s) W_3(s)} \varphi_s + \frac{\left(W_1(s) W_k(s) - 1\right) W_2(s)}{1 + W_1(s) W_2(s) W_3(s)} M_y.$$

It is easy to see that the last equation is reduced to the form

$$\varphi_0 \approx \frac{W_1(s) W_2(s)}{1 + W_1(s) W_2(s) W_3(s)} \varphi_s$$

under conditions

$$W_k(s) = \frac{1}{W_1(s)} \;\rightarrow\; W_k(s) \approx \frac{1}{k_1}.$$

Thus, when changing external influences acting on the control object, the controlled coordinate remains close to the extremum of the stabilized quality.

It should be noted that the stabilization system automatically compensates the influence on the control object of only measured external disturbances. Usually, control is carried out according to the main disturbance, which causes the greatest deviations of the controlled variable from the set value. Such an external perturbation is determined, as a rule, experimentally based on the conditions for the possible functioning of the system based on the analysis of the dependencies between the controlled variable and external perturbations.

The problem can also be solved by using self-adjusting passive adaptation with a closed loop along the adjustable coordinate of the stabilization system.

The block diagram of a typical stabilization system with a closed adaptation loop along an adjustable coordinate is shown in Fig. 5.

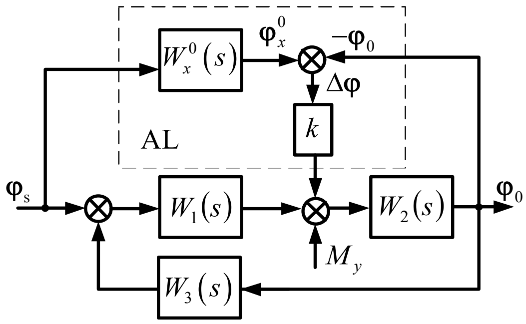

Fig. 5. Structural diagram of a system with a closed adaptation loop

The adaptation loop (AL) includes a reference model with a transfer function equal to the desired transfer function

$$W_x^0(s) = \frac{W_1(s)W_2(s)}{1+W_1(s)W_2(s)W_3(s)}$$

according to the control signal of the stabilization system, a comparison device (adder) of an adjustable coordinate φ_0 with the output value φ_x^0 of the model, and an amplifier with a gain factor k.

The control object is subject by disturbing influences M_y. The mismatch signal $\Delta\varphi$ of the controlled coordinate and the standard model, after amplification, is fed to the control object with the transfer function $W_2(s)$.

We find the transfer functions of the system:

- by control signal

$$W_x = \frac{W_1 + W_x^0 k}{1+W_1W_2W_3+W_2k} W_2,$$

- by disturbing disturbance

$$W_y = \frac{W_2}{1+W_1W_2W_3+W_2k}.$$

By choosing the gain $k = k_m$ sufficiently high, i.e. providing $k_m W_2(s) >> 1 + W_1(s)W_2(s)W_3(s)$ and $\frac{1}{k_m} \to 0$, we obtain the equation of the adaptive system

$$\varphi_0 = W_x^0(s)\varphi_s - \frac{1}{k_m}M_y \approx W_x^0(s)\varphi_s.$$

Thus, when external influences change, the controlled coordinate will remain close to the reference one – to the extremum of the maintained quality.

If the extrema of the quality criterion (Fig. 3c) change not only in the level $J_3 < J_2 < J_1$ but also in the direction, when $M_{y3}(t) > M_{y2}(t) > M_{y1}(t)$ the disturbing influences change, i.e. correspond to different values of the variable parameter of the system $\mu_{m3} > \mu_{m2} > \mu_{m1}$, it is advisable to apply adaptive systems with optimization of the quality of control - systems of extreme control (ECS).

Control quality optimization is understood as ensuring the maximum quality criterion J_i under an external disturbance M_{yi} by changing the variable parameter of the system to the value μ_{mi}.

To determine the extremum of the control quality criterion, both search and non-search ECS can be used.

Searchless systems solve the problem of determining the extremum analytically. They have high speed, but are very complex systems, and their implementation in practice faces certain technical difficulties.

The block diagram of the search ECS is shown in Fig. 6.

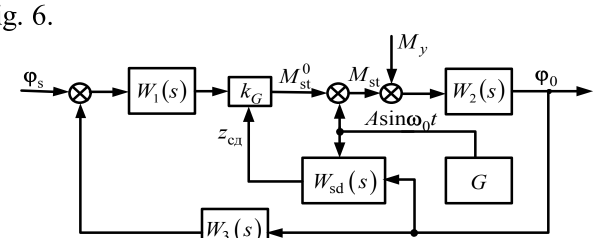

Fig. 6. Structural diagram of the extreme control system

Here is the transfer function $W_1(s) = \frac{G_m}{T_2^2 s^2 + T_1 s + 1}$.

A feature of the system is the presence of a probe signal generator G and a synchronous detector SD in its composition.

The quality criterion $J \equiv \Delta\varphi_0$ is taken to be the accuracy of the system, and the variable parameter $\mu \equiv M_{st}\{k_G G_m\}$ is the moment of stabilization, which is determined by the operational rigidity of the stabilization system.

The moment of stabilization M_{st} is formed on the basis of two signals: the signal $M_{st}^0 = \text{const}$ of the regulator and the trial harmonic signal $A\sin\omega_0 t$ of small amplitude $\left(A << M_{st}^0\right)$, generated by the generator G

$$M_{st} = M_{st}^0 + A\sin\omega_0 t\ .$$

The signal $M_{st}^0 = \text{const}$ determines the position of operating point 1 on the extreme characteristic of the system (Fig. 7a).

The response of the system on a complex signal can be found by the graphic-analytical method, as shown in Fig. 7a or represented by the Taylor series

$$\Delta\varphi_0\left\{M_{st}^0 + A\sin\omega_0 t\right\} = \Delta\varphi_0\left\{M_{st}^0\right\} + \left.\frac{d\Delta\varphi_0}{dM_{st}}\right|_{M_{st}=M_{st}^0} A\sin\omega_0 t. \qquad (1)$$

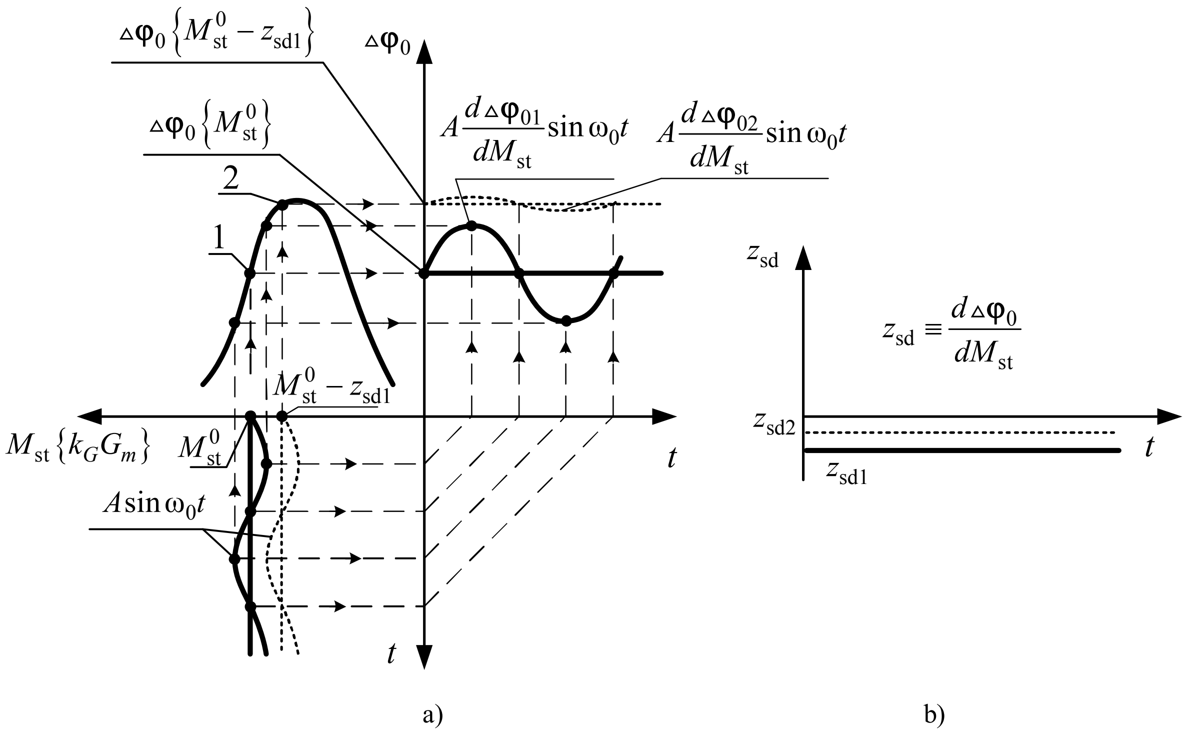

Fig. 7. Finding the optimal level of control quality: (a) is the process; (b) is the signal of synchronous detector

The main output signal corresponding to the regulator signal $M_{st}^0 = \text{const}$ will be constant $\Delta\varphi_0\left\{M_{st}^0\right\} = \text{const}$ with an amplitude determined by the position of operating point 1.

The harmonic component of the output signal $\Delta\varphi_0$, according to (1), turns out to be proportional to its derivative with respect to the signal M_{st}, and its phase is proportional to the sign of this derivative. On Figure 7a, the amplitude of the harmonic component of the signal $\Delta\varphi_0$ is designated as $A\frac{d\Delta\varphi_{01}}{dM_{st}}$, and its phase is equal to zero $\varphi = 0°$, which corresponds to the derivative $\frac{d\Delta\varphi_0}{dM_{st}} > 0$ in the vicinity of the operating point 1.

The synchronous detector extracts the harmonic component $A\frac{d\Delta\varphi_{01}}{dM_{st}}\sin\omega_0 t$ from the main output signal $\Delta\varphi_0$ and converts it into a constant signal (Fig. 7b), the level z_{sd1} of which is proportional to the derivative $\frac{d\Delta\varphi_{01}}{dM_{sd}}$, and the polarity is determined by the phase of the harmonic component. In the case under consideration, minus polarity "–" corresponds to the zero phase $\varphi = 0°$ of the harmonic component.

The signal of the synchronous detector is supplied (see Fig. 6) to the controller. As a result, the signal M_{st}^0 decreases to the value $(M_{st}^0 - z_{sd1})$. Operating point 1 is shifted (Fig. 7a) to position 2 with a speed proportional to $\frac{d\Delta\varphi_{01}}{dM_{st}}$.

The output signal of the system, corresponding to the controller signal $\left(M^0_{\text{st}} - z_{\text{sd1}}\right)$, rises to the value $\Delta\varphi_0\left\{M^0_{\text{st}} - z_{\text{sd1}}\right\}$. The amplitude of the harmonic component of the signal $\Delta\varphi_0$ decreases to a value $A\dfrac{d\Delta\varphi_{02}}{dM_{\text{st}}}$ due to a decrease in the steepness of the extreme characteristic in the vicinity of the operating point 2. The phase remains the same $\varphi = 0°$.

The signal of the synchronous detector is reduced to a value z_{sd2} proportional to the decrease in the amplitude of the harmonic component $A\dfrac{d\Delta\varphi_{02}}{dM_{\text{st}}}$, while maintaining the same polarity. As a result, the controller signal decreases to the value $\left(M^0_{\text{st}} - z_{\text{sd1}} - z_{\text{sd2}}\right)$, and the operating point tends to the extremum at a speed proportional to $\dfrac{d\Delta\varphi_{02}}{dM_{\text{st}}} < \dfrac{d\Delta\varphi_{01}}{dM_{\text{st}}}$.

The process will continue in time until the value of the controller signal becomes equal to $M_{\text{st}m}$, at which the operating point reaches the peak of the extreme characteristic.

At the moment when the operating point reaches the extremum, the output signal of the system reaches the maximum value $\Delta\varphi_0\left\{M_{\text{st}m}\right\}$, and the amplitude of the harmonic component becomes equal to zero, because at the extreme point $\dfrac{d\Delta\varphi_0}{dM_{\text{st}}} = 0$. Consequently, the signal at the output of the synchronous detector goes to zero $z_{\text{sd}} = 0$.

When the operating conditions of the system change and the extreme characteristic shifts to the left, the operating point 1 may be on its right branch. The processes of searching for and maintaining the optimal level of control quality will be similar to those described above with the only difference that the harmonic component $A\dfrac{d\Delta\varphi_{01}}{dM_{\text{st}}}$ of the output signal $\Delta\varphi_0$ will change the phase to $\varphi = 180°$, which corresponds to the derivative $\dfrac{d\Delta\varphi_0}{dM_{\text{st}}} < 0$ in the vicinity of the operating point 1. This will lead to a change to "+" the polarity of the output signal of the synchronous detector, and, consequently, an increase in the controller output signal $\left(M^0_{\text{st}} - z_{\text{sd1}}\right)$. The operating point 1 will tend to the extremum from right to left.

Thus, the presented extreme control system is a system with deviation control. The derivative $\dfrac{d\Delta\varphi_0}{dM_{\text{st}}}$ is taken as the controlled value, because its value determines the speed of movement of the working point to the extremum, and the sign of the derivative determines the direction of movement towards it. Equality $\dfrac{d\Delta\varphi_0}{dM_{\text{st}}}$ to zero characterizes the achievement by the working point the position of the maximum of the extreme characteristic. An illustration of this position is shown in Fig. 8.

In practice, it is customary to tune stabilization systems for dynamic objects through two channels - the channel of the angular deviation sensor and the channel of the angular deviation speed sensor of the control object. In this case, extreme control can be carried out with respect to two variable parameters.

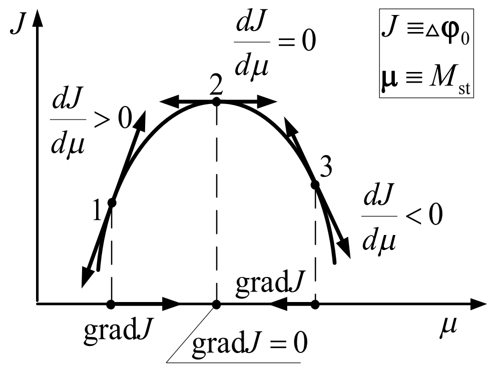

Fig. 8. Determination of the direction of movement of the operating point to the extremum

With the same quality criterion $J \equiv \Delta\varphi_0$ is the accuracy indicator of the stabilization system, it is advisable to take as variable parameters $\mu_1 = M_G\left\{k_G G_m\right\}$ is the component of the stabilization moment, which is formed through the channel of the angular deviation sensor and is determined by the operational rigidity of the stabilization system, and $\mu_2 = M_D\left\{k_D D_m\right\}$ is the component of the stabilization moment, which is formed through the channel of the angular deviation speed sensor and is determined operational damping of the stabilization system.

In the case when the quality criterion is a function of two variable parameters $J\left(\mu_1, \mu_2\right)$, the condition for its extremum will be zero at the extremum point of all partial derivatives

$$\frac{dJ}{d\mu_1} = 0, \quad \frac{dJ}{d\mu_2} = 0.$$

The direction of movement towards the extremum is determined by the vector, whose projections on the coordinate axes $\mu_i\ (i=1,2)$ are respectively equal to the partial derivatives

$$\operatorname{grad} J = \bar{k}_1 \frac{dJ}{d\mu_1} + \bar{k}_2 \frac{dJ}{d\mu_2},$$

where $k_i\ (i=1,2)$ are the unit vectors of the axes.

The vector $\operatorname{grad} J$ is directed towards the extremum and is called the gradient of the quality criterion. At the extreme point $\operatorname{grad} J = 0$.

Figure 9 shows the gradient $\operatorname{grad} J$ of the quality criterion for two variable parameters μ of the stabilization system for dynamic objects.

Thus, the availability of information about the derivatives $\frac{dJ}{d\mu_i}$ makes it possible to organize the movement of the operating point to the extremum of the quality criterion. The main methods, in addition to the described gradient method, are: the steepest descent method, the Gauss-Seidel method, the random search method.

The gradient method involves the simultaneous change of the variable parameters $\mu_{1,2}$ so as to ensure the movement of the operating point in a direction close to the instantaneous direction of the gradient vector. In this case, the speed of change of variable parameters should be proportional to the corresponding derivatives of the quality criterion with respect to the parameter μ_i

$$\left.\begin{aligned} \frac{d\mu_1}{dt} &\equiv \frac{dJ}{d\mu_1} \\ \frac{d\mu_2}{dt} &\equiv \frac{dJ}{d\mu_2} \end{aligned}\right\}.$$

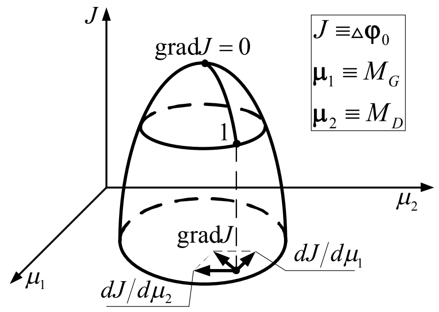

Fig. 9. Determining the direction of movement of the operating point to an extremum at two variable parameters

The gradient method is illustrated in Fig. 10a. The operating point smoothly moves along the trajectory $1-2-3-J_{\max}$ normal to the surface $J(\mu_1, \mu_2) = \text{const}$.

When implementing a step-by-step movement of the operating point to the extremum, it is necessary that each fixed step $\Delta\mu_{1,2}$ in changing the variable parameter must be proportional to the derivative of the quality criterion with respect to the corresponding parameter $\mu_{1,2}$

$$\Delta\mu_1 \equiv \frac{dJ}{d\mu_1}, \quad \Delta\mu_2 \equiv \frac{dJ}{d\mu_2}.$$

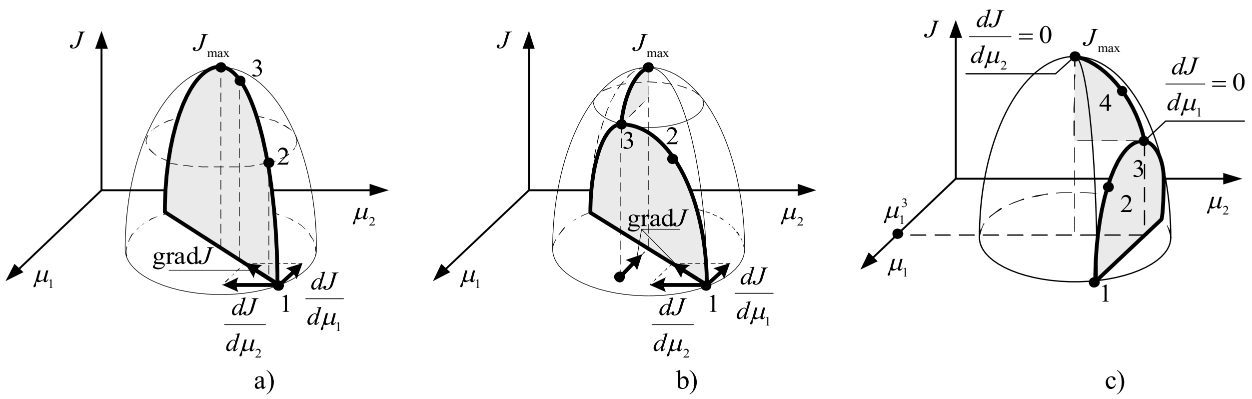

Fig. 10. Extremum search methods: (a) is the gradient; (b) is the fastest descent; (c) is the Gauss–Seidel

The gradient method with step-by-step movement is characterized by a small range of fluctuations near the extremum point.

The steepest descent method is shown in Fig. 10b. The movement of the working point 1 is organized along the initial direction of the gradient vector grad$J$ and is carried out (trajectory $1-2-3$) until the derivative of the quality criterion along the accepted direction becomes equal to zero (the increment of the quality criterion J does not stop). This corresponds to point 3. At point 3, a new direction of the gradient grad$J$ is determined and movement is organized in a new direction (trajectory $3-J_{\max}$) until the increment of the quality criterion stops. In the general case, the process is repeated until the extremum point is reached.

The method is characterized by a quick exit to the extremum region. Near the extremum, more accurate methods can be applied, such as the gradient.

The Gauss–Seidel method consists in changing the variable parameters $\mu_{1,2}$ in turn (Fig. 10c). With a fixed value of the parameter μ_2, the parameter μ_1 changes until the corresponding component $\frac{dJ}{d\mu_1} = 0$ of the gradient becomes equal to zero. The operating point moves along the path 1–2–3. The next step changes the parameter μ_2, at a fixed value of the parameter $\mu_1 = \mu_1^3 = \text{const}$, before going to zero $\frac{dJ}{d\mu_2} = 0$. The operating point moves along the path $3 - 4 - J_{\max}$. The extreme has been reached. The method is not complicated in technical implementation, but it takes a certain time to determine the extremum of the quality criterion.

The random search method is based on a random change in the variable parameters in each of the operating point positions. So, from the starting point, k arbitrary trial changes of the variable parameters are made. For each of them, the increment ΔJ of the quality criterion is fixed. The step with the best result is remembered. The working step is made in the direction of the vector with the best trial result. In the new position of the operating point, the trial measurements are repeated, and the "best" vector is again selected. Search operations continue until the operating point reaches an extremum.

Note that in practice, the methods for determining derivatives $\frac{dJ}{d\mu_i}$ and methods for finding the extreme um of the quality criterion are interdependent, since their implementations are connected by the same technical solutions.

IV. Conclusions

The advantage of self-tuning passive adaptation for stabilization systems of dynamic objects is quite obvious. It consists in choosing a rigid structure and constant parameters of the controller. The complication and rise in the cost of the system in this case are minimal, and in addition, there is no need to control parametric multiplicative perturbations due to changes in the physical characteristics of the stabilization system.

Based on the type of extreme characteristics of the criterion for assessing the quality of stabilization systems, it is possible to apply adaptive control to them with both stabilization and quality optimization.

The implementation of non-search extremal systems in practice is associated with certain technical difficulties. In systems for stabilizing dynamic objects, it is proposed to use search extremal systems for one or two variable parameters.

The methods for determining the search rates for the extremum of the quality criterion and the methods for searching for the extremum are interdependent, since their implementations are connected by the same technical solutions. Options for possible solutions are given.

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О. К. Аблесімов, І. О. Коновалюк, Р. В. Завгородній. Адаптивні системи стабілізації динамічних об’єктів

Існує велика кількість динамічних об’єктів, для керування якими доцільно застосовувати принципи адаптації. Причини застосування принципів адаптації можна поєднати у дві основні групи: мінливість та складність характеристик об’єктів та середовища; зростаючі вимоги до точності та техніко-економічних характеристик систем. Відмінність адаптивних систем від оптимальних у тому, що у оптимальних системах показник якості забезпечується певних параметрів об’єкта, то адаптивних – для різних параметрів з допомогою дії додаткових елементів адаптації. Вибір того чи іншого підходу визначається попередньою інформацією про об'єкт (процес) або прийнятим критерієм якості. У статті наведено основні підходи до вибору можливих варіантів адаптивних систем зі стабілізацією та оптимізації якості управління системами стабілізації динамічних об'єктів, виходячи з виду екстремальної характеристики критерію оцінки їх якості.

Ключові слова: система стабілізації; блок-схема; екстремальна характеристика; контур адаптації; еталонна модель; екстремальне керування; робоча точка; пошук екстремуму.

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