AUTOMATIC CONTROL SYSTEMS

UDC 681.511.4 (045)

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REACTION OF STABILIZATION SYSTEM ON THE COMMANDS OF OPERATOR. ACCURACY OF STABILIZATION

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Abstract*—*The accuracy estimation method of stabilization systems of inertial control objects, that operates on a movable base in modes of stabilization and stable guidance at random disturbance influences and control signals is considered.

Index terms—The transfer function; control object; damping; stiffness; disturbing moment; a control signal; spectral density; amplitude and phase frequency response dispersion; mean square error; the cross-correlation; characteristic polynomial.

I. INTRODUCTION

During the estimation of the control quality and choosing the regions of exploitation regulations of the stabilization systems of inertial control objects, working on a movable base, it is disallowed only to take into account the quality rates, which characterizes the reaction of the system only on previously chosen custom external action.

It is known [1] that the processes of changing of the amplitude, speed and acceleration of mobile bases when moved by terrain are random stationary process, which are dependent from road cutting, its quality, and also from dynamic properties of suspension, rates of motion etc. It was understood [2] that according to structural analysis of control objects, that external disturbance moments, which may act on stabilization systems, are functionally dependent from parameters of fluctuation of a base.

Control signals, formed by the operator at the input of the stabilization system, during targeting a control object or tracking the objects of observation, are also random functions of time. It is stipulated by the randomicity of the relative movement of movable base and the object of observation. In result, the operator creates a random control signal at the input of system in order to offset errors of aiming.

Consequently, control signals of operator, acting on a stabilization system of a control object, that works on a movable base, as well as external perturbations are random functions of time. Thus, it is necessary to use statistical methods to evaluate the response of the automatic control system on external perturbations and operator commands.

II. SOLUTION OF THE PROBLEM

The analysis of the stabilization systems shows that the systems which are different by the construction have the same structure and the same transfer functions. This makes us to observe the approach to their analysis on the generalized structural scheme [3], which is shown at the Fig. 1.

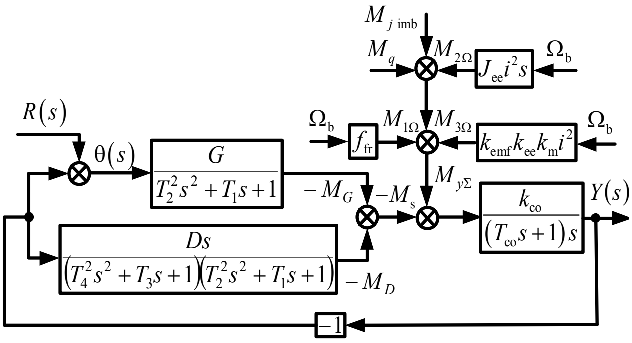

Fig. 1. The generalized structural scheme of the stabilization system

The following designations are accepted in structural scheme: $W_{\text{co}}(s)=\dfrac{k_{\text{co}}}{(T_{\text{co}}s+1)}$ is the transfer function of a control object; $G=k_{\text{ds}}k_{\text{reg}}$ is the stiffness of a system which is considered by the gain coefficient of the deflection sensor k_{ds} and the regulator k_{reg}; $D=k_{\text{sds}}k_{\text{reg}}$ is the damping of a system which is considered by the gain coefficient of the speed deflection sensor k_{sds} and regulator k_{reg}; $M_{y\Sigma}(s)$ is the total disturbing moment which impacts on the control object; M_S is the moment of stabilization; $R(s)$ is the control signal which is formed by an operator.

The spectral densities of the moments of forces, which are formed by an operator at the input of the deflection sensor, are shown at the Fig. 2. Characteristics are measured during the middlecross-country motion. The spectral densities analysis shows that operator is able only to elaborate the most low-frequent part of external disturbances since its pass band is limited by the frequency of 6 rad/s (1 Hz).

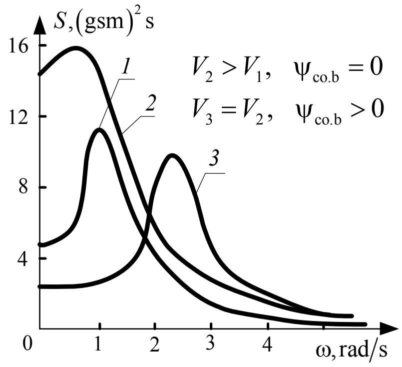

Fig. 2. The spectral densities of the moments of targeting, which are formed by an operator

Most effectively operator fulfills external disturbances, the frequency of which is less than 3 rad/sec (less than 0.5 Hz). Therefore, in real terms, the operator can compensate the deviations caused by goings of gyro angle sensor, low-frequency disturbances, caused by changes in azimuth movement of the object on the ground. The deviations, caused by high-frequency part of the spectrum of perturbations, the operator can not compensate physically.

From the theory of random processes and statistical dynamics it is known that the connection between the spectral density $S(\omega)$ of a random signal, acting on the input of the linear system and the spectral density $S_{os}(\omega)$ of the output signal is formed by the correlation:

$$S_{os}(\omega) = S(\omega)\left|W(j\omega)\right|^2,$$

where $W(j\omega)$ is the amplitude-phase-frequency characteristic of the system regarding to observed input; $S(\omega) = \frac{2}{\pi}\int_0^\infty R(\tau)\cos\omega\tau d\tau$ is a spectral density of the input signal.

If the spectral density of the output signal $S_{os}(\omega)$ is known, it is possible to detect its dispersion

$$D = \int_0^\infty S_{os}(\omega)d\omega,$$

as well as corresponding to it mean-squared error (MSE),

$$\sigma = \sqrt{D},$$

which is a criterion of the quality of the system upon addition to its input a random signal.

Therefore, to calculate the dispersion D or mean square error σ of the stabilization system is necessary to know the spectral density of the total disturbing moment and the corresponding amplitude-phase-frequency response of the system.

In case when the system has several input signals according to the principle of superposition the spectral density at the output of the system must be determined by taking into account each of the components and their cross correlation

$$S_{os\Sigma}(\omega) = S_1(\omega)\left|W_1(j\omega)\right|^2 + S_2(\omega)\left|W_2(j\omega)\right|^2 + \ldots + S_{12}(\omega)W_1^*(j\omega)W_2(j\omega) + S_{21}W_1(j\omega)W_2^*(j\omega) + \ldots +,$$

where $S_{12}(\omega)$ and $S_{21}(\omega)$ are spectral densities of cross correlated input signals; $W_1^*(j\omega) = W_1(-j\omega)$ and $W_2^* = W_2(-j\omega)$ are complex conjugates functions of the amplitude-phase-frequency characteristics of the system relatively to observed input signals.

When performing engineering calculations of accuracy of stabilization systems generally believe that fluctuations of the base in different planes are not correlated with each other. Also assumed that there is no cross-correlation between operator control signals and fluctuations of base. Sometimes, in order to simplify the calculations all input signals with the help of preliminary structural transformation are leaded to any one input and their total spectral density is calculated.

In determining the accuracy of the stabilization system usually considered that the operator signal is zero, and the gyroscopic sensor angle is ideal (predetermined angle $\alpha_{pa} = \text{const}$).

Stability error is defined as the result of impact on the control object the total disturbing moment. Determination of the spectral density of the total disturbing moment is produced by the known spectral densities of fluctuations base and under known structural links between disturbing moment and angular fluctuations of the base.

For stabilization system of inertial control object, operating on a movable base, determining of the spectral density of total disturbing moment, which is the geometric sum of a number of components, is very difficult. The task is simplified by using the principle of superposition.

According to the structural diagram in Fig. 1, we have

$$\bar{M}_{y\Sigma} = \bar{M}_{1\Omega} + \bar{M}_{2\Omega} + \bar{M}_{3\Omega} + \bar{M}_{q} + \bar{M}_{j\,\mathrm{imb}},$$

where M_q and $M_{j\,\mathrm{imb}}$ are moments of static and dynamic imbalance of the control object, respectively; $M_{1\Omega} = f_{\mathrm{fr}}\Omega_{\mathrm{b}}$ is the moment of friction forces in the control object reliance; $M_{2\Omega} = J_{\mathrm{em}} i^2 s\Omega_{\mathrm{b}}$ is the inertial moment of the executive engine, reduced to the axis of rotation of the control object; $M_{3\Omega} = k_{\mathrm{emf}} k_{\mathrm{ee}} k_{\mathrm{m}} i^2 \Omega_{\mathrm{b}}$ is the moment of the back EMF of the executive engine (or its analogue), resulted to the axis of rotation of the control object. Each of the moments is connected with the parameters of fluctuations of the base.

Experimentally established that in a frontal location of the control object relative to the base, the greatest share has the disturbing moment

$$\bar{M}_{\Omega\Sigma} = \bar{M}_{1\Omega} + \bar{M}_{2\Omega} + \bar{M}_{3\Omega},$$

caused by horizontal angular fluctuations of the movable base.

The transfer function of the disturbing moment according to Fig. 1 is

$$W_{M_{\Omega\Sigma}}(s) = \frac{M_{\Omega\Sigma}}{\Omega_{\mathrm{b}}} = f_{\mathrm{fr}} + J_{\mathrm{ee}} i^2 s + k_{\mathrm{emf}} k_{\mathrm{ee}} k_{\mathrm{m}} i^2.$$

The spectral density of the disturbing moment can be found on the basis of the spectral density of the velocity of fluctuation of the moving base and squares of the modules of the transfer functions of each of the channels of formation a perturbation of the control object

$$S_{M_{\Omega\Sigma}}(\omega) = S_{M_{1\Omega}}(\omega) + S_{M_{2\Omega}}(\omega) + S_{M_{3\Omega}}(\omega) \tag{1}$$
$$= \left(f_{\mathrm{fr}}^{\,2} + J_{\mathrm{ee}}^2 i^4 \omega^2 + k_{\mathrm{emf}}^2 k_{\mathrm{ee}}^2 k_{\mathrm{m}}^2 i^4\right) S_{\Omega\,\mathrm{b}}(\omega).$$

It should be noted, that the accuracy of the stabilization system is fully characterized by the quantity and nature of the variation of discrepancy error

$$\theta(t) = r(t) - y(t).$$

Let us assume that the probability characteristics of random perturbation $M_{\Omega\Sigma}(t)$ are known.

$$S_{\theta}(\omega) = \left|W_{sm}(j\omega)\right|^2 S_{M_{\Omega\Sigma}}(\omega)$$
$$= \frac{k_{\mathrm{co}}^2 \left|\left(1 - T_2^2\omega^2 + jT_1\omega\right)\left(1 - T_4^2\omega^2 + jT_3\omega\right)\right|^2}{\left|A(j\omega)\right|^2} S_{M_{\Omega\Sigma}}(\omega), \tag{2}$$

where $S_{M_{\Omega\Sigma}}(\omega)$ is the spectral density of disturbance; $\left|W_{sm}(j\omega)\right|^2$ is the square of the module of the frequency transfer function of the error of the external perturbation.

Revealing the value of the spectral density of the disturbance action, according to (1) we obtain

$$S_{\theta}(\omega) = k_{\mathrm{co}}^2\left(f_{\mathrm{fr}}^{\,2} + J_{\mathrm{ee}}^2 i^4 \omega^2 + k_{\mathrm{emf}}^2 k_{\mathrm{ee}}^2 k_{\mathrm{m}}^2 i^4\right)$$
$$\cdot \frac{\left|\left(1 - T_2^2\omega^2 + jT_1\omega\right)\left(1 - T_4^2\omega^2 + jT_3\omega\right)\right|^2}{\left|A(j\omega)\right|^2} S_{\Omega\,\mathrm{b}}(\omega). \tag{3}$$

Integration of the expression (3) on the entire frequency range allows to determine the dispersion and the mean square value of the variation of discrepancy error

$$\sigma_{\theta} = \sqrt{D_{\theta}} = \sqrt{\frac{1}{2\pi}\int_{-\infty}^{\infty} S_{\theta}(\omega) d\omega}. \tag{4}$$

In case when the course angles of the control object are close to zero, the mean square error, that is calculated by the formulas (3) and (4), makes more than 75% of the summary error of the stabilization system, that is completely characterized its accuracy.

Performed statistical calculations of stabilization systems accuracy show that the value of the mean-square deviation of the control object from the desired direction depends both from the nature of fluctuations of the moving base (spectral densities of the disturbing moments), and from construction and adjustment parameters of the system, the values of which determine the amount of square of the modulus of the amplitude-frequency characteristic of the system.

Figure 3 as an example, shows the amplitude – frequency $\left|W_{sm}(j\omega)\right| = A_m\big|_{M_{y\Sigma}}(\omega)$ characteristics of the stabilization system for various combinations of adjustment coefficients. With decreasing the damping k_D of the system the resonance peak characteristics becomes clearly defined, and with increasing k_G stiffness – the peak shifts towards higher frequencies.

Figure 4 presents the amplitude – frequency characteristics of the stabilization system taking into account the channels of formation of external disturbances.

For each of the possible adjustments, in turn, will fit a certain spectral density of discrepancy error of stabilization system. In addition, if we consider that the spectral density of angular fluctuations of the movable base depends on the soil on the track of movement becomes clear the complexity of solving the problem of optimization the adjustment of the system. Essentially for each the specific conditions of movement corresponds a certain rational combination of control parameters.

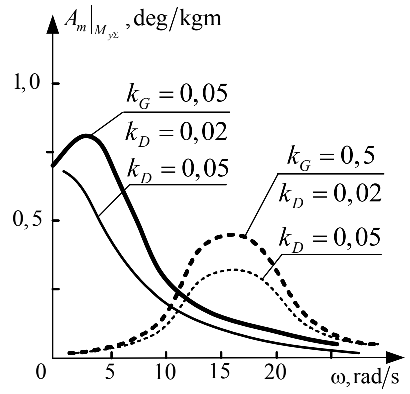

Fig. 3. Amplitude-frequency characteristics of the stabilization system

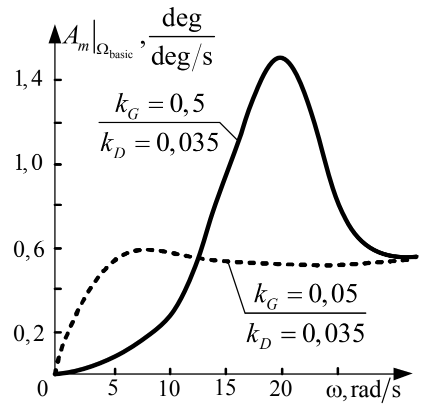

Fig. 4. The amplitude-frequency characteristics taking into account the channels of formation the external disturbances

To take full advantage of the technical capabilities of stabilization systems in various conditions can be offered special nomograms of optimal adjustments for typical traffic conditions a movable base. The specific interest represents the development of corrective devices, providing automatic change the system parameters on the specific traffic conditions to ensure the highest accuracy of stabilization. To be expected inclusion the automatic control of accuracy and selftuning in the schemes of stabilization systems.

To evaluate the accuracy of the system in a mode of stabilized targeting except disturbing moments must be taken into account the statistical characteristics of the operator (see Fig. 2).

Let us assume that probability characteristics of a random control signal are also known. Let us find according to Fig. 1, the transfer function of the discrepancy error

$$W_s(s) = \frac{\theta(s)}{R(s)}$$

$$= \frac{(T_{co}s+1)s(T_2^2s^2+T_1s+1)(T_4^2s^2+T_3s+1)+k_{co}Ds}{A(s)}.$$

Let us give the last expression a view

$$W_s(s) = \frac{G(s)}{A(s)},$$

where $G(s)$ is the characteristic polynomial of the open-loop system:

$$G(s) = a_6s^6 + a_5s^5 + a_4s^4 + a_3s^3 + a_2s^2 + k_{co}Ds\ .$$

In accordance with the principle of superposition discrepancy error of the system is defined as

$$\theta_\Sigma(s) = W_s(s)R(s) + W_{sm}(s)M_{y\Sigma}(s)\ . \qquad (5)$$

Taking into account the random nature of the control signal and disturbance, after substituting in (5) the values of the frequency transfer functions $W_s(j\omega)$, $W_{sm}(j\omega)$ and spectral densities of control signal $S_r(\omega)$ and disturbance $S_{My\Sigma}(\omega)$, we obtain an equation for calculating the spectral density of the total discrepancy error of the system

$$S_{\theta\Sigma}(\omega) = \frac{|G(j\omega)|^2}{|A(j\omega)|^2}S_r(\omega)$$

$$+k_{co}^2\left(f_{fr}^{\ 2} + J_{ee}^2 i^4\omega^2 + k_{emf}^2 k_{ee}^2 k_m^2 i^4\right)$$

$$\cdot\frac{\left|(1-T_2^2\omega^2+jT_1\omega)(1-T_4^2\omega^2+jT_3\omega)\right|^2}{|A(j\omega)|^2}S_{\Omega\text{ b}}(\omega).$$

In determining the reaction of the stabilization system on the operator's control signals it is also necessary to consider the impact of operational adjustments on the formation of the amplitude-frequency characteristics of the system.

Figures 5, 6 show a family of amplitude-phase frequency and amplitude-frequency characteristics of the stabilization system relative to the operator's signal. The characteristics obtained at constant stiffness and variable damping.

In the case of increasing stiffness the resonance peak of the curve shifts towards higher frequencies. Analysis of these characteristics shows that to ensure the required accuracy in a stabilized aiming mode requires an appropriate adjustment of system.

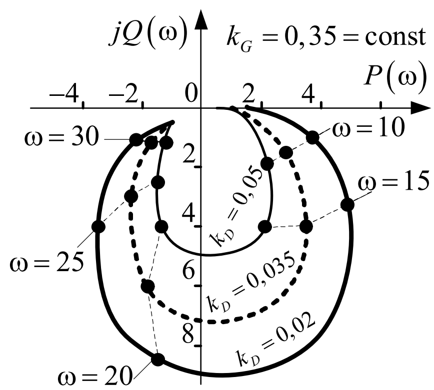

Fig. 5. Amplitude-phase frequency characteristics by the control channel

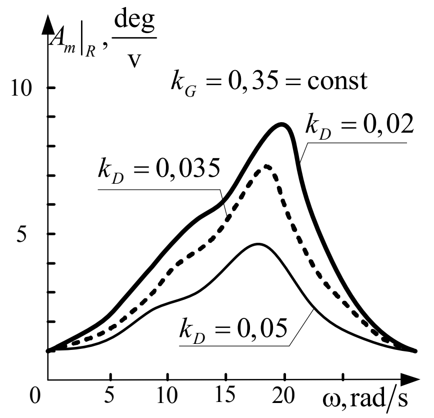

Fig. 6. Amplitude-frequency characteristics by the control channel

Thus, the technical conditions for operational adjustments of stabilization systems must be set in such a way that simultaneously provides high-quality tracking and maximum accuracy stabilization.

III. Conclusions

Availability of information on probability characteristics of the control signals of operator and disturbances allows the developer of stabilization systems of inertial control objects, working on a movable base, to choose the parameters of the controller so as to ensure maximum difference of the peaks of the amplitude-phase frequency characteristics of the systems and the spectral densities of the aforementioned signals. In this case, can be ensured maximum accuracy of the system in modes of stabilization and stabilized aiming.

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Received October 15, 2015.

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О. К. Аблесімов, Л. В. Бардон, Н. І. Кутова. Реакція системи стабілізації на команди оператора. Точність стабілізації

Розглянуто методику оцінювання точності систем стабілізації інерційних об’єктів керування, що працюють на рухомій основі в режимах стабілізації та стабілізованого наведення при випадкових збурюючих впливах і сигналах керування.

Ключові слова: передатна функція; об'єкт керування; демпфірування; жорсткість; збурюючий момент; сигнал керування; спектральна щільність; амплітудно-фазова частотна характеристика; дисперсія; середньоквадратична помилка; взаємна кореляція; характеристичний багаточлен.

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А. К. Аблесимов, Л. В. Бардон, Н. И. Кутовая. Реакция системы стабилизации на команды оператора. Точность стабилизации

Рассмотрена методика оценки точности систем стабилизации инерционных объектов управления, работающих на подвижном основании, в режимах стабилизации и стабилизированного наведения при случайных возмущающих воздействиях и сигналах управления.

Ключевые слова: Передаточная функция; объект управления; демпфирование; жесткость; возмущающий момент; сигнал управления; спектральная плотность; амплитудно-фазовая частотная характеристика; дисперсия; среднеквадратическая ошибка; взаимная корреляция; характеристический многочлен.

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