AUTOMATIC CONTROL SYSTEMS

UDC 681.511.4 (045)

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CORRECTION OF THE QUALITY OF STABILIZATION SYSTEMS

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Abstract—*Considered the methods of determining the desired frequency characteristics of the stabilization systems of the inertial control objects while the synthesis of their corrective devices.*

Index terms—The correction device; inverse transfer function; spectral density; amplitude and phase frequency characteristic; the desired frequency characteristics; inverse amplitude and phase frequency characteristic.

I. INTRODUCTION

The generalized structural scheme of the stabilization system of inertial control object, working on a movable base, is shown at the Fig. 1.

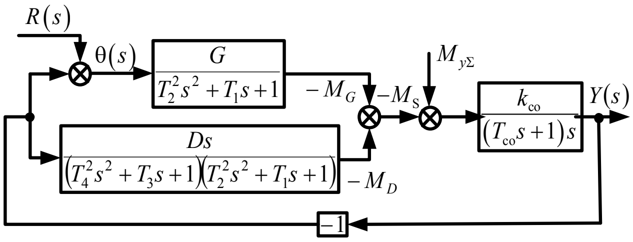

Fig. 1. The structural scheme of the stabilization system

The following designations are accepted in structural scheme: $W_{co}(s)=\dfrac{k_{co}}{(T_{co}s+1)}$ is the transfer function of a control object; $G=k_{ds}k_{reg}$ is the stiffness of a system which is considered by the gain coefficient of the deflection sensor k_{ds} and the regulator k_{reg}; $D=k_{sds}k_{reg}$ 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.

The illustrated structural scheme does not always allow to obtain the required quality of the control processes at the selected design parameters of elements. Besides feedback by the absolute angular velocity of the control object into the structure of the regulator of the stabilization system are usually introduced an additional parallel and serial corrective devices to ensure a given quality.

II. SOLUTION OF THE PROBLEM

Parallel corrective devices are implemented as rigid and flexible feedbacks covering an element, a chain of elements or the entire system. Hard negative feedbacks are used relatively rarely for the correction of quality. This is because that the introduction of negative rigid feedback, providing speed increasing and expansion of the linearity zone, at the same time reduces the transfer coefficient of the covered element or the chain of elements. As a result - increasing of the control errors. The most widely for the purposes of quality correction are applied the flexible feedbacks - feedbacks from the derived output value of the element (a chain of elements) or system. Since the flexible feedbacks are acting only during the transients, their introduction allows to correct the quality of governance without changing the static properties of the system.

In general, the inverse transfer function of the open-loop system, adjusted by the ideal differentiating feedbacks, has the form:

$$E_{ol}^{(c)}(s)=E_{ol}(s)+k_1s+k_2s^2+k_3s^3+\ldots, \qquad (1)$$

where $E_{ol}(s)$ is the inverse transfer function of the system, that is not corrected; $k_1,k_2,k_3,\ldots$ are coefficients of flexible feedback of the corresponding order by dimension second.

Inverse amplitude and phase frequency characteristic (APFC) of the corrected system according to equation (1) will be:

$$E_{ol}^{(c)}(j\omega)=U_E^{(c)}(\omega)+jV_E^{(c)}(\omega),$$

where

$$U_E^{(c)}(\omega)=U_E(\omega)-k_2\omega^2+k_4\omega^4-\ldots;$$
$$V_E^{(c)}(\omega)=V_E(\omega)+k_{1\partial}\omega-k_3\omega^3+\ldots .$$

Therefore, the coordinates of each point of the original characteristic $E_{ol}(j\omega)$ with the introduction of flexible feedbacks acquire an increments

$$\Delta U_E(\omega) = -k_2\omega^2 + k_4\omega^4 - \ldots ,$$
$$\Delta V_E(\omega) = k_1\omega - k_3\omega^3 + \ldots ,$$

and the whole characteristic is shifted on the plane $U_E(\omega) \to jV_E(\omega)$.

Fig. 2 shows the feedback APFC deformation of the open loop system when introduced the four first derivatives of control value.

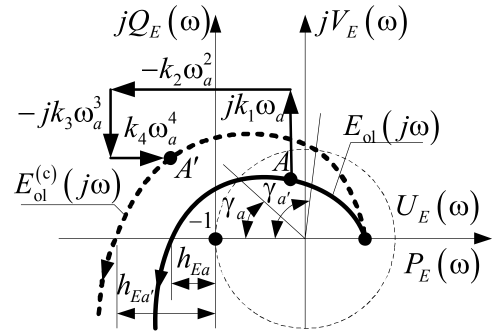

Fig. 2. The offset of the point of inverse APFC of the open-loop system $E_{ol}(j\omega)$, when flexible feedbacks are introduced

Effect of flexible feedbacks by the first and third derivatives so as the effect of the feedbacks by the second and fourth derivatives are mutually opposite. Feedbacks by the third and fourth derivatives have a little effect on the initial (low frequency) part of the characteristic and significantly distort its high-frequency part.

In the stabilization systems of inertial control objects, operating on a movable base, the forced oscillations have a low frequency spectrum, depending on the perturbation and control signals. Therefore, for correction the quality generally are used the feedbacks by the first two derivatives - by speed and by acceleration of the control object.

Application of the feedback by the first derivative (by the velocity) increases the stability margins in modulus $h_{Ea'} > h_{Ea}$ and phase $\gamma_{a'} > \gamma_a$, shifting up (Fig, 2) the characteristic $E_{ol}(j\omega)$. It is necessary to mean that in this case the tracking error is increases.

Application of the feedback by the second derivative (by the acceleration) increases the stability margin in modulus, but reduces the stability margin in phase, since the characteristic $E_{ol}(j\omega)$ is shifting to the left due to the component $-k_2\omega^2$. In this case the stability region is expanding, but at the same time increases the transient recovery time. This demonstrate, in particular, a decreasing of the frequency ω_p of the positiveness of characteristic $P(\omega)$, with which the transient recovery time related by the ratio $t_{tr} > \dfrac{\pi}{\omega_p}$.

What was said above should be considered when selecting the type of flexible correcting feedback in stabilization systems.

Serial corrective devices are usually realized in the form of differentiating or integro-differentiating passive DC circuits. The differentiating circuits along with the expansion of the area of stability of the system improve its action in time, providing the forcing of transients.

Fig. 3 shows the effect from the sequential correction circuit (SCC) on the region of stability of the stabilization system. SCC moves to the right the low-frequency stability border, thus enabling to regulate the system on a larger stiffness. In the same figure is compared the ideal and the real differentiating circuits. Comparison demonstrates that the non-ideality of the differentiating circuit reduces its impact on the effectiveness of the system.

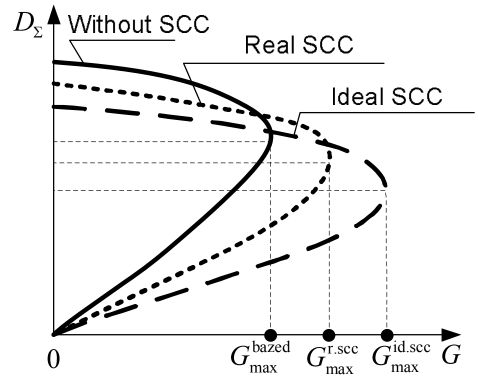

Fig. 3. Impact of SCC on the stability region

Raising the margin of stability of the system while simultaneously forcing of the transients - important advantage of the successive differentiating contours. The widespread use of these contours for the correction the quality of system is also caused by the simplicity of their constructive realization.

The main disadvantages of the successive differentiating contours include:

1) significant (by 10 times or more) reduction of the amplification coefficient of stabilization system, requiring a corresponding increase in the transfer coefficients of other units or the introduction of special amplifiers;

2) high sensitivity to interference (noises);

3) the difficulty of implementing of contours for AC control signals and therefore the necessity to have in the system the phase-sensitive amplifiers.

Much less often differentiating circuits apply the integrating SCC. Application of the integrating circuit (ideal) allows to increase an order of magnitude system astatism, but leads to deterioration of its stability.

In order to choose one or the other type of corrective device and determine its parameters, you must compare the original (uncorrected) system with the desired system. Comparisons are usually conducted on logarithmic amplitude and phase frequency characteristics.

When correction is serial transfer function of the desired (corrected) open-loop system will be equal to:

$$W_{\text{ol.des}}(s) = W_{\text{ol}}(s)W_{\text{c}}(s), \tag{2}$$

where $W_{\text{ol}}(s)$ is the transfer function of the original (uncorrected) system; $W_{\text{c}}(s)$ is the transfer function of SCC.

Hence the amplitude phase frequency characteristic of the correcting device can be determined from the from the relation:

$$W_{\text{c}}(j\omega) = \frac{W_{\text{ol.des}}(j\omega)}{W_{\text{ol}}(j\omega)}.$$

Proceeding to logarithmic and phase frequency characteristics, we have:

$$\left.\begin{aligned} L_{\text{c}}(\omega) &= L_{\text{ol.des}}(\omega) - L_{\text{ol}}(\omega); \\ \varphi_{\text{c}}(\omega) &= \varphi_{\text{ol.des}}(\omega) - \varphi_{\text{ol}}(\omega). \end{aligned}\right\} \tag{3}$$

Thus, the logarithmic and phase frequency characteristics of the serial correcting device determines as the difference between the desired and original characteristics. Typically, determination of $L_{\text{c}}(\omega)$ is made graphically (Fig. 4).

In case of parallel correction, transfer function of desired (corrected) open-loop system will be

$$W_{\text{ol.des}}(s) = \frac{W_{\text{ol}}(s)}{1 + W_{\text{cov}}(s)W_{\text{fbc}}(s)}, \tag{4}$$

where $W_{\text{cov}}(s)$ is the transfer function of the elements, that are covered by the feedback correction; $W_{\text{fbc}}(s)$ is the transfer function of the feedback correction.

Taking into account that by any method of correction must be obtained the same desirable characteristic, will equate (2) and (4), substituting $s = j\omega$:

$$W_{\text{c}}(j\omega) = \frac{1}{1 + W_{\text{cov}}(j\omega)W_{\text{fbc}}(j\omega)}. \tag{5}$$

For the frequency range in which

$$W_{\text{cov}}(j\omega)W_{\text{fbc}}(j\omega) \ll 1$$

correction is not required, since $W_{\text{c}}(j\omega) \cong 1$.

For the frequency range when

$$W_{\text{cov}}(j\omega)W_{\text{fbc}}(j\omega) \gg 1$$

will have:

$$L_{\text{c}}(\omega) = -\left[L_{\text{cov}}(\omega) + L_{\text{fbc}}(\omega)\right]. \tag{6}$$

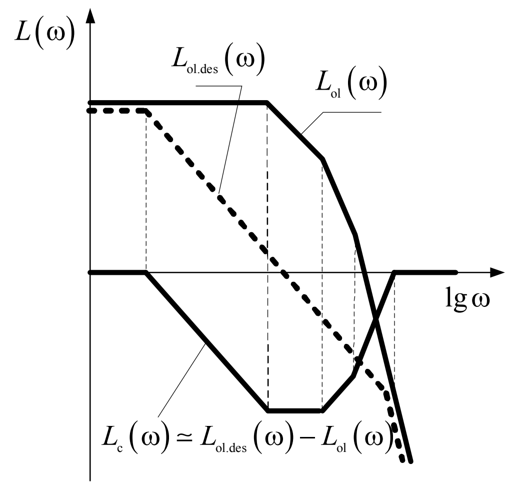

Fig. 4. LAFC determination of the correcting device

Having defined by equation (3) the characteristic $L_{\text{c}}(\omega)$ and knowing the characteristic $L_{\text{cov}}(\omega)$, we can find:

$$L_{\text{fbc}}(\omega) = -\left[L_{\text{cov}}(\omega) + L_{\text{c}}(\omega)\right]. \tag{7}$$

Using special tables, by known characteristics $L_{\text{c}}(\omega)$ or $L_{\text{fbc}}(\omega)$, it is possible to select the scheme and find the parameters of the serial or parallel correcting device

Below we consider two cases for determining the desired characteristics, that most frequently meet in the synthesis of corrective devices of stabilization systems.

A. Determination of the desired frequency characteristics of the stabilization system by a given type of transition

While designing the stabilization system can be assigned not the individual parameters of the control quality, but characteristic of the transition process, which occurs in the system under the action of the control signal or external perturbation. Required characteristic of the transition process can be tentatively constructed also with the help of its individual parameters $t_{\text{rt}}, t_{\text{ps}}, y_{\text{osh}}, n$.

Usually given the characteristic of the transition process as the reaction on a step change of the control signal or the external disturbance under zero initial conditions (Fig. 5a). This kind of characteristic is not satisfy the conditions of absolute integrability and can not be represented by a Fourier integral. With this in mind, let us consider the function

$$y(t)=Y(t)-Y_{st}, \tag{8}$$

satisfying the conditions of absolute integrability, since when $t\to\infty$ $y(t)\to 0$ (Fig. 5b).

Applying to the function (8) direct Fourier transformation, we obtain

$$\int_0^\infty y(t)e^{-j\omega t}dt=\frac{W(j\omega)}{j\omega}-\frac{Y_{st}}{j\omega}. \tag{9}$$

After transformation the equation (9), we obtain the amplitude and phase frequency characteristic of a closed system:

$$W(j\omega)=Y_{st}+j\omega\int_0^\infty y(t)e^{-j\omega t}dt. \tag{10}$$

The real and imaginary parts of the APFC are respectively:

$$\left.\begin{aligned}P(\omega)&=Y_{st}+\omega\int_0^\infty y(t)\sin\omega t dt;\\ Q(\omega)&=\omega\int_0^\infty y(t)\cos\omega t dt.\end{aligned}\right\} \tag{11}$$

The integrals in (11) can be accurately calculated only for the simplest functions $y(t)$. Therefore it is advisable to use for the approximate calculations $P(\omega)$ and $Q(\omega)$ the trapezoidal components of the function $y(t)$ instead of the function itself.

If $y(t)$ can be approximately represented as a rectangular trapezoid with bases t_p and t_o and height y_o, the integrals will be equal:

$$\begin{aligned}\omega\int_0^\infty y(t)\sin\omega t dt&=y_o+\frac{y_o}{\omega}\cdot\frac{\sin t_p\omega-\sin t_o\omega}{t_p-t_o};\\ \omega\int_0^\infty y(t)\cos\omega t dt&=\frac{y_o}{\omega t_p}\cdot\frac{\cos t_o\omega-\cos t_p\omega}{t_p-t_o}.\end{aligned} \tag{12}$$

When approximating the characteristic $y(t)$ by multiple trapezoids (Fig. 5c) so that $\sum_1^i y_{oi}=-Y_{st}$, we obtain:

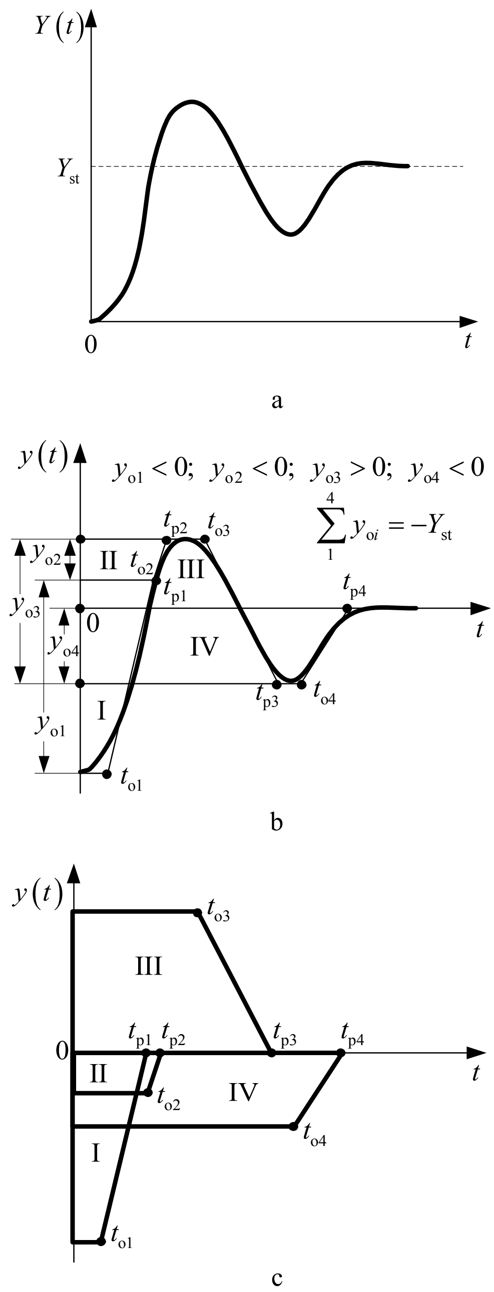

Fig. 5. Approximation of the transition process by trapezoids: (a) is the initial $Y(t)$; (b) is the characteristic $y(t)=Y(t)-Y_{st}$; (c) are trapezes

$$\begin{aligned}P(\omega)&=Y_{st}+\sum_1^i P_i(\omega)=\frac{1}{\omega}\sum_1^i y_{oi}\frac{\sin t_{pi}\omega-\sin t_{oi}\omega}{t_{pi}-t_{oi}};\\ Q(\omega)&=\sum_1^i Q_i(\omega)=\frac{1}{\omega}\sum_1^i y_{oi}\frac{\cos t_{oi}\omega-\cos t_{pi}\omega}{(t_{pi}-t_{oi})t_{pi}}.\end{aligned} \tag{13}$$

By equation (13) is approximately calculated desired frequency characteristics of the system, a comparison of which with the frequency characteristics of the original (uncorrected) system allows you to choose the necessary correction devices for obtaining a predetermined transient.

B. Determination of the desired frequency characteristics of the stabilization system by minimum of the stabilization error

If we know the spectral density of a random external perturbation acting on the control object, the desired frequency response of the stabilization system should be determined by minimizing the error of stabilization.

Let us assume that the spectral density $S_{му}(\omega)$ of the total perturbation moment is known, for example, calculated on the basis of the spectral densities of the fluctuations of the movable base. Also known stability region of the stabilization system (calculated or derived experimentally). Inside this area is allocated the area of desired adjustments.

By choosing in the region of possible adjustments a number of points (1, 2, 3, 4) with different values G and D, we build for each of them (Fig. 6) the reverse amplitude-phase frequency characteristics of the open-loop system

$$E_{ol}(j\omega) = U_E(\omega) + jV_E(\omega)$$

and their corresponding inverse amplitude and phase frequency characteristics

$$E(j\omega) = 1 + E_{ol}(j\omega) = P_E(\omega) + jQ_E(\omega)$$

of the closed system relative to the disturbance.

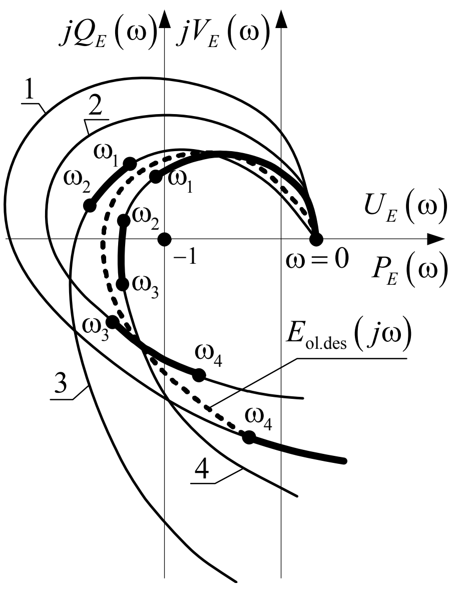

Fig. 6. Inverse APFC of the open-loop and closed-loop systems

Then, for each of the selected operating points determine the spectral density of the error of stabilization system

$$S_y(\omega) = S_{му}(\omega) A_{my}^2(\omega) = \frac{S_{му}(\omega)}{P_E^2(\omega) + Q_E^2(\omega)},$$

where $A_{my}(\omega)$ is the amplitude-frequency response of a closed system relative to the disturbance.

The founded spectral densities $S_y(\omega)$ are drawn on a single graph (Fig.7). Graphically define the lower envelope (fatty bottom curve) of spectral densities errors.

Frequency intervals $0-\omega_1; \omega_1-\omega_2; \omega_2-\omega_3$ and so on belong to the finite portions of different spectral densities of stabilization error. They determine which of the baseline characteristics $E_{ol}(j\omega)$ in this frequency range provides a minimum error of stabilization.

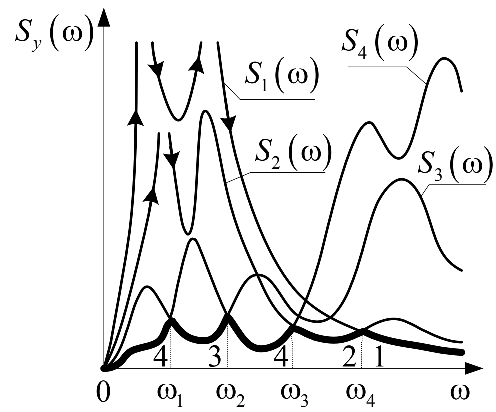

Fig. 7. The spectral densities of system errors

These portions are shown in characteristics of Fig. 6. Connecting them by a smooth line (dotted line in Fig. 6) is approximately getting the reverse amplitude-phase frequency characteristic of the desired system $E_{ol.des}(j\omega)$. Knowing $E_{ol.des}(j\omega)$ we define $L_{ol.des}(j\omega)$ and by the usual method we choose the type parameters of the serial correcting device.

If the spectral density of the external disturbance is unknown , the intervals of frequencies, in which the desired characteristic $E_{ol.des}(j\omega)$ coincides with the areas of initial characteristics $E_{ol}(j\omega)$, can be approximately defined by the lower envelope of the family of the amplitude-frequency characteristics $A_{my}(\omega)$ of the closed system.

In all cases, after an approximate determination of the desired frequency characteristics is advisable to check their compliance with the lower envelope of the $S_y(\omega)$ family or $A_{my}(\omega)$, and if it is necessary, to clarify the approximating areas.

Let us note that the described method of determining the corrective devices can use as an input the experimental or the computational characteristics.

Conclusions

The main difficulty of choosing of corrective devices for the automatic control systems is to determine of the species of desired frequency characteristics to provide the desired quality of control. This explained primarily by the fact that in the technical conditions for the design are usually set requirements that characterize the efficiency of the system as a whole, rather than separate indicators of quality. Consequently the desired characteristics is often necessary to build approximately according to very general requirements for the quality of the control.

The considered methods for determining the desired characteristics allow to solve the problem of correcting the quality of stabilization systems.

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Received January 17, 2016.

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О. К. Аблесімов, Л. В. Бардон, Н. І. Кутова. Корекція якості систем стабілізації

Розглянуто способи визначення бажаних частотних характеристик систем стабілізації інерційних об'єктів керування під час синтезу їх коригувальних пристроїв.

Ключові слова: коригувальний пристрій; зворотна передатна функція; спектральна щільність; амплітудно-фазова частотна характеристика; бажані частотні характеристики; зворотні амплітудно-фазові частотні характеристики.

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А. К. Аблесимов, Л. В. Бардон, Н. И. Кутовая. Коррекция качества систем стабилизации

Рассмотрены способы определения желаемых частотных характеристик систем стабилизации инерционных объектов управления при синтезе их корректирующих устройств.

Ключевые слова: корректирующее устройство; обратная передаточная функция; спектральная плотность; амплитудно-фазовая частотная характеристика; желаемые частотные характеристики; обратные амплитудно-фазовые частотные характеристики.

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