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doi:10.15199/48.2020.10.32

Structure Optimization of Functionally Sustainable Electromechanical Systems

***Abstract**. Structural schemes of functional-stable systems is proposed for a closed discrete system of electromechanical system automatic control. Quadratic quality criterion and structural scheme of the optimal restoring device are proposed. A theorem on quadratic criterion minimization is proposed and proved to recover control. The structural schemes of functionally stable direct and indirect action systems is presented. The optimal by generalized quadratic error criterion restorative management are proposed for functionally stable direct action systems*

Streszczenie.** W artykule przedstawiono schematy strukturalne systemów funkcjonalno-stabilnych dla zamkniętego dyskretnego automatycznego układu sterowania systemem elektromechanicznym. Zaproponowano kwadratowe kryterium jakości i schematy strukturalne optymalnego urządzenia przywracającego. W analizowanym układzie sterowania poprzez minimalizację kwadratowego wskaźnika jakości przywrócono stabilność układu działania bezpośredniego. **Optymalizacja struktury zamkniętego dyskretnego automatycznego układu sterowania systemem elektromechanicznym

Keywords: functional stability, restoration, electromechanical system.
Słowa kluczowe: stabilność funkcjonalna, przywracanie, układ elektromechaniczny.

Introduction

The theory of functional stability set back at the end of the 20th century and combines the concepts of reliability, survivability and safety, and provides for the restoration of complex systems [1-6]. Today the theory emerging to provide reliable operation of onboard information and measurement complexes of aircraft [1-3] is used in many scopes of activity to ensure the reliable functioning of complex technical systems [4-6]. The paper [5] shows theoretical possibility of creating functionally stable electromechanical systems (EMS). To design a functionally stable EMC, it is necessary to provide [1-6]:

- abnormal situation (AS) detection;
- its identification;
- restrict or localize the effect of AS to the system;
- develop control function in case of AS emergence and redistribute resources.

Let's consider the first stage - the detection of Abnormal Situation. Today, there are many approaches to the identification of parameters of electromechanical systems and their elements [7-12]. All of them are reduced either to comparing the parameters of the existing EMC with the previously calculated parameters [8-10], or predicting the state of the EMC on the basis of mathematical modelling of its processes in real-time [13-19]. There was insufficient attention to the issue of substantiating the signs of AS and further state identification.

An important component of functionally stable systems are algorithms of identification, working under the influence of random processes. The random function distribution $X(t)$, $t \in T$ with values in some measurable space in the space of all functions of time t, representing $t \in T$, is unambiguously determined by the sequence of its coordinated finite-dimensional distributions (Kolmogorov's theorem). Consequently, the problem of complete system statistical analysis is to determine all finite-dimensional distributions of the state vector, regarded as a random function of time. In most cases, it is sufficient to know only the one-dimensional distribution of the state vector, regarded as a random function of time. Then the problem of analysis is reduced to the definition of only one-dimensional distribution of the state vector. However, for a number of important practical tasks, the knowledge of finite-dimensional distributions is necessary. In particular, the problem of probability calculation of a random process output in the system from a bounded region requires knowledge of the distributions of the state vector of a sufficiently high dimension. It is necessary to know the two-dimensional distribution when dealing with the problem of conditionally optimal extrapolation of processes in stochastic systems [1-3].

The problems of evaluation in the systems can be divided into two classes. The first class includes the problems associated with result evaluation after finishing all experiments or observations. The second class involves the problems associated with processing the results of measurements in real time, that is, directly in the experiment or observation processes. The particularity of the first class evaluation problems is the use of all measurements results, while the second class problems may include only the observation results received up to this point in time. It must be emphasized that it is pointless to apply second-class problem solving techniques for a posterior evaluation, since this will only lead to a reduction in the accuracy of the evaluation. Real-time evaluations require tight limitations to admissible valuation.

The evaluation problem in arbitrary stochastic systems with unlimited delay has not yet been fully resolved. Such systems are sometimes referred to stochastic differential equations. Then all evaluation problems are reduced to the corresponding problems for stochastic systems [2, 3]. Therefore, it is necessary to optimize the structure of functionally stable electromechanical systems.

Mathematical model

The works [1-13, 18, 19] use a variety of (linear, nonlinear, probabilistic, etc.) continuous or discrete dynamic models that contain state and monitoring equations of the dynamic system.

For a mathematical description of thyristor control systems (TCSs), modern asynchronous motor drives often use the following vector-matrix equation and the corresponding system of equations in a matrix form [13]:

$$p\vec{i} + G\vec{\phi} + \vec{C} + Ap\vec{i_v} = 0 , \quad (1)$$

where $\vec{i} = (i_1, i_2, ..., i_6)^T$; $\vec{\phi} = (\phi_1, \phi_2, ..., \phi_6)^T$ is a current vector of external branches and vector potentials of TCS external nodes, that is, the branches out of it and nodes as points of possible connection of TCS to the scheme of the investigated system of asynchronous electric drive; G, $\vec{C}$ is the matrix and the vector the elements of which are determined by the parameters of TCS; $\vec{i}$ is a vector of currents of a three-phase bipolar thyristor key; A is a matrix determined by the internal scheme connecting the phase branches of bipolar thyristor switches and throttles.

Let's we make a description of a dynamic object (Fig. 1 a) on the basis of Equation (1) in the form of linear difference equations:

(2) $$Q(q)y(n) = q^{k+1}P_u(q)U(n) + P_\xi(q)\xi(n),$$

where $y(n)$ – initial value; $U(n)$ – control influence; $\xi(n)$ – external influence (disturbance); $Q(q)$, $P_u(q)$, $P_\xi(q)$ – polynomials of q; a_n, b_n, c_n – coefficients of polynomials; q – delay operator: $q^m\chi(n) = \chi(n{-}m)$ (sometimes the delay operator q^{-1} is used in the literature, so $q^{-m}\chi(n) = \chi(n{-}m)$).

It is assumed that polynomials P_u and P_ξ are stable, that is, they have all zeros outside the single circle $|q| < 1$, which corresponds to the minimal phase portrait.

Disturbance is a sequence of independent and equally distributed random variables such that:

(3) $$M\{\xi(n)\} = 0, \; M\{\xi(n)\xi(n-m)\} = \begin{cases} 0, & m \neq n \\ \sigma_\xi^2, & m = n \end{cases}.$$

In the general case, the equation of the restoring component (Fig. 1 b) can be represented as

(4) $$R(q)U(n) = P_r(q)r(n) - P_y(q)y(n),$$

where $r(n)$ – input influence.

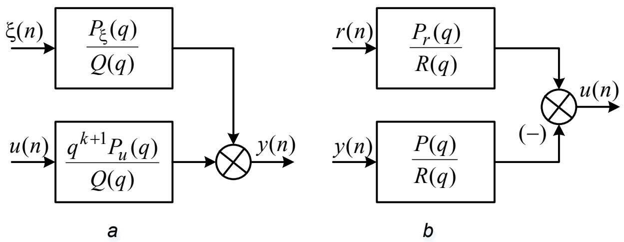

Fig.1. Block diagrams of dynamic object (a) and control device (b)

Excluding the object (2) and the control device (4) $U(n)$ from the equations, we obtain the equation of a closed system:

(5) $$G(q)y(n) = q^{k+1}P_u(q)P_r(q)r(n) + P_\xi(q)R(q)\xi(n),$$

where

(6) $$G(q) = Q(q)R(q) + q^{k+1}P_u(q)P_y(q),$$

is a characteristic polynomial of a closed system.

Structural schemes of a closed system are shown in Fig. 2. The choice of polynomial restoring device $R(q)$, $P_r(q)$, $P_y(q)$ provides for the properties necessary in the closed system. It is obvious that this choice depends on the polynomial of the object $Q(q)$, $P_u(q)$ and $P_\xi(q)$. To provide functional stability, a dynamic object must be controlled so that when the stationary input randomly effects $r(n)$, the object output $y(n)$ is the closest to the output $y_0(n)$ of the given system – the reference model.

(7) $$G^0(q) = y_0(n) = q^{k+1}H^0(q)r(n),$$

where $G^0(q)$, $H^0(q)$ are given stable polynomials of N_3 and N_4 degree, respectively.

We take adopt a generalized quadratic criterion [1, 2, 4, 5] as a degree of proximity:

(8) $$I_0 = M\left\{\left[\frac{G^0(q)}{D^0(q)}e(n)\right]^2\right\},$$

where

(9) $$e(n) = y(n) - y_0(n),$$

is an error; $G^0(q)$ and $D^0(q)$ stable polynomials of N_4 and N_5 degree, respectively.

The structural scheme of an optimal restoring device is shown in Fig. 3. The solution of the synthesis problem is to determine the parameters of block control unit, in which the criterion (8) reaches minimum. Therefore, fulfillment of the conditions of the theorem allows us to assert that an optimal control device exists.

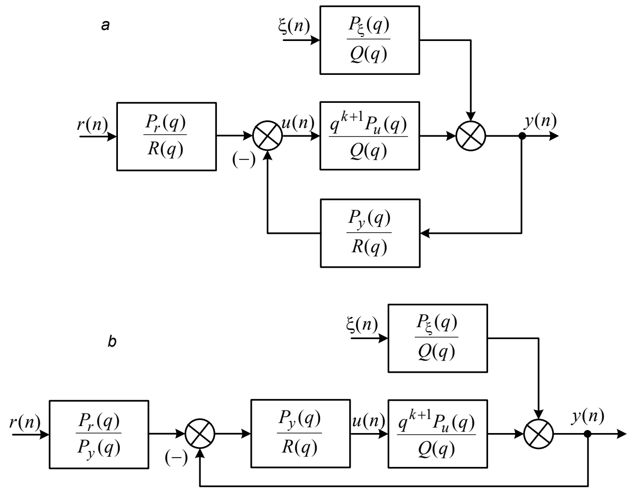

Fig.2. Block diagrams of closed system

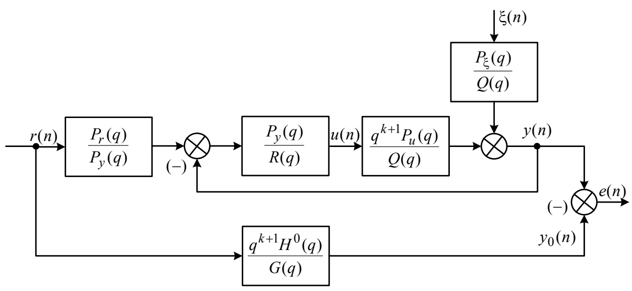

Fig.3. Block diagram of optimal restoring device

Results and Discussion

In accordance with criterion (8), we can formulate a theorem on optimal control of an object, which is described by equations (2).

Theorem. For a minimum-phase object (2), optimal control minimizing the criterion (8) is determined by equation (4), in which:

(10) $$\begin{aligned} R(q) &= G^0(q)D^0(q)P_u(q)S(q); \\ P_r(q) &= H^0(q)C^0(q)P_\xi(q); \\ P_y(q) &= G^0(q)P(q). \end{aligned}$$

The polynomials herewith:

(11) $$\begin{aligned} S(q) &= 1 + S_1^* q + \cdots + S_k^* q^k; \\ P(q) &= g_0^* + g_1^* q + \cdots + g_{N_7}^* q^{N_7}; \\ N_7 &= max[N_2 + N_{5-k-1}, N + N_6 + 1], \end{aligned}$$

satisfy the polynomial equation

(12) $$C^0(q)P_\xi(q) = D^0(q)Q(q)S(q) + q^{k+1}P(q).$$

For optimal restorative management

(13) $$C^0(q)P_\xi(q)=D^0(q)Q(q)S(q)+q^{k+1}P(q),$$

and the minimum value of the criterion (8) is equal

(14) $$I_{min}=M\left\{\left[\frac{C^0(q)}{D^0(q)}e_{opt}(n)\right]^2\right\}=\sigma_\xi^2[1+\sum_{m=1}^{k}(S_m^q)^2].$$

The proof of this theorem is obtained directly from the calculation of $C^0(q)P_\xi(q)e(n)$ due to the error expression (9), the polynomial equation (12), and the object equation (2).

Really

$$C^0(q)P_\xi(q)e(n)=q^{k+1}[D^0(q)P_u(q)S(q)U(n)+P(q)y(n)-$$
$$-C^0(q)P_\xi(q)y_0(n+k+1)]+D^0(q)P_\xi(q)S(q)\xi(n).$$

Equating zero to the square brackets, we obtain:

(15) $$C^0(q)P_\xi(q)e(n)=q^{k+1}[D^0(q)P_u(q)S(q)U(n)+$$
$$+P(q)y(n)-C^0(q)P_\xi(q)y_0(n+k+1)]+$$
$$+D^0(q)P_\xi(q)S(q)\xi(n).$$

Replacing in accordance with (7) $y_0(n+k+1)$ to $\frac{H^0(q)}{G^0(q)}r(n)$ we obtain the equation of the optimal restoring device (4), (10). The equality remaining in this case coincides with (13), and hence it takes place (14).

It is convenient to present the equation of the control device, so as to separate the unknown polynomials from the known, predefined polynomials $G^0(q)$, $H^0(q)$, $C^0(q)$, $D^0(q)$. Then, taking into account (10), we get the equation (4)

(16) $$R_1(q)U(n)=R_\xi(q)\bar{r}(n)-P(q)\bar{y}(n),$$
$$R_1(q)=P_u(q)S(q)=b_0^*+h_1^*(q)+\cdots+h_{N_{1+k}}^*(q)^{N_{1+k}},$$

where

(17) $$\bar{r}=\frac{H^0(q)C^0(q)}{G^0(q)D^0(q)}r(n),\quad \bar{y}(n)=\frac{1}{D^0(q)}y(n).$$

The input influence $r(n)$ and the output quantity $y(n)$ are received through the corresponding known filters with transmitting functions

(18) $$\frac{H^0(q)C^0(q)}{G^0(q)D^0(q)},\quad \frac{1}{D^0(q)}.$$

The optimal control device equation (16) can be represented in a recurrent form

(19) $$U(n)=\frac{\left[\bar{r}(n)-\alpha^{*T}Z(n)\right]}{b_0^*},$$

where $\alpha^*=(b_0^*,h_1^*,\dots,h_{N_1+1}^*,q_0^*,q_1^*,\dots,q_{N_7}^*,C_1^*,\dots,C_{N_8}^*)^T$, $Z(n)$ – vector of observations.

Let's consider the structural scheme of an optimal restorative filter (Fig. 4).

The dimensions of the vectors α^* and $Z(n)$ increase with increase of k delay, consequently, the complexity of the restoring device increases.

Thus, for complete equation priori information (15), (19) determine optimal control according to the generalized quadratic error criterion (8). Having incomplete priori information, that is, when the parameters of the control object (2) are unknown, the analogous (19) of the equation determines only the structure of optimal control, then equation (19) is replaced by

(20) $$U(n)=\frac{\left[\bar{r}(n)-\alpha^T Z(n)\right]}{b_0},$$

where α – a satisfactory vector of parameters of the restoring device.

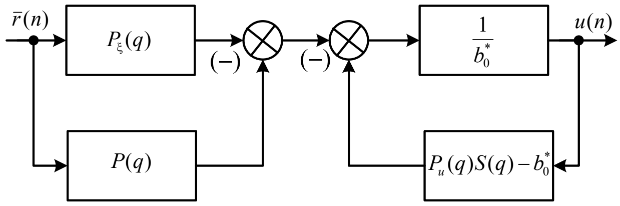

Fig.4. Block diagram of optimal restoring filter

Therefore, equation (20) determines only the structure of the optimal restoring filter.

The above structure of the control device is the basis of the construction of functionally stable systems. In these systems, the vector of parameters $\alpha=\alpha(n)$ of the restoring device should vary in such a way as to ensure the optimality of the whole system over time. This is achieved when $\alpha(n)\rightarrow\alpha^*$ at $n\rightarrow\infty$.

Functionally-stable systems can be divided into two types - indirect and direct. In indirect functionally stable systems, the change of control parameters $\alpha(n)$ occurs based on the results of the object identification [1-3, 5].

According to the vector estimates of $\Theta(n)$ of the object parameters (2), obtained on the basis of the processing of observations, the estimates of the parameters of the restoring device $\alpha(n)$ are calculated.

(21) $$\theta^*=(a_1^*,\dots,a_N^*,b_0^*,b_1^*,\dots,b_{N_1}^*,C_1^*,\dots,C_{N_2}^*)^T.$$

The block diagram of an indirect functional-stable system is depicted in Fig. 5. The adaption circuit in it contains the identification device generating the estimates of $\Theta(n)$, and the calculator, which, according to $\Theta(n)$ evaluates the estimates of $\alpha(n)$ and changes the parameters of the restoring device.

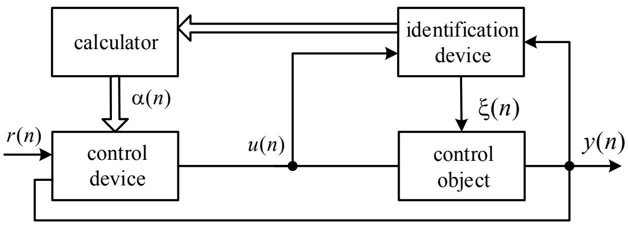

Fig.5. Block diagrams of indirect functional stable system

The change in the parameters of the recovery device in direct, functionally-stable systems occurs directly on the basis of observations. They are not required when identifying the object. The structural scheme of a direct functional-stable system is depicted in Fig. 6. The adaption circuit includes only the adjustment device, which, by observation, changes the parameters of the recovery device [1-4].

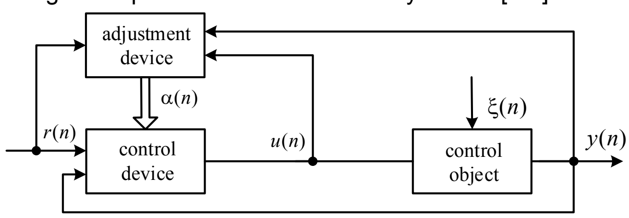

Fig.6. Block diagrams of direct functional stable system

Indirect functionally stable systems include systems with explicit identification, and to direct ones - systems with implicit identification and systems with a reference model [1-3].

Conclusions

Based on the process analysis in the systems of automatic control, it is suggested to use a structural scheme of optimal restoring device.

A quadratic quality criterion is proposed as a refinement to equation (14) for a minimal phase object, described by a system of differential equations,

Based on the equation of the restoring device, it has been put forward and demonstrated the requirements for restorative management.

Based on the analysis of the structural scheme of the optimal restoring device (Fig. 4), the structural schemes of functionally stable indirect action systems (Fig. 5) and direct action (Fig. 6) are proposed.

A theorem for optimal restoring control of a discrete system with a quadratic quality criterion is formulated and proved.

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