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Adaptive System for Controlling an Object with Input Saturation

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ABSTRACT: This article presents a modification of the self-tuning loop of the adaptive controller coefficients for control systems in the class of single-channel objects with input restriction. The algorithm developed in real time provides functional operability of an adaptive system with a reference model based on checking the conditions of uniform asymptotic stability of motion.

KEYWORDS: control object, controller, adaptive system with reference model, asymptotic stability, single-channel object, control algorithm.

I. INTRODUCTION

The use of adaptive control systems in various areas of production [1] raises questions of ensuring their operability in the process of functioning. Usually, when solving many problems of synthesis of adaptive control systems, the presence of an input constraint is often ignored, which as a result can lead to a deterioration in the quality or loss of performance of the developed control systems.

II. RELATED WORK

One of the first schemes of an adaptive object control system with an input constraint was proposed in [2], which was followed by the development of various methods for constructing adaptation systems [3-13]. Adaptive systems with the reference model [13] and its modified schemes, which ensure both the limitation of all signals of a closed system and the convergence of the tracking error to zero, are most widely used. For such systems, one of the most important problems is to ensure the asymptotic stability of motion in the full phase space, including coordinate and parametric mismatches [3]. A distinctive feature of these systems is the introduction of a switch into the adaptation circuit, which, by changing the speed of setting the coefficients of the regulator, partially or completely compensates for the effect of input saturation.

Numerous literature sources on the theory of adaptive control contain a significant number of works devoted to the study of the conditions of asymptotic stability of the motion of adaptive systems with the model [14]. However, such results are obtained and strictly justified only in the case when a single-channel object with saturation satisfies the following assumptions:external interference is absent; state variables of the control object are available for measurement; the values of some parameters of the object are known or allow for their identification.

III. FORMULATIONOFTHEPROBLEM

Consider the problem of controlling a parametrically indeterminate single-channel object with input saturation without measuring its state variables and with a constant external disturbance.

Let the main contour of an adaptive system with a reference model in the state space be described by the equations [5]:

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$$\frac{d\phi}{dt}=(A_0+\Delta A(t)+\Delta K(t))\phi+(B_0+\Delta B(t)+\Delta N(t))\sigma(g(t)),\ y(t)=\phi_1(t),\ \phi(0)=\phi_0,\ (1)$$

where $\phi=(\phi_1,\ \phi_2...\phi_n)^T$ is the vector of the state of main circuit system; a ϕ_0 - vector of initial conditions; $g(t)=(g_1(t),g_2(t)...g_m))^T$ – vector a continuous time-limited input control actions; $y(t)\in R$ – adjustable output; A_0, B_0– constant matrix of dimension $n\times n$ and $n\times m$, respectively, the matrix A_0 is assumed in the form of Frobenius of the bottom row which has the form $[a_0,a_1,....,a_{n-1}]n$; $\Delta A(t)$,$\Delta B(t)$ -matrix parametric perturbations; $\Delta K(t),\Delta N(t)$ - matrix of tunable coefficients of the main circuit; $\sigma(g(t))$ is a function of the saturation.

$$\sigma(g(t))=\sigma(t)=\begin{cases}\sigma_0,\ g(t)>\sigma_0,\\ g(t),|g(t)|\le\sigma_0,\\ -\sigma_0,\ g(t)<\sigma_0,\end{cases}\qquad(2)$$

where $\sigma_0>0$ is a known constant that characterizes the saturation level.

We will assume that the system has complete information about the state vector of the main contour. The elements of matrices $\Delta A(t)$,$\Delta B(t)$ change in an unknown way in advance. Elements of matrices $\Delta K(t),\Delta N(t)$ allow for purposeful change. It is necessary to change the matrix $\Delta K(t),\Delta N(t)$ in the process of functioning of the system, depending on the information available for measurement, so that the dynamic properties of the main contour (3.38) are preserved despite the change in parametric perturbations $\Delta A(t)$,$\Delta B(t)$. In accordance with the principle of constructing adaptive systems with a reference model [3, 15], the reference model is described by equations in the form:

$$\frac{d\phi_m}{dt}=A_0\phi_m+B_0r(t),\quad \phi_m(0)=\phi_0,\ y_m(t)=\phi_{1m}(t),\ k_m(t)=\chi^T\phi_m(t),\qquad(3)$$

where $\phi=(\phi_{m1},\phi_{m2}...\phi_{mn})^T$ is the state vector of the model; $y_m(t),k_m(t)$ is the main and auxiliary outputs; $r(t)\in R$ is the task.

IV. SOLUTION OF THE TASK

The control system, like [16, 17], uses an explicit reference with two outputs, which is equivalent to using two reference models. While using the core reference model (OM) is formed of the desired behavior of the control object, and due to the auxiliary reference model (VEM) provided the desired dynamics of the main control circuit (CMOS).

Note that if the equations (3) are rewritten in the images:

$$y_m(s)=W_{O\text{ЭМ}}(s)r(s)=L^T(sE-A_0)^{-1}B_0r(s)=\frac{b_0}{a_0(s)}r(s),\qquad(4)$$

$$k_m(s)=W_{B\text{ЭМ}}(s)r(s)=\chi^T(sE-A_0)^{-1}B_0r(s)=\frac{b_0\chi(s)}{a_0(s)}r(s),\qquad(5)$$

where $W_{O\text{ЭМ}}(s)$, $W_{B\text{ЭМ}}(s)$ is the transfer functions of the OEM and VAM, it is clearly seen that the structure of the transfer function (5) admits simplification. Indeed, by selecting the values of the coefficients of vector $\chi=[1,\chi_1,\chi_2,......,\chi_{n-1}]^T$ from the condition.

$$a_0(s)=(s+a_*)\chi(s)=(s+a_*)(s^{n-1}+\frac{\chi_{n-2}}{\chi_{n-1}}s^{n-2}+....+\frac{\chi_1}{\chi_{n-1}}s+\frac{1}{\chi_{n-1}})\chi_{n-1},\qquad(6)$$

where a_* is any of the roots of the polynomial $a_0(s)=s^n+a_{0(n-1)}s^{n-1}+....+a_{01}+a_{00},$, we obtain that the VEM is an inertial link of the 1st order, i.e.

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$$k_m(s) = W_{ВЭМ}(s)r(s) = \frac{a_* b_0}{s + a_*} r(s). \quad (7)$$

The structure of the adaptive controller is defined as follows:

$$g(t) = l(t)r(t) - \sum_{i=1}^{n} c_i(t)\phi_i(t), \quad (8)$$

where $l(t)$ and $c_i(t)$ are the self-tuning coefficients.

Let us consider algorithms for changing matrices $\Delta K(t), \Delta N(t)$ to provide some modification of the considered adaptive system. Subtracting from (1) equation (2), we obtain a system of equations describing the motion of an adaptive system with a reference model in the form:

$$\frac{d\varepsilon}{dt} = A_0\varepsilon + Y\phi + Zg(t), \quad (9)$$

$$\frac{dY}{dt} = \hbar P\varepsilon\phi^T + R_y(t), \quad \frac{dZ}{dt} = -\hbar P\varepsilon\phi^T(t) + R_z(t), \quad (10)$$

where $\varepsilon = (\phi - \phi_m)$ is the error between the vectors of the object state reference model; $Z = (\Delta B(t) + \Delta N(t)),$ – parametric error; $R_y(t) = d\Delta A(t)/\mathrm{dt},$ $R_z(t) = d\Delta B(t)/\mathrm{dt},$ - speed parametric perturbations; $\hbar = const > 0$ - number; P - positively defined matrix defined by the equation $A_0^T P + PA_0 = Q,$ where Q - negative-definite matrix.

In [3] it is proved that the motion of

$$\varepsilon \equiv 0,\ Y \equiv 0,\ Z \equiv 0, \quad (11)$$

systems (9), (10) at

$$R_y(t) \equiv 0,\ R_z(t) \equiv 0, \quad (12)$$

stable by Lyapunov, and provided that the system of functions

$$\{r_1(t), r_2(t), \ldots, r_m(t), \phi_{m1}(t), \ldots, \phi_{mn}(t)\} \quad (13)$$

is linearly independent uniformly non-vanishing, the motion (11) under condition (12) is uniformly asymptotically stable, and therefore stable under constantly acting perturbations

$$R_y(t) \neq 0,\ R_z(t) \neq 0, \quad (14)$$

at least for small rates of change $R_y(t), R_z(t)$ over time, i.e. there are $R_y^0 = const > 0,$ $R_z^0 = const > 0,$ such that when

$$\left\|\frac{d\Delta A(t)}{dt}\right\| \leq R_y^0, \quad \left\|\frac{d\Delta B(t)}{dt}\right\| \leq R_z^0, \quad (15)$$

The motion (11) of the system (9), (10) remains stable under the condition (14).

If, assuming measurable state variables $\phi(t)$, the algorithms for self-tuning the coefficients of the regulator (8) are synthesized as follows [14-16]:

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$$\frac{dl(t)}{dt}=\begin{cases} h_0 r(t)v(t)\tilde{\delta}(t), \forall |v(t)>v_0,| \\ 0, \qquad \forall |v(t)\le v_0,| \end{cases}, \tag{16}$$

$$h_0 = const > 0,\ v_0 = const > 0,\ l(0)=0,$$

$$\frac{dc_i(t)}{dt}=\begin{cases} -h_i\phi_i(t)v(t)\tilde{\delta}(t), \forall |v(t)>v_0,| \\ 0, \qquad \forall |v(t)\le v_0,| \end{cases} \tag{17}$$

$$h_i = const > 0,\ c_i = 0,\ i=\overline{1,n},$$

additionally changing the speed of adjustment of the regulator coefficients using a dynamic switch described by the equation

$$\tau\frac{d\tilde{\delta}(t)}{dt}+\tilde{\delta}(t)=\delta(t),\ \tilde{\delta}(t)=0,\ \tau=const>0, \tag{18}$$

where τ is the specified time constant; $\tilde{\delta}(t)$ is the output of the dynamic switch; $\delta(t)$ is the switching function of the form

$$\delta(t)=\begin{cases} 1,\ \forall[\sigma(g(t))-g(t)]v(t)\ge 0, \\ \delta_0, \forall[\sigma(g(t))-g(t)]v(t)<0, \end{cases} \tag{19}$$

$$0<\delta_0 = const <1,$$

the synthesis of adaptation algorithms in the system (2) will be carried out on the basis of the hyperstability criterion. hence, like [18-20], the following inequalities will need to be satisfied:

$$\eta(0,t)=-\int_0^t \mu(\theta)v(\theta) > -h_0 = const, \forall t>0. \tag{20}$$

The synthesis of algorithms for adjusting the coefficients of the adaptive controller and the type of switching function is associated only with the resolution of the integral Popov inequality (20) [17].

Expressions (20) can be converted to the following form:

$$\eta(0,t)=l_0^{-1}\left\{\int_0^t (l(\theta)-l_0)r(\theta)v(\theta)d\varsigma-\sum_{i=1}^{n}\int_0^t (c_i(\theta)-c_{0i})\phi_i(\theta)v(\theta)d(\theta)+\right.$$

$$\left.+\int_0^t[\sigma(g(\theta))-g(\theta)]v(\theta)d(\theta)\right\},$$

Hence, the control system(2), (16) - (19) due to the fulfillment of condition (20), it is hyper-stable and adaptive, in which the auxiliary control goal will be achievable

$$\lim_{t\to\infty}|v(t)|\le d_1 = const.$$

At the same time, taking into account

$$v(s)=W_{OKY}(s)\mu(s)=g^T(sE-A_M)^{-1}B_M\mu(s)=\frac{b_M g(s)}{a_M(s)}\mu(s)=\frac{a_* b_M}{s+a_*}\mu(s),$$

the main goal of management will also be fulfilled

$$\lim_{t\to\infty}|\Delta y(t)|\le d_0 = const.$$

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IV. CONCLUSION

Thus, we propose a real-time algorithm for ensuring the functional performance of an adaptive system with a reference model based on checking the conditions of uniform asymptotic stability of motion. In contrast to adaptive control systems with a static switch in the control coefficient adjustment loop, the use of a dynamic switch allows you to more effectively compensate for the effect of input saturation in cases where the initial conditions are non-zero, the relative order of the object is greater than one, and the state variables are not measured. To solve the problem, it is proposed to use a two-level adaptation, and the second level of adaptation serves to minimize the additional input impact applied to the system. At the same time, the desired quality of operation of the control object is guaranteed under conditions of a priori uncertainty, in the presence of constantly operating external and parametric interference.

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