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Method for Synthesis of State Controller with Observer for an Electrohydraulic Power Transmission System

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***Abstract*— This paper deals with the synthesis of state controller with observer for an electrohydraulic power transmission system. There is shown a method for synthesis of the state controller with observer and the realization for electrohydraulic system. The controller coefficients are obtained from preliminary defined performance definitions. The system has been modeled, and step responses curves are obtained from computer simulation. Main results are given in a few graphics.**

Keywords*— *state controller with observer, electrohydraulic system, dynamic processes modeling and simulation

I. Introduction

The dynamic characteristics of hydraulic drive systems can be improved by using modern control methods. Hydromechanical regulators, servo valves with mechanical feedback on the position of the plunger, etc. are used. [1], [2], [3], [4]. For processing and transmission of signals in hydraulic drive systems, electrical and electronic components are used. This makes it possible to improve the static and dynamic properties of hydraulic systems by applying electronic control circuits. The power and cost of microprocessors today allow the development of more modern control concepts, and thus the achievement of more successful control systems. Researchers have made numerous attempts to increase the accuracy of the dynamic positioning of electrohydraulic systems by improving algorithms for control and evaluation of states. Popular approaches include classical feedback and compensation schemes, as well as variants of state observers and Kalman filters, including linear and nonlinear extensions [7], [8], [9], [10]. Analogous control approaches are also used in electropneumatic positioning systems [9], [10]. When analyzing the performance of electro-hydraulic traction systems, it is important to evaluate positioning errors in dynamic mode [11], [12], [13].

II. State Controller Design

In real technical systems, controllers are used to impose a certain static and dynamic behavior on the output variable of interest. The limited possibilities of influence in the often used single-loop feedback and PID controllers can be expanded by using multi-loop controls. The common feature of this approach is the “State Controller” method, in which all state variables are used as feedback [1], [5], [9], [10].

A prerequisite for using this concept is knowledge of the dynamic behavior of the object to be controlled. In general, it is described by a system of first-order nonlinear differential equations of the form:

$$\frac{d\,\mathbf{x}(t)}{dt} = \dot{\mathbf{x}}(t) = f\big(\mathbf{x}(t), \mathbf{u}(t)\big);$$
$$\mathbf{y}(t) = g\big(\mathbf{x}(t)\big); \qquad (1)$$

where, $\mathbf{x}(t)$, $\mathbf{u}(t)$, $\mathbf{y}(t)$ - state, input and output vector.

For the nonlinear description of the system defined in this way, there is no general rule for forming a controller. The theory of linear systems is considered complete and its application in the synthesis of a control system is to some extent accessible, starting from the linear approximate description of the object in the form [1], [3]

$$\frac{d\,\mathbf{x}(t)}{dt} = \dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + b\mathbf{u}(t); \qquad (2)$$
$$y(t) = c\mathbf{x}(t).$$

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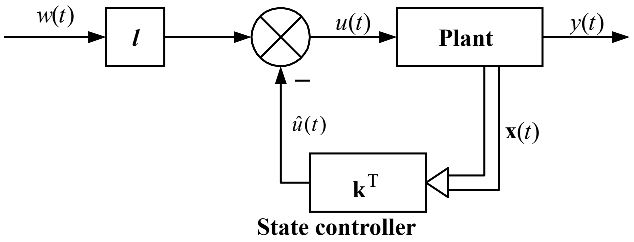

Fig. 1. System with state controller.

Figure 1 shows the fundamental structure of a "State Controller" system. The error signal is formed by a linear combination of the state variables.

$$\hat{u}(t) = \sum_{i=1}^{n} k_i \; x_i(t) = \mathbf{k}^{\mathrm{T}} \mathbf{x}(t) \quad (3)$$

By selecting the individual feedback coefficients, the behavior of the system in dynamic mode can be influenced. This concept is applicable when the state variables are measurable quantities. When the state variables cannot be technically captured or are unmeasurable, approximate quantities are created and used instead of the actual ones. One of these possibilities is the approximate differentiation of the measured output quantity. In this way, the velocity and acceleration can be obtained from the displacement coordinate. The disadvantage of this approach is that it results in a noisy signal, which can be cleaned by low-pass filtering, but ultimately leads to unsuitable results when differentiating.

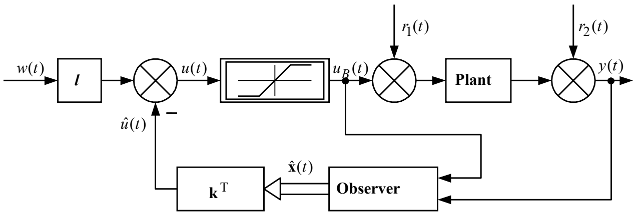

Fig. 2. System with state loop and observer.

It is recommended to observe the state, in which the required quantities are obtained by knowing the input and output quantities of the object. The application requires complete observability of the system, i.e., to be able to see all its internal movements at the output of the object. For the system, when an observer is included, the structure shown in Fig. 2 is obtained.

In this scheme, the observer represents a dynamic system that can be sized so that the vector of output quantities $\hat{\mathbf{x}}(t)$ in the case without disturbances ($r_1 = r_2 = 0$) transitions with a given dynamics to the states of the object $\mathbf{x}(t)$ and tracks them with zero dynamic error.

When removing the initially existing observation error, it is irrelevant for the behavior of the system that approximate values $\hat{x}_i(t)$ are used instead of the true state variables $x_i(t)$ The aforementioned restriction on the error signal does not lead to an observation error if it is reproduced before the input to the object. As shown in Fig. 2. with an artificially limited error signal $u_B(t)$, the observer is given the input signal that actually affects the object after the restriction.

In this approach, known as time domain representation, the design of the observer is reduced to some simplification of the linear functional $\hat{u}(t) = \mathbf{k}^{\mathrm{T}} \mathbf{x}(t)$. The error signal is given by $u(t) = l\, w(t) - \hat{u}(t)$.

The design of a state observer controller is conveniently done in the frequency domain [1], using the well-developed apparatus of transfer functions. The transfer function of the object can be determined by:

$$W_O(s) = \frac{Y(s)}{U(s)}, \quad (4)$$

with

$$W_O(s) = \mathbf{C}^{\mathrm{T}} \left(s\mathbf{I} - \mathbf{A}\right)^{-1} \mathbf{b} \quad (5)$$

or directly by object identification. In this case, the latter approach does not often require complex modeling of the internal structure. The output signal of the controller $U(s)$ as a function of $Y(s)$, $W(s)$, $U_B(s)$, is represented in the form

$$U(s) = \frac{Z_{Ry}(s)}{\Delta(s)} Y(s) + \frac{Z_{Rw}(s)}{\Delta(s)} W(s) - \frac{Z_{Ru}(s)}{\Delta(s)} U_B(s) \quad (6)$$

The transfer functions

$$\frac{Z_{Ry}(s)}{\Delta(s)}, \frac{Z_{Rw}(s)}{\Delta(s)}, \frac{Z_{Ru}(s)}{\Delta(s)}$$

of the individual control channels describe the relationship between the input variables $Y(s)$, W(s), $U_B(s)$ and the output variable $U(s)$. The polynomial $\Delta(s)$ in the denominator is called the observer polynomial, the polynomials Z_{Ry}, Z_{Ru} and Z_{Rw}, must be defined in such a way that the desired behavior of the system is achieved for a given polynomial $\Delta(s)$.

Before determining the unknown polynomials of the controller, the question of the existing possibilities for formulating the desired behavior of the system must be clarified. In state control, it is customary to specify the internal values of the controlled system (assigning the poles). This method is easy to implement and helps with little experience in designing appropriate controllers.

The transfer functions of the closed system are defined as the basis for determining the poles

by disturbance:

$$W_{r1}(s) = \frac{Z_O(s)\left[\Delta(s) + Z_{Ru}(s)\right]}{N_O(s)\left[\Delta(s) + Z_{Ru}(s)\right] + Z_O(s) Z_{Ry}(s)} \quad (7)$$

$$W_{r2}(s) = \frac{N_O(s)[\Delta(s) + Z_{Ru}(s)]}{N_O(s)[\Delta(s) + Z_{Ru}(s)] + Z_O(s) Z_{Ry}(s)} \quad (8)$$

on assignment

$$W_w(s) = \frac{Z_{Rw}(s) Z_O(s)}{N_O(s)[\Delta(s) + Z_{Ru}(s)] + Z_O(s) Z_{Ry}(s)} \quad (9)$$

The coefficients of the still unknown polynomials $Z_{Ry}(s)$ and $Z_{Ru}(s)$ must be determined in such a way that the characteristic polynomial of the closed system has the desired poles, these are the poles of the transfer functions $W_{r1}(s)$, $W_{r2}(s)$ and $W_w(s)$.

The design of the controller is based on the fact that the poles of the observer must also be poles of the closed system. Thus $\Delta(s)$, must be a divisor of the polynomial in the denominator of (7), (8) and (9). The remaining poles are summed in the polynomial $\widetilde{N}(s)$.

The design equation for setting poles is

$$N_O(s)[\Delta(s) + Z_{Ru}(s)] + Z_O(s) Z_{Ry}(s) = \widetilde{N}(s)\Delta(s) \quad (10)$$

The solution of the design equation using the known polynomials $N_O(s)$ and $F_O(s)$ (each of the n-th degree, corresponding to the order of the object) and the polynomials that should be given $\Delta(s)$ (degree n_B) and $\widetilde{N}(s)$ (degree n). The unknown polynomials $Z_{Ry}(s)$ and $Z_{Ru}(s)$ are also taken with degree. Thus, on the left side of the design equation, a polynomial of degree $(n + n_B)$ with total $2(n_B + 1)$ unknown coefficients in the polynomials $Z_{Ry}(s)$ and $Z_{Ru}(s)$ is obtained. On the right side of equation (10) is also a polynomial of degree $(n + n_B)$, whose coefficients are known.

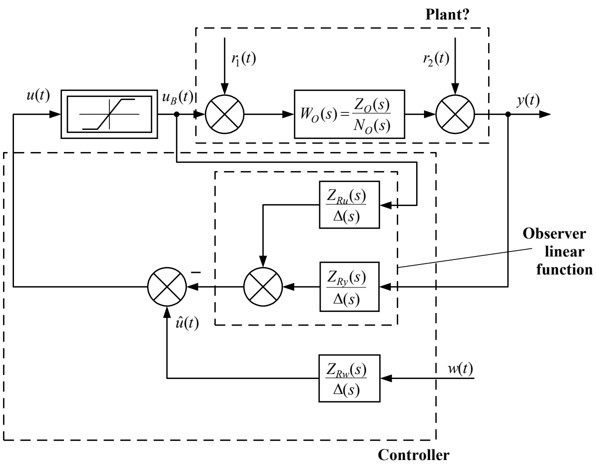

Fig. 3. Block diagram of a regulator with observer.

Equating the coefficients in front of the same degrees s of the left and right sides of the design equation leads to $n + n_B + 1$ equations with $2(n_B + 1)$ unknowns. Generalized, they form a system of linear equations with unknown coefficients – Fig. 4. Before solving them with standard software, the solvability of the linear system of equations must be determined in principle. Depending on the degree of the observer n_B, this system of equations must be uniquely determined. Unique solvability is obtained when the number of unknowns is equal to the number of linearly independent equations, i.e.

$$2(n_B + 1) = n + n_B + 1 \quad (11)$$

This leads to the choice of observer degree

$$n_B = n - 1 \quad (12)$$

solution of the polynomial equation $Z_O(s)Z_{Ry}(s) + N_O(s)Z_{Ru}(s) = \left[\tilde{N}(s) - N_O(s)\right]\Delta(s)$

polynomial		koefficients	
$Z_O(s)$ $N_O(s)$	$< n$ n	$f_0, f_1, \ldots, f_{n-1}$ $g_0, g_1, \ldots, g_n \;;\; g_n = 1$	Plant
$Z_{Ry}(s)$ $Z_{Rw}(s)$ $Z_{Ru}(s)$	n_B n_B n_B	$a_0, a_1, \ldots, a_{n_B}$ $b_0, b_1, \ldots, b_{n_B}$ $c_0, c_1, \ldots, c_{n_B} \;;\; c_{n_B} = 0$	Controller
$\Delta(s)$ $\tilde{N}(s)$	n_B n	$d_0, d_1, \ldots, d_{n_B} \;;\; d_{n_B} = 1$ $e_0, e_1, \ldots, e_n \;;\; e_n = 1$	Poles

$$\begin{bmatrix}
f_0 & 0 & 0 & 0 & \cdots & 0 & g_0 & 0 & 0 & 0 & \cdots & 0 \\
f_1 & f_0 & 0 & 0 & \cdots & 0 & g_1 & g_0 & 0 & 0 & \cdots & 0 \\
\vdots & f_1 & f_0 & 0 & \cdots & 0 & \vdots & g_1 & g_0 & 0 & \cdots & 0 \\
f_{n-1} & \vdots & f_1 & . & . & 0 & g_{n-1} & \vdots & g_1 & . & . & 0 \\
0 & f_{n-1} & \vdots & . & . & f_0 & 1 & g_{n-1} & \vdots & . & . & g_0 \\
0 & 0 & f_{n-1} & . & . & f_1 & 0 & 1 & g_{n-1} & . & . & g_1 \\
0 & 0 & 0 & . & . & \vdots & 0 & 0 & 1 & . & . & \vdots \\
\vdots & \vdots & \vdots & . & . & f_{n-1} & \vdots & \vdots & \vdots & . & . & g_{n-1} \\
0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & \cdots & 1
\end{bmatrix}
\begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_{n_B} \\ c_0 \\ c_1 \\ \vdots \\ . \\ c_{n_B} \end{bmatrix}
=
\begin{bmatrix}
e_0 - g_0 & & & & \\
e_1 - g_1 & e_0 - g_0 & & & \\
\vdots & e_1 - g_1 & e_0 - g_0 & & \\
e_n - g_n & \vdots & e_1 - g_1 & \ddots & \\
0 & e_n - g_n & \vdots & \ddots & e_0 - g_0 \\
0 & 0 & e_n - g_n & . & e_1 - g_1 \\
0 & 0 & 0 & . & \vdots \\
\vdots & \vdots & \vdots & \ddots & . \\
0 & 0 & 0 & 0 & e_n - g_n
\end{bmatrix}
\begin{bmatrix} d_0 \\ d_1 \\ \vdots \\ . \\ d_{n_B} \end{bmatrix}$$

$n + n_B + 1 \qquad 2(n_B + 1) \qquad n + n_B + 1 \qquad n_B + 1$

Fig. 4. Linear system of equations for solving the design equation (10)

III. Implementing A Controller With A State Observer In Analog Technology

The synthesis of the regulator is reduced to determining the coefficients in the transfer functions in the three branches of the regulator Fig. 3. The implementation of the regulator is carried out by building analog networks, whose behavior at the input and output is characterized by the transfer functions. By separately building the individual branches based on the common polynomial – denominator $\Delta(s)$, it is possible to give a generalized idea of the system. In the practical implementation of the regulator, this is an advantage due to the reduced number of structural elements - integrators. Fig. 6 shows an analog model of the regulator in the normal form of the observer with a minimum number of integrators n_B . The electrohydraulic system is represented by a linear model [2], whose structural diagram and transfer function are shown in Fig. 5. The transfer function of the open system is recorded at reception $K_m = 0$.

$$K_1 = \frac{K_u K_i K_{\varphi x} K_y}{T_x (1 + K_{\varphi x} K_{rx})}$$ - total gain of the open system;

$$T_1 = \sqrt{\frac{T_n{}^2 T_{\varphi x}}{1 + K_{\varphi x} K_{rx}}} \;; T_2 = \sqrt{\frac{T_n{}^2 + 2\xi_n T_n T_{\varphi x}}{1 + K_{\varphi x} K_{rx}}} \;;$$

$$T_3 = \frac{T_{\varphi x} + 2\xi_n T_n}{1 + K_{\varphi x} K_{rx}}$$ - time constant

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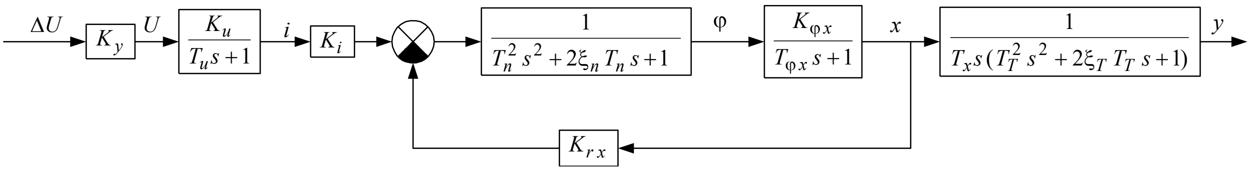

$$W(s)=\frac{Y(s)}{\Delta U(s)}=\frac{K_1}{s(1+T_u s)(T_T{}^2 s^2+2\xi_T T_T s+1)(T_1{}^3 s^3+T_2{}^2 s^2+T_3 s+1)} \tag{13}$$

Fig. 5. *Structural diagram of the open system*

After opening the brackets and arranging by powers of and neglecting some of the small coefficients, the transfer function of the open system can be written in the form:

$$W_O(s)=\frac{\beta_1}{g_0 s^4+g_1 s^3+g_2 s^2+g_3 s} \tag{14}$$

IV. SINTHESIS THE CONTROLLER

The regulator is designed with the degree of the observer being one less than the degree of the regulated object. The values of the roots of the observer are recommended by [1].

$$n_B=n-1=3$$

$$\Delta(s)=(s-s_1)(s-s_2)(s-s_3);\ s_{1,2,3}=-300\,\mathrm{s}^{-1}$$

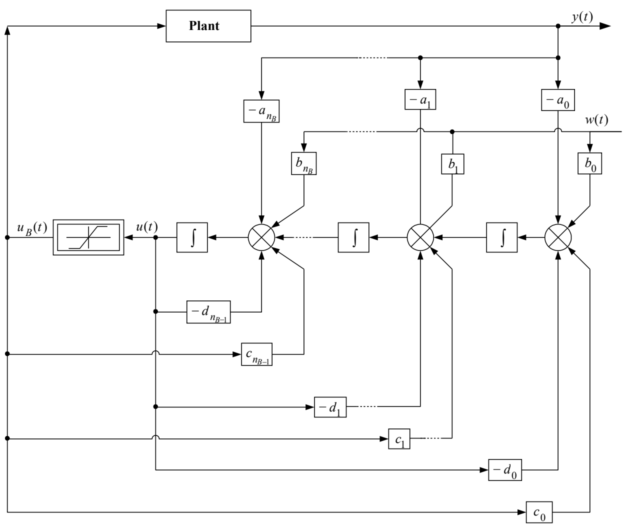

Fig. 6. Analog model of a state controller with an observer

For the auxiliary polynomial in the design equation (10), the degree must match the degree of the object [1].

$$n=4$$

$$\tilde{N}(s)=(s-s_1)(s-s_2)(s-s_3)(s-s_4)$$

$$s_1=-160\,\mathrm{s}^{-1};\ s_{2,3}=(-160\pm j160)\,\mathrm{s}^{-1};$$

$$s_4=-2000\,\mathrm{s}^{-1}$$

The design equation is solved by solving the linear system of equations – Fig. 4 using the MathCad software. The results are shown in Table 1.

TABLE I. THE RESULTS SOLVING THE LINEAR SYSTEM OF EQUATIONS

Polynomial	Power	Coefficients	
$Z_O(s)$	3	925925, 3, 0, 0, 0	Plant
$N_O(s)$	4	85185.185, 855.5, 14, 1	
$Z_{Ry}(s)$	3	$4.78.10^{11}, 0.109.10^{11}, 0.11.10^{9}, 5.49.10^{11}$	Controller
$Z_{Rw}(s)$	3	1, 0, 0	
$Z_{Ru}(s)$	3	$1.79.10^{9}, 3.23.10^{6}, 2.46.10^{3}, 0$	
$\Delta(s)$	3	$2.7.10^{7}, 2.7.10^{5}, 900, 1$	Poles according equation (10)
$\tilde{N}(s)$	4	$1.64.10^{10}, 2.13.10^{8}, 1.06.10^{6}, 2480, 1$	

The electrohydraulic system with a state controller with an observer is modeled using the MatLab Simulink software. The transient processes for a rectangular and sawtooth input signal are simulated. Fig. 7 and Fig. 8 show the graphs of the output quantity, speed and acceleration.

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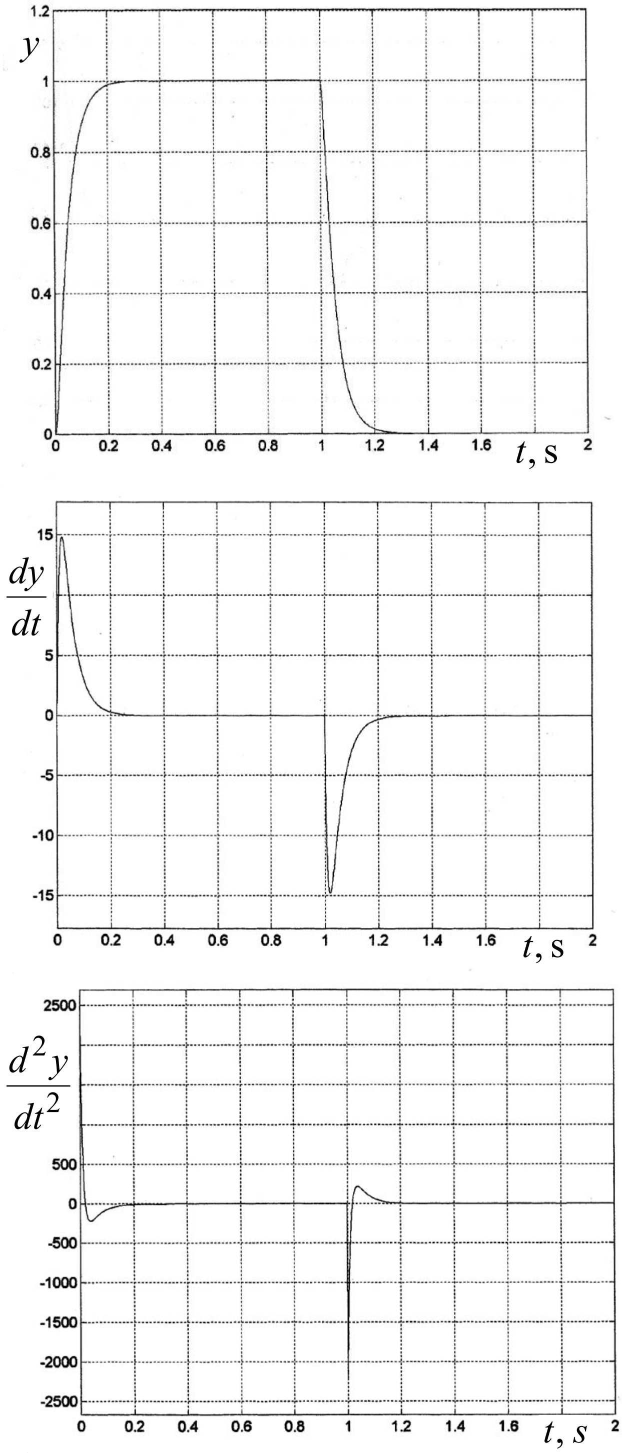

Fig. 7. Transient processes in an electrohydraulic system with a state controller with an observer for a rectangular input signal

V. RESULTS AND DISCUSION

A method for synthesis of state controller with an observer for controlling an electrohydraulic system for linear models of low-order objects is presented. For the good operability of the system, it is necessary to accurately determine the parameters of the object. It is recommended to use identification of the unknown parameters by experimental dynamic characteristics [3].

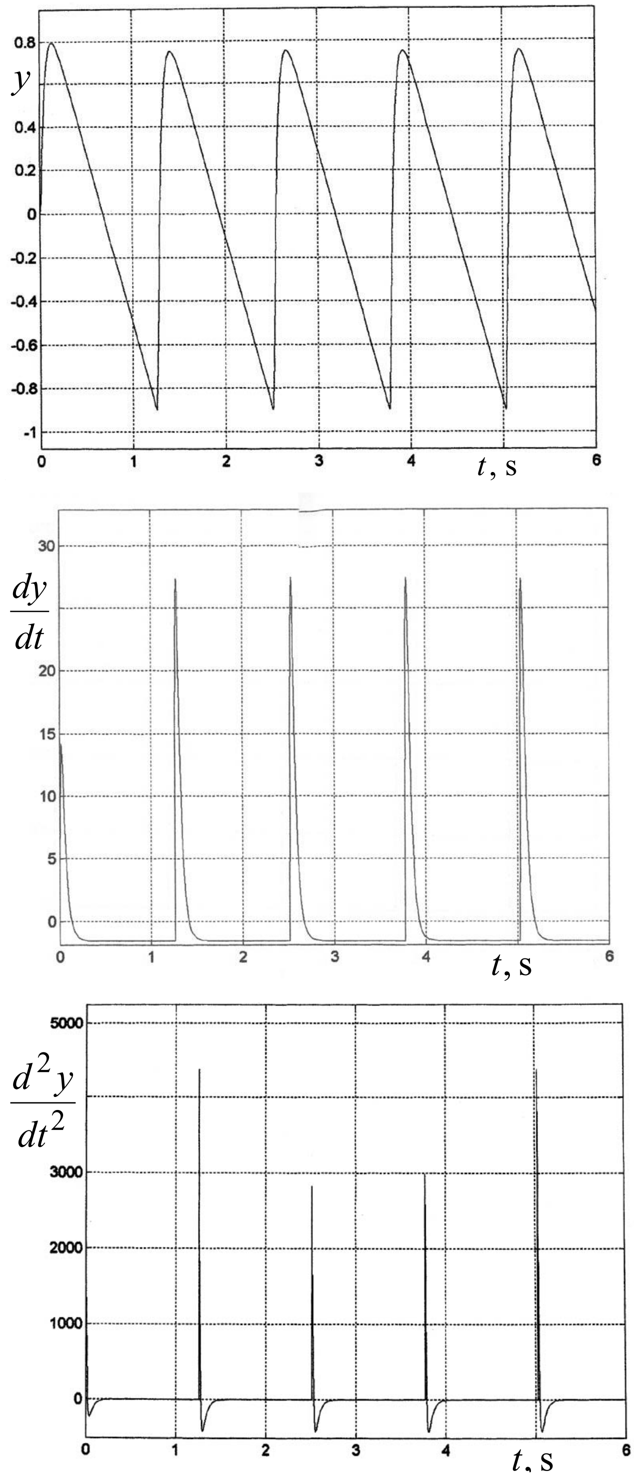

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Fig. 8. Transient processes in an electrohydraulic system with a state controller with an observer at a sawtooth input signal

VI. Conclusion

In addition to an analog implementation of a controller with an observer, a digital one can also be made, in which microprocessor technology is used to control the system. Improved operation of the observer is achieved by incorporating guiding and perturbing models to compensate for disturbances and good task tracking.

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