Study of the dynamics of an electro-hydraulic servo drive physical model on FESTO learning system

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Abstract: The task of conducting research for dynamics improvement of an electro-hydraulic servo drive by including compensators on FESTO hydraulic learning system with low permissible inertial loads on the drive was considered. It has been suggested to simulate large inertial loads, which increase the time constant of the loaded hydraulic cylinder by attaching additional volumes filled with working fluid to the cavities of the executive hydraulic cylinder of the electro-hydraulic servo drive. The efficiency and clarity of the synthesis of compensators for an electro-hydraulic servo drive achieved with the MATLAB/Simulink software environment integration into FESTO hydraulic learning system has been shown.

1. Introduction
The development of a mathematical model of an electro-hydraulic drive in the form applicable to controllersynthesis and the determination of its parameters is an integral part of the task of controllersynthesis for the electro-hydraulic servo drives (EHSD) [1-4]. Since any mathematical model of a plant has a certain degree of inaccuracy, it is necessary to check the quality of regulation on the real plant. However, in laboratory environment it is often impossible to conduct studies of hydraulic systems with high power and high inertial loads [5-10]. In this case, it becomes appropriate to conduct research of the controllers on the lessloaded physical model of the EHSD with the reduction of its mathematical model parameters to the analogous parameters of the mathematical model describing the controlled object from the viewpoint of the developed controller. This is especially important for educational institutions when it is necessary to learn the controller synthesis methods with experimental confirmation of the obtained results at thereal plants.

The aforementioned approach to the study of the control laws synthesis [11] and the study of the EHSD characteristics on its physical model, based on FESTO laboratory hydraulic learning system (figure 1), has been implemented in the laboratory of the “Hydromechanics, Hydromachines and Hydro-Pneumoautomatics” department of Bauman MSTU.

The hydraulic learning system includes MOOG high-speed hydraulic directly actuated servo valve (HSV) with a valve position feedback (figure 2), an inertial load mechanism with two hydraulic
cylinders installed opposite to each other and with a linear potentiometric feedback sensor, electronic PID controllers and state feedback controllers, the personal computers.

**Figure 1.** Research system based on the hydraulic learning system FESTO.

**Figure 2.** Hydraulic directly actuated servo valve (HSV) and its passport characteristics.

To enable the study of dynamic processes taking place in the EHSD and controller synthesis, the learning system was equipped with National Instruments PCI-6024E board, MATLAB/Simulink/RealTime Windows Target software, that allow to synthesize EHSD controllers and to develop control system programs that run on Windows in real time. The maximum sampling rate is 20 kHz.

To combine the process of controller synthesis with experimental studies of the EHSD and its elements, the authors have developed programs to control a research system that perform in an automated mode: the formation of typical step and harmonic input signals with automatic frequency variation in a given range; determination of the parameters of the EHSD mathematical model and its elements according to experimentally determined frequency characteristics; the EHSD control with synthesized compensators; experimental data registration and processing.

As a result of modernization, it becomes possible to conduct the entire chain of EHSD controller synthesis on one FESTO hydraulic learning system: development, implementation and research.

Works on the controller synthesis are performed in the following sequence:

1. Determination of the mathematical model parameters of the EHSD assembled on FESTO learning system according to experimentally determined transient processes or frequency characteristics of the hydraulic drive.

2. Synthesis of compensators and determination of their parameters using, in particular a LQR technique or numerical optimization methods in the MATLAB/Sisotool software package, Optimization Toolbox integrated in FESTO learning system.

3. Study of the EHSD work with synthesized controllers on the mathematical model in the MATLAB/Simulink software package integrated into FESTO learning system.
4. Study of the real work of the EHSD physical model with synthesized controllers with registration of experimental data in the MATLAB/Simulink/RealTime Windows Target software package.

2. Mathematical modeling of the EHSD physical model

A scheme of the studied EHSD physical model, assembled on the basis of FESTO hydraulic learning system, is shown in figure 3. Obtaining a linearized mathematical model of the EHSD is an important step in the controller synthesis [12, 13]. The mathematical description of the EHSD work, the linearized mathematical model and its areas of applicability are described in detail in [14, 15].

![Figure 3](image-url) The scheme of the research system for studying the EHSD dynamics.

![Figure 4](image-url) The EHSD linearized mathematical model block-diagram: $K_{\text{amp}}$ – the electronic amplifier gain; $K_{\text{HSV}}$ – the HSV gain; $T_{\text{HSV}}$ – the HSV time constant; $T_{\text{HD}}$ – the hydraulic drive time constant; $T_{c}$ – the time constant of the loaded hydraulic cylinder; $\xi_c$ – the hydraulic cylinder damping coefficient; $K_{\text{pt}}$ – the potentiometric feedback sensor gain; $Y_{\text{rod}}$ – the position of the hydraulic cylinder rod; $U_{\text{req}}$, $U_{\text{pt}}$ – the input required signal and the rod position feedback sensor, respectively.

The EHSD linearized mathematical model can be represented by the block-diagram shown in figure 4 [14, 15]. The time constant of the loaded cylinder is determined by the formula:

$$T_c = \frac{mV_0}{2BF_p^2},$$  \hspace{1cm} (1)
where
\( m \) is the load mass moved by the EHSD;
\( V_0 \) is the volume of the cylinder cavity and the hydraulic lines connecting the hydraulic valve to this cavity;
\( B \) is the oil bulk modulus;
\( F_p \) is the working area of the piston.

The mass of the load, which determines an inertial load of the EHSD assembled at FESTO hydraulic learning system, is 27.5 kg. It can be found that the time constant of the loaded hydraulic cylinder \( T_c \), defined by the expression (1) for the inertial load, is practically equal to the HSV time constant \( T_{HSV} \), if the parameters of the transfer functions for the EHSD with existing hydraulic elements were calculated. This greatly complicates the task of optimal control, since it requires, as a rule, an improvement the quality of control of the HSV. In order to create the EHSD physical model with the ability to control optimization, considering the existing EHSD hydraulic elements as an unchangeable part, with the possibility of linearizing its mathematical model, the time constant of the loaded hydraulic cylinder \( T_c \) (1) have to be increased. To do this, we increase the volume of the hydraulic cylinder cavities \( V_0 \), connecting them to additional tanks with the working fluid (figure 3). This allows, without increasing the load weight on FESTO hydraulic workstation, to approximate the EHSD physical model time constant \( T_c \) to the \( T_c \) of the EHSD with a large inertial load, and provides an opportunity to explore the laws of the EHSD control on its physical model with the existing electro-hydraulic elements.

To determine the parameters of the mathematical model shown in figure 4, a numerical optimization that ensures the maximum coincidence of the frequency characteristics of the EHSD physical model and its mathematical model (figure 5) at a given amplitude of a reference signal [16], is carried out.
Figure 5. Frequency characteristics of the EHSD open loop, determined experimentally and calculated for a mathematical model with optimized parameters.

The frequency characteristics of the EHSD physical model are determined experimentally by the first harmonic of the measured EHSD response to the input harmonic signal. The processing of experimental data with the determination of Bode plot was carried out in accordance with the method given in [17]. The studies are carried out with an open loop plant for greater accuracy in determining the parameters of the mathematical model. The optimization of the mathematical model parameters was carried out by the lease squares method.

The parameters of the linear mathematical model (figure 4), which provide the best approximation of the frequency characteristics of the mathematical model to the experimentally determined frequency characteristics of the EHSD assembled on FESTO hydraulic workstation, are shown below:

\[
K_{\text{amp}} = 20; \quad \frac{K_{\text{HSV}} \cdot K_{\text{pt}}}{\tau_{\text{HD}}} = 1.3763; \quad T_{\text{HSV}} = 0.003; \quad T_{\text{c}} = 0.0086; \quad \zeta_{\text{c}} = 0.2646.
\]

3. Synthesis of the EHSD controllers on FESTO hydraulic learning system

Figure 6 shows the EHSD testing with a stepwise varying input signal, experimentally determined on FESTO hydraulic learning system, when operating without compensators and with compensators synthesized using the linearized mathematical model with the parameters defined above. To reduce the workstation oscillations during the EHSD operation (both in the experimental determination of frequency characteristics and in the study of transient processes), on the back of the workstation, a similar EHSD is assembled (figure 3) with the same parameters. The control signal is supplied to the HSV inputs of both drives from one computer in antiphase. Therefore, Fig. 6 shows the changes in the positions of the hydraulic cylinder rods of hydraulic actuators simultaneously working on two sides of the hydraulic workstation.

Figure 6. EHSD transients without compensators and with compensators, synthesized by the linearized mathematical model.

Synthesis of compensators in the EHSD control loop can be carried out using a variety of methods [3, 4, 6, 8, 11, 18, 19], including the LQR method and numerical optimization methods using the
MATLAB/Sisotool software installed on the learning system. As an example, let us consider the improvement in the dynamics of the EHSD assembled on FESTO hydraulic workstation, using state components feedback. A block diagram of the EHSD with state feedback controller is shown in figure 7.

\[ \dot{X} = AX + Bu \] (2)

- \( X \) – plant state vector;
- \( U \) – control signal applied to the input of the electronic amplifier;
- \( K \) – state components feedback gain;
- \( K_1 \) – main feedback coefficient, the first element of the vector \( K \).

It is necessary to track some external signal of the setting device, which is denoted \( U_{req}(t) \). Since the system is tracking, the input signal \( U_{req}(t) \) had to be multiplied by the main feedback factor \( K_1 \). Thus, the control signal is determined by the equation

\[ u(t) = U_{req}(t) \cdot K_1 - K^T \cdot X(t) \] (3)

The synthesis of a controller with state components feedback consists of defining the vector \( K \). One of the ways to determine \( K \) is to use the MATLAB/Sisotool package. In this case, we choose a block diagram defining the location of the transfer functions of the EHSD unchangeable part and the compensators corresponding to equation (3), in Control Architecture window of MATLAB/Sisotool package (figure 8).
Figure 8. MATLAB/Sisotool software package windows.

After that, we introduce the defined above transfer function of the EHSD unchangeable part into MATLAB/Sisotool and determine the transfer functions of the compensators that need to be added to the EHSD loop. The software package determines the coefficients of the controller automatically if the required positions of the zeros and poles of the developed controller in the zero-pole portrait of the EHSD or the boundaries of the desired transition process in the corresponding package windows (Solodovnikov borders [13]), are set as shown in figure 8.

The EHSD transient processes without additional feedbacks and with state components feedback with the coefficients defined in the MATLAB/Sisotool package are shown in figure 9. Here and below, for comparison, both graphs of transient processes calculated numerically using the linearized mathematical model (dashed lines) and experimentally on EHSD physical model (solid lines) are presented. The transient processes of the EHSD without compensators (oscillatory processes in figure 9) and EHSD with calculated state components feedback gain (aperiodic processes in figure 9) are shown. The oblique and horizontal lines on the graph show the boundaries of the desired transition process, which were used to synthesize the compensators in MATLAB/Sisotool.

Figure 9. Theoretical (dashed) and experimental (continuous) transient processes of the EHSD on FESTO research system.

Another way to determine the state feedback gain $K$ is to solve the LQR problem. According to the method described in [11], we introduce the additional requirement of finding the roots of the characteristic equation of a closed system inside a circle of radius $\rho$ and with center at $(-\alpha,0)$ with $\alpha > \rho \geq 0$.

If equation (2) is written in the Laplace form

$$sX(s) = AX(s) + BU(s) \quad (4)$$
and a new variable $\zeta = \frac{s + \alpha}{\rho}$ that converts the original circle with $\rho$ radius in the $s$ region into a unit circle on the $\zeta$-plane located at the origin, is introduced, then the transformed state-space model has the form

$$\zeta X(\zeta) = \frac{1}{\rho}(\alpha I + A)X(\zeta) + \frac{1}{\rho}BU(\zeta).$$

(5)

In the shift operator region, it will be written

$$qX[k] = A_qX[k] + B_qu[k].$$

(6)

where

$$q(f[k]) = f[k+1]$$

is the shift operator.

The stability of a discrete system requires the poles to have modules less than one, i.e. were inside the unit circle centered at the origin. Therefore, let’s solve the task of constructing a discrete controller applied to (6) by solving the corresponding algebraic Riccati equation

$$A^T(P - PB_q \left( R + B_q^TPB_q \right)^{-1}B_q^TP)A_q + Q - P = 0,$$

and equations determining the coefficients of the $K$

$$K = \left( R + B_q^TPB_q \right)^{-1}B_q^TPA_q,$$

where

$A$, $B$ are the matrices defining the parameters of the linear mathematical model of the plant (4);

$Q$, $R$ are the weighting matrices of the cost function

$$J = \int_{0}^{\pi} X^TQXdt + \int_{0}^{\pi} u^TRudt;$$

$P$ is a matrix-solution to the Riccati equation.

Mentioned solutions can be obtained using the MATLAB function `dlqr`.

Figure 10 shows the theoretical and experimental transient processes of the EHSD with the state components feedback controller synthesized using LQR on FESTO research system for parameters $\rho = 50$, $\alpha = 120$; matrices $Q, R$ are identity.
For the EHSD the state vector contains: position, speed and acceleration of the plunger, the position of the HSV valve. The rod position is determined by the potentiometric position sensor. The used proportional HSV has built-in feedback on the valve position with the electrical signal output indicating its current position. There are also FESTO electronic blocks, which determine the first and second derivatives of the main feedback signal and include them in the control loop. However, their effectiveness is limited by measurement noise in the control loop.

As a result of the fact that the EHSD is controlled by the MATLAB/Simulink/RealTime Windows Target package included in the EHSD control loop, it is possible to implement an observer that determines in real time the state components that are used in the synthesized controller but are not available for direct measurement. The block diagram of the EHSD with the developed observer [11, 19] is shown in figure 11.

The dashed line highlights the part of the circuit implemented in the MATLAB/Simulink software package on a computer included in the EHSD control loop (the program runs in real time with 5 kHz
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sampling rate). The part, that is not highlighted, is the plant (without $K_{\text{amp}}$). The control object is represented on the diagram by the electrohydraulic drive linearized model. The research was carried out when the input signal on the observer was represented either the measured position of the spool (figure 11), or the control signal $U$, applied to the input of the electronic amplifier. Transient processes of the physical model of an EHSD with state components feedback controller determined by the observer are shown in figure 6.

4.Conclusions

The proposed method of increasing the hydraulic cylinder time constant greatly expands the possibilities of using FESTO hydraulic learning system for studying the EHSD dynamic properties. The integration of MATLAB software environment into the research system complements MATLAB with physical models of electro-hydraulic control objects that are assembled individually (similar to mathematical models in MATLAB/SimScape). On the other hand, FESTO hydraulic learning systems are provided with a powerful software environment for modeling, control and analysis, which makes the synthesis of control laws for hydraulic drives and their elements effective and intuitive. It becomes possible to verify the results of the simulation and the synthesis of compensators directly during the process of developing the modeling and control laws, “without leaving” the MATLAB software development environment. This modernization of FESTO hydraulic learning systems brings them to a level that allows conducting research of dynamic processes in the EHSD and its elements.

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