Hardware-in-the-loop modeling applied to FESTO hydraulic learning system

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Abstract. The issue of Hardware-in-the-loop modeling in Matlab/Simulink using a physical model of an electrohydraulic servo drive implemented on FESTO learning system is considered. As an example, the synthesis of state components feedback coefficients for the electrohydraulic servo drive control is discussed. The paper provides the block-diagrams for connecting FESTO physical model to Matlab software and algorithms that allow using Matlab for automatic optimization of the controller parameters directly during the operation of the electrohydraulic servo drive physical model. Thus, already at the stage of optimizing the parameters of the controller, its operation as part of a real hydraulic system is studied.

Introduction
Numerical optimization of the controller parameters usually uses a mathematical model of the control object [1–7]. In [2], it was shown that it is possible to determine the electrohydraulic servo drive (EHSD) mathematical model parameters by analyzing the experimentally determined frequency characteristics of its physical model implemented on FESTO hydraulic learning system with the Matlab/Simulink software environment connected to it. There was also considered the LQR synthesis of the EHSD in Matlab/Simulink and the possibility of studying its work on the EHSD physical model. As a result, it becomes possible to conduct all stages of the synthesis of hydraulic system controllers on one research system: determining the parameters of the mathematical model, synthesizing the controllers, and studying their operation on physical models (Fig. 1).

In general, the behavior of the EHSD changes depending on its mode of operation [8, 9]. Therefore, when solving a certain class of problems, it is advisable to study a controller operation as a part of a real hydraulic system at the stage of its synthesis [10, 11]. That is, to use Hardware-in-the-loop (HIL) modeling in the controller synthesis process [12–18]. Also, HIL modeling with elements of automatic conduct of the experiment series can be used for structural and parametric identification of mathematical models of the hydraulic systems under study and their control systems [11].
Fig. 1. Theoretical (dashed) and experimental (solid) EHSD transients on FESTO research system at different settings of the state components feedback coefficients.

**Synthesis of the FESTO EHSD controllers in the HIL modeling mode**

To optimize the controller parameters directly on the EHSD physical model, a hardware-software complex of HIL modeling based on FESTO hydraulic learning system was developed. The controller parameters are determined in Matlab software package using optimization methods. In optimization process automatic mode, the operation of the EHSD physical model with various controller parameter values is repeatedly investigated. The quality criteria are determined by analyzing changes in the state components feedback of the physical model that working out the specified input signals.

The block-diagram of the hardware-software complex is shown in Fig. 2.

![Diagram](image-url)
The optimization module, in this example, determines the state components feedback coefficients that are optimal according to the integral quality criterion ITAE. 

\[ I = \int_0^\infty |U_{req} - U_{pr}| \cdot t \cdot dt \]

During the optimization process, the Simulink program «Physical Model Run» (PMR) is repeatedly run (Fig. 2). It provides sequential launch of the real EHSD physical model with changeable parameters of its controller.

Simulink PMR program contains:
- the block for setting the controller parameters;
- the module that generates desirable position of the hydraulic cylinder rod (for example, a square wave);
- the module that calculates the quality criterion needed to optimize the synthesized controller parameters.
- the block for emergency shutdown of the physical model in case of the EHSD state will be out of the allowed area.

The PMR program also provides bringing the EHSD physical model to the initial state for each iteration of determining the controller parameters.

The composition of the hardware-software complex may vary depending on the type of problems solved using the research complex of HIL modeling.

The physical model of the EHSD based on FESTO learning system with remotely adjustable feedback coefficients

The scheme of FESTO hydraulic system inclusion in the HIL is shown in Fig. 3.

![Fig. 3. Connection diagram of FESTO learning system to personal computer (PC) while studying the parameters of the EHSD controller with the parameters of the control object, which can be changed during its operation.](image)

The notation conventions for Fig. 3: HSV — the hydraulic servo valve; bv1, bv2 — the ball valves; \( U_{HSV} \) — the HSV control signal (in effect a control piston setpoint position value); \( U_{VP} \) — the measured position of the HSV control piston; \( M_1 = 27.5 \text{ kg} \), \( M_2 = 10 \text{ kg} \). — the masses of
the inertial load (main and additional, respectively). Status controller — the unit, shortly described below, \( y_{rod} \) — the position of the hydraulic cylinder rod; \( U_{pt} \) — the rod position feedback signal.

FESTO hydraulic learning system includes an electronic signal amplification and conversion unit (Status controller) (Fig. 4) (Part Number 162253). It implements the main feedback and feedbacks for the first and second derivatives of the main feedback signal. The direct circuit and feedback coefficients for the first and second derivatives are set by status controller potentiometers.

Three main features of the status controller were used while working on FESTO hydraulic research system:
1. control signal power amplifier;
2. analog state components feedback controller with adjustable coefficients;
3. the first and second derivatives of the main feedback signal.

Fig. 4. Status controller front panel.

If the physical model is used directly in the process of synthesizing a controller running on the computer, then there is a need to change the feedback coefficients of the linear controller during the operation of the EHSD from the program on the computer. This can be achieved by implementing a part of the controller on the control computer [1]. The software part of the controller will make a dynamic correction of the control signal by adding an additive to it (Fig. 5). The additive \( \Delta U \) provides a change in the state components feedback coefficients of the EHSD from those pre-set \( K \) on the status controller unit (Fig. 4) to the required ones \( \bar{K} \).

\[
\Delta U = f_{\Delta U} \left(U, U_{pt}, \dot{U}_{pt}, \ddot{U}_{pt}, \bar{H}K, \bar{K}\right).
\]

Let us define the structure and parameters of the linear controller with dynamic correction. Let us assume that the status controller unit has coefficients \( \left[H_{K_1}, H_{K_2}, H_{K_3}\right] \). They will remain unchanged. During the operation of the physical model it is necessary to set the state components feedback coefficients equal to \( \left[K_1, K_2, K_3\right] \).

Let us write down the expressions for the signal sent to the HSV as functions defined by the feedback coefficients.
Given the $U_{HSV}$ equality in both equations, we can write an expression defining the additive $[\Delta U]$:  

$$[\Delta U] = \left( K_1 - \frac{H}{K_1} \right) \cdot U + \left( \frac{H}{K_2} - K_2 \right) \cdot \left( \frac{H}{K_3} - K_3 \right) \cdot s + \left( \frac{H}{K_4} - K_4 \right) \cdot s^2 \cdot U_{pt}$$  

If we use the output signals of the status controller unit that compute the first and second derivatives of the feedback signal (Fig. 5), the resulting expression that defines the correction additive to the input signal at the input of the status controller unit takes the form:  

$$[\Delta U] = \left[ \frac{-H}{K_1} \ K_1 \ K_2 \ K_3 \right] \begin{bmatrix} U_{pt} - U \\ \frac{Kv}{H} \\ \frac{Kv}{H} \\ \frac{Kv}{H} \end{bmatrix}$$  

$U_{pt}$, $kv$, $ka$ signals are taken from the corresponding outputs of the status controller unit (Fig. 4).

Figure 6 shows transients of the EHSD with two implementations of the same controller with coefficients $[K_1 \ K_2 \ K_3] = [1.64 \ 0.00325 \ 0.00016]$. In one case, these coefficients were set on the status controller. The status controller input received a step signal $U$ (unchanged for time $t > 0$). In the second case, the coefficients $\frac{H}{K} = [1.58 \ 0.0154 \ 0.000353]$ were pre-set on the status controller, and the final coefficients of the controller were provided by an additive $\Delta U$ calculated using the formula (5) (the $U + \Delta U$ Signal is shown in Fig. 6). As you can see from the graphs, the transition processes of the EHSD completely coincide.
Conclusions
Using the example of Matlab environment and FESTO hydraulic learning system, the possibility of creating a complex of HIL modeling have been considered. That allows to combine the mathematical description of the actuating mechanism and the physical model of the control object into a single complex for the purpose of conducting research in automatic and automated mode. The developed approaches and algorithms have shown that it is possible to synthesize controllers using automatic optimization of the controller parameters directly in the process of operation of the EHSD physical model.

This significantly expands the capabilities of both the software package and FESTO hydraulic learning system that implements the physical model of the EHSD when conducting training and research.

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