Mathematical modeling and analysis of the influence of various regulators on the quality of the transient hydraulic drive with throttle control.

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Abstract. This article provides an analysis of transients in various hydraulic drive regulators. Hydraulic drives are widely used in a number of areas of power engineering and other types of equipment, which is due to a number of advantages, such as: small size and weight with high energy consumption, high speed, high positioning accuracy, a wide range of operating pressures and speeds of executive bodies.

Introduction

Hydraulic actuators [1-5] are widespread in a number of areas of power engineering and other types of equipment, which is due to a number of advantages, such as: small size and weight with high energy intensity, high speed, high positioning accuracy, a wide range of operating pressures and speeds of movement of the executive bodies.

The most widely used electro-hydraulic drives (EHD) with throttle control. In connection with the specifics of the work, their requirements are high requirements for ensuring reliability, stability, optimal values of static and dynamic characteristics.

Static and dynamic characteristics of drives can be improved through the use of various corrective devices (controllers). In this paper, several types of correction devices are considered: the introduction of additional feedbacks on state variables (state controller), the introduction of additional pressure feedback, and the P-controller.

The first type (state controller) is based on the formation of feedback loops according to the state coordinates, which give the servo drive closed in position to the desired location of the roots of the characteristic equation of its linear model (poles of the transfer function).

The introduction of additional pressure feedback makes it possible to increase the damping coefficient of a system with a large inertial load. Significant pressure values in the cavities of the hydraulic actuator allow practically realizing pressure feedback without additional amplification steps.

The use of a P-controller is associated with a control method based on the law of proportional control, in which the characteristics of the output signal are proportional to the characteristics of the input signal.

In this work, the influence of the proposed regulators on the quality of the transient EHD process was also studied, and their comparative analysis was carried out.
Mathematical model of hydraulic drive with throttle control

To compile a mathematical model, we consider the dynamics of individual elements of the hydraulic drive.

The equation of motion of the piston of a loaded hydraulic cylinder:

\[ p_n F_c - (P_{mp})_c - c_{ca} (y - y_m) = m_p \frac{d^2 y}{dt^2} \]

where \( p_n = p_1 - p_2 \) — pressure difference in the cavities of the hydraulic cylinder under the action of the load.

The equation of the load on the rod of the hydraulic cylinder:

\[ m \frac{d^2 y_m}{dt^2} + k_{mp} \frac{dy_m}{dt} + (c_{ca} + c_u) y_m = c_{ca} y \]

In real hydraulic drive systems, there are often non-linearities that distort the characteristics of drive elements. In order to avoid excessive complication of the mathematical model, we consider only the basic nonlinearities that can affect the dynamics of the process.

The fluid flow rate \( Q_s \) is determined by the flow-differential characteristic of the spool, which in the general case non-linearly depends on the movement of the spool \( x_s \) and the pressure difference \( p_n \) in the hydraulic cylinder cavities:

\[ Q_s = Q_s (x_s, p_n) = k_s \cdot x_s \cdot \sqrt{ \frac{p_p - p_{cl} - p_n \cdot \text{sign}(x_s)}{2} } \]

Where \( k_s = \mu_s \cdot \pi \cdot d_s \cdot k_p \cdot \sqrt{\frac{2}{\rho}} \) — specific (referred to the unit of movement of the spool) conductivity of the windows of the spool valve.

In this work, to optimize the parameters, we used the criterion for the product of time \( t \) and absolute error \( I(t) = ITAE \) (Integral of Time multiplied by Absolute value of Error). It has found widespread application in practice by providing a compromise between the overshoot value and the transition time. Mathematically, it is calculated as follows:

\[ I = \int_0^T \left| e(t) \right| dt \]

Since integration to infinity is practically impossible, the criterion consists in choosing a value of \( T \) large enough so that \( e(t) \) for \( t > T \) is negligible.

Mathematical Modeling Results

The simulation was carried out in the MATLAB Simulink software package based on the classical linear system model. The following structural diagrams were created.
Fig. 1. General view of the structural scheme for comparing the P-controller and the state controller.

Fig. 2. Block diagram of a linear model with feedback on the position of the cylinder head (P-regulator).
Fig. 3. Structural diagram of a linear model with feedback on acceleration, speed and position of the cylinder head (state controller).

The following transient graphs were obtained:

Fig. 4. Transient system with a P-controller (yellow) and with a state controller (blue).

Criteria for assessing the quality of transients are shown in table 1.
Table 1

| Type of controller       | $\sigma$, % | $t_{t,p}$ | $t_{c}$ |
|--------------------------|-------------|-----------|---------|
| P-controller            | 3,81        | 0,145     |         |
| State controller         | 3,28        | 0,0445    |         |

Further, taking into account in the mathematical model that the flow-differential characteristic of the hydraulic drive is non-linear, we study the effect of various types of corrective devices on the transient process (TP) of the system (Fig. 5).

Red color shows the TP of the system with a state controller;
Yellow color indicates the TP of the system with position feedback (P-controller);
The blue color shows the TP of the system with the optimized value of the gain (regulation coefficient) of the P-controller;
The blue color shows the TP of the system with feedback (F) by pressure;
The numerical values of the results of mathematical modeling are presented in table 2.

Table 2

| Type of controller       | $\sigma$, % | $t_{t,p}$ | $t_{c}$ | $K_{vc}$ |
|--------------------------|-------------|-----------|---------|----------|
| Status controller        | 1,01        | 0,0396    |         | 3,0071   |
| P-controller             | 5,2         | 0,144     |         | 1,39     |
| Optimized P-controller   | 0,559       | 0,0986    |         | 1,1738   |
| Pressure differential feedback | 6,0  | 0,071     |         | 1,58     |
Figure 6 and 7 shows the structural diagram of the ITAE criterion. Using this criterion optimal F coefficient were obtained for speed (6.6711), acceleration (0.07552) and pressure drop ($2 \cdot 10^{-8}$).

![Fig. 6. ITAE calculation block diagram](image)

**Fig. 6. ITAE calculation block diagram**

![Fig. 7. Block diagram of a hydraulic actuator with ITAE calculation](image)

**Fig. 7. Block diagram of a hydraulic actuator with ITAE calculation**

**Conclusion**

During the work, an analysis of three types of regulators for electro-hydraulic drives was carried out, their dynamic characteristics were obtained.

It was found that the introduction of additional pressure feedback can significantly reduce the time of the transient process and its oscillation, but at the same time it has the largest dynamic error.

The use of a P-controller as a correcting device (without optimization) has significant drawbacks in the form of a large dynamic error and the longest transient time. Optimization based on the integral ITAE criterion contributes to a significant decrease in the dynamic error — by 9.3 times, but the transition time does not change significantly.

The best EHD quality indicators are provided by the state regulator. When this regulator is connected to the drive circuit

**References**

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