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Nonlinear simulation of electrohydraulic drive for technological equipment

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Abstract. The problem of nonlinear simulation of the dynamic characteristics of the electrohydraulic servo drives with throttle regulation for technological equipment is considered. The mathematical model for investigation of the nonstationary work processes in the drives has developed. The model adapted for drives of the technological equipment, built using standard modules, in particular, an electrohydraulic amplifier and a hydraulic cylinder. The estimation of the basic parameters of the mathematical model is carried out using the technical certificate data of the drive devices. The recommendations are given on setting initial data for numerical simulation. For numerical integration of the nonlinear mathematical model of the nonstationary work processes software was developed in the environment of the MATLAB. In addition to the integration subroutine, the software includes a source data file, a control program and a subroutine for calculating the right parts of the system of ordinary differential equations. The example of the calculation of the dynamic characteristics for the electrohydraulic servo drive with throttle regulation is presented.

1. Introduction

A modern technological equipment, in particular, the equipment for mechanical processing, presents ever increasing requirements [1-5] to the characteristics of drives for the accuracy of the implementation of the optimal laws of motion of the output unit. The achievement of arbitrary kinematics of working body in equipment with power of up to 8 kW is ensured by using an electrohydraulic servo drive (EHSD) with throttle regulation [6-9].

An important stage in the development and design of the EHSD is the assessment of stability, quality of regulation and correction of the dynamic properties of the drive. The implementation of this stage is associated with the development of the mathematical models of the nonstationary working processes occurring in the drive.

The mathematical models for the study of the dynamic characteristics of the EHSD, presented in the literature [10-14], cannot be generalized to the whole group of drives that are used in technological equipment. A number of them are oriented to the certain constructions of drive devices [15-20], in particular, the electrohydraulic amplifiers. Basically, the authors consider two-stage amplifiers of the nozzle-flap-spool type with the spring spool support [1, 2, 7, 8].

The most mathematical models require the definition of parameters that cannot be estimated from the technical certificate data of standard devices or displayed at the preliminary design stage. Convenient linear models allow for number of significant simplifications [1, 21-23] (approximation of flow-pressure characteristics, exclusion of saturation and dead zones, etc.) and, as a consequence, have
low accuracy. Since the design of drives is most often carried out on the basis of standard modules [8, 15, 16], in this connection there is a need to develop the universal typical model mathematical model of the EHSD that should adequately reflect the characteristics of the elements and the dynamic processes for a limited set of parameters, contained in the technical data of serially produced devices.

The aim of the paper is the development of the typical nonlinear mathematical model of the nonstationary work processes in the EHSD with throttle regulation, which allows to study the dynamic characteristics of the drives using the technical certificate data of incoming devices.

2. Research of electrohydraulic servo drive
We distinguish the main elements of the EHSD: the hydraulic cylinder (HC), the electromechanical hydraulic amplifier (EMHA), i.e., electrohydraulic servo valve, which includes an electromechanical transducer (EMT) and a hydraulic amplifier (HA), the feedback gauge (FB), the electronic block (EB). In what follows, we consider the settlement scheme of the drive shown in figure 1.

![Figure 1. The settlement scheme of the EHSD.](Image)

The dynamic characteristics for the HC with a double stock are widely accepted [1, 6, 7] by the system of equations that includes the equations of motion of the piston and the equations of the balance of the flow rates in cavities of the HC with allowance for the compressibility of the working fluid:

\[
m \frac{dV}{dt} = p_1 F_1 - p_2 F_2 - c y - k_f V - R - R_d \text{sign}V;
\]

\[
\frac{dy}{dt} = \frac{V}{H/2} \leq y \leq H/2;
\]

\[
\frac{W_p + F_1 (H/2 + y)}{E_f} \frac{dp_1}{dt} = Q_1 - F_1 V;
\]

\[
\frac{W_d + F_2 (H/2 - y)}{E_f} \frac{dp_2}{dt} = -Q_1 + F_2 V.
\]

In equations (1-4): \( y \), \( V \) - displacement and speed of the piston (usually the displacement of the piston is taken from its average position); \( p_1, p_2 \) - pressure in the cavities of the HC; \( m \) - reduced mass of the moving parts; \( F_1, F_2 \) - effective areas; \( c \) - stiffness of the positional load; \( k_f \) - coefficient of the viscous friction force; \( R_d \) - force of the dry friction; \( R \) - load; \( H \) - stroke of the piston; \( Q_1, Q_2 \) - fluid flow rates in the EMHA lines; \( E_f \) - modulus of elasticity of the working fluid; \( W_p, W_d \) - "dead" volumes of the pressure and drain lines.

Despite the large nomenclature [2, 9], the FB is usually described as a linear non-inertial link connecting the feedback voltage \( U_{fb} \) and the displacement \( y \).
where \( k_{fb} \) – transfer coefficient of the FB.

EMHA in the nomenclature of a serially produced hydraulic equipment are presented as a throttling distributors and distributors with the proportional control [15, 16]. In the output cascade of the EMHA amplification, a spool hydraulic amplifier is usually used, the settlement scheme of the output cascade of which is shown in figure 2. It is proposed to relate the displacement of the spool from the neutral position \( x_s \) with the current in the control winding \( i_i \) by a linear dynamic link of the second order

\[
T_{2a}^2 \frac{d^2 x_s}{dt^2} + T_{1a} \frac{dx_s}{dt} + x_s = k_{xi} i_i;
\]

where \( k_{xi} \) – transfer coefficient of the EMHA.

The time constants \( T_{2a}, T_{1a} \) in a known manner [1, 2, 6] are determined from the frequencies \( \nu_1, \nu_2 \) of the phase shift by -45\(^0\) and -90\(^0\), respectively:

\[
T_{2a} = \frac{1}{2\pi\nu_2}; \quad T_{1a} = \frac{1}{2\pi\nu_1} - \frac{2\pi\nu_1}{(2\pi\nu_2)^2}.
\]

Moving the spool has limitations

\[
|x_s| \leq x_{max};
\]

where \( x_{max} \) – maximum displacement of the spool from the neutral position.

The equations for the flow rates in the lines connecting the EMHA with the HC, taking into account the positive overlapping of a spool slot in the distribution sleeve (see figure 2), have the form:

\[
Q_i = \begin{cases} 
\mu_p \pi d \cdot k_n \left( x_s - h_p \right) \sqrt{\frac{2}{p}} \left| p_{ps} - p_i \right| \text{sign} \left( p_{ps} - p_i \right), & x_s > h_p; \\
0, & |x_s| \leq h_p; \\
\mu_p \pi d \cdot k_n \left( x_s + h_p \right) \sqrt{\frac{2}{p}} \left| p_i - p_d \right| \text{sign} \left( p_i - p_d \right), & x_s < -h_p;
\end{cases}
\]

Figure 2. The settlement scheme of an output cascade of the EMHA.
$Q_2 = \begin{cases} 
\mu_d k_d \left( x_i - h_p \right) \sqrt{\frac{2}{\rho} \left| p_{ps} - p_d \right| \text{sign} \left( p_{ps} - p_d \right)}, & x_i > h_p; \\
0, & |x_i| \leq h_p; \\
\mu_d k_d \left( x_i + h_p \right) \sqrt{\frac{2}{\rho} \left| p_{ps} - p_d \right| \text{sign} \left( p_{ps} - p_d \right)}, & x_i < -h_p; 
\end{cases}$

(10)

where $p_{ps}, p_d$ — pressure of pump station and on a drain; $h_p$ — size of the positive overlap (figure 2); $\mu_d$ — flow coefficient of the spool slot [2, 7]; $d_s$ — diameter of the spool; $k_d$ — coefficient of a completeness of use of the perimeter of the spool; $\rho$ — density of the working fluid.

EB at the stage of a preliminary design of the EHSD is considered as an ideal amplifier

$$U_g = k_g (U - U_{fb});$$

(11)

where $U$ — input (control) voltage; $U_g$ — voltage on the EB exit; $k_g$ — EB gain coefficient.

The output cascade of the EB is connected to the control winding of the EMHA and forms with it a common electrical circuit containing both active and inductive resistance. Therefore, without considering the back emf, for the control winding we have the following differential equation

$$L_c \frac{di_c}{dt} + R_{ic} i_c = U_{fb};$$

(12)

where $L_c$ — inductance of the control winding; $R_{ic}$ — active resistance of the electrical circuit.

Also, the EB limits the current in the electrical circuit to the maximum value $i_{max}$ for the control winding of the EMHA

$$|i_c| \leq i_{max}. $$

(13)

Thus, the typical nonlinear mathematical model of the nonstationary work processes in the EHSD with throttle regulation can be represented by the system of the equations (1-13).

For the numerical simulation of the dynamic characteristics, one can give the following recommendations for setting initial parameters. Since at the predesign stage serial produced drive units were selected, at this stage, some parameters are either known or estimated: the stroke of the piston $H$; the mass of the moving parts $m$; the pressure of pump station $p_{ps}$ and on drain $p_d$; the modulus of elasticity of the working fluid $E$; the "dead" volumes of the pressure $V_p$ and drain $V_d$ lines; the position load stiffness $c$; the EB gain coefficient $k_g$. According to the technical specifications of the HC are evaluated: the effective areas $F_1, F_2$; the coefficient of the viscous friction force $k_f$; the force of the dry friction $R_d$. The transfer coefficient of the FB $k_{fb}$ is estimated from the technical data of the sensor. According to the technical specifications (technical certificate data) of the EMHA, the time constants $T_{1a}, T_{2a}$ — the inductance of the control winding $L_c$; the active resistance of the electrical circuit $R_c$ (resistance of the EMHA control winding considering the resistance of the output cascade of the EB); the maximum current $i_{max}$ (or nominal current $i_{nom}$); the maximum flow rate $Q_{max}$ (or nominal flow $Q_{nom}$) are set. The maximum displacement $x_{max}$ of the spool can be estimated from the expressions (9, 10), and the value of the transfer coefficient $k_{f_{12}}$ from the equation (6) in the statics as $k_{f_{1}} = x_{max}/i_{max}$. Note that the value of the dimensionless overlap $h_p/x_{max}$ can be taken equal to the relative current of the dead zone (in commercially available EMHA not more than 0.02).

For the numerical integration of the nonlinear mathematical model of the nonstationary work processes in the EHSD with throttle regulation by the Runge-Kutta method of the 4th order, the software was developed in the environment of the package of applied programs MATLAB [24, 25] for automation of engineering and scientific calculations. In addition to the integration subroutine, the software includes a source data file, a control program and a subroutine for calculating the right parts of the system of ordinary differential equations.
3. Discussion

In comparison with the known nonlinear EHSD models [2, 12, 13], which consider the main factors that cause the nonstationary processes (fluid compressibility, inertia of the output unit, inductance of the electrical circuit, dynamic properties of the EMHA), the presented model requires a smaller number of the initial parameters and is universal for a drive constructed according to the typical scheme shown in figure 1. The mathematical model is adapted to the drives of technological equipment for mechanical processing [16, 26-30], built on the basis of standard modules, and allows to study the dynamic characteristics of a drive using the technical certificate data of incoming devices.

Considering the basic nonlinearities gives a noticeable advantage in the accuracy of calculation in comparison with linear models. This is shown by the results of numerical simulation of the transient processes at the various levels of the input signal, presented in a dimensionless form in the figures 3-6: figure 3 – the dimensionless voltage on the EB exit; figure 4 – the dimensionless displacement of the spool from the neutral position; figure 5 – the dimensionless speed of the piston; figure 6 – the dimensionless displacement of the piston. As can be seen, the magnitude of the dimensionless jump \( \mathcal{U} \) of the control voltage affects not only the duration of the transient process, but also its nature and quality.

**Figure 3.** The voltage on the EB exit.

**Figure 4.** The displacement of the spool from the neutral position.

**Figure 5.** The speed of the piston.

**Figure 6.** The displacement of the piston.

The calculations are performed for the following basic initial data: \( F_1 = F_2 = 0.00915 \, m^2 \) (which corresponds to diameter of the piston 125 mm and diameter of the stocks 63 mm); \( H = 0.5 \, m \); \( p_p = 32 \times 10^6 \, Pa \); \( p_s = 0.2 \times 10^6 \, Pa \); \( \rho_r = 0.1 \times 10^6 \, Pa \); \( W_p = 0.002 \, m^3 \); \( R = -5 \times 10^3 \, N \) (pulling force); \( R_{df} = 0 \); \( c = 0 \); \( \kappa = 5 \times 10^4 \, kg/s \); \( m = 500 \, kg \); \( \rho_p = 54 \, V/m \); \( Q_{max} = 0.00638 \, m^3/s \); \( p_{max} = 32 \times 10^6 \, Pa \); \( T_{1a} = 0.00117 \, s \); \( T_{2a} = 0.00127 \, s \) (which corresponds to the phase shift -45° and -90° at the frequencies \( \nu_1 = 80 \, Hz \) and \( \nu_2 = 125 \, Hz \)); \( \rho_p / h_{max} = 0.01 \); \( L_e = 1.0 \, H \); \( R_e = 100 \, \Omega \); \( i_{max} = 0.3 \, A \); \( k_g = 6 \).
In general, the results of calculations based on the obtained mathematical model are in good agreement with the results of calculations on a more complete nonlinear models and experimental data of other authors [1, 2, 7, 10, 16], which makes it possible to state the adequacy of the presented mathematical description of the EHSD.

4. Conclusion

Thus, the typical nonlinear mathematical model of the nonstationary work processes in the EHSD with throttle regulation is proposed. The mathematical model is adapted for drives of the technological equipment for mechanical processing, which built on the basis of standard modules, in particular, EMHA and HC. The model allows to study the dynamic characteristics of the drive using the technical certificate data of incoming devices.

The recommendations were given on setting initial data for numerical simulation. For numerical integration of the nonlinear mathematical model of the nonstationary work processes software was developed in the environment of the MATLAB. The example of the calculation of the dynamic characteristics for the EHSD with throttle regulation was presented.

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