Design Calculation of Automatic Rotary Motion Electrohydraulic Drive for Technological Equipment

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Abstract. The article is devoted to the development of electrohydraulic drives for technological equipment. The engineering method for the design calculation of automatic electrohydraulic rotary motion drive with volume regulation was presented. This method allows evaluating the main parameters and choice drive elements and devices using the maximum load moment and hydraulic motor rotation velocity, predicting its static and dynamic characteristics. The electrohydraulic drive's automatic control system was proposed considering the control object's observation noise and stochastic perturbation. The example of design calculation for the automatic electrohydraulic drive parameters for technological equipment for the following input data was performed: maximum load moment $M_{max} = 120$ N.m; maximum rotation frequency $n_{max} = 2100$ rpm; reduced inertia moment of the rotating parts $J = 0{,}8$ kg.m^2. The possibility of using a serially produced axial piston-regulated pump with an inclined disk and an unregulated hydraulic motor with an inclined washer was shown. The drive's mathematical model parameters as an object of automatic control were determined based on hydraulic machines' passport data. The research of the system's dynamic characteristics was carried out.

Keywords: Engineering method · Volume regulation · Automatic control system · Dynamic characteristics

1 Introduction

The use of hydraulic drive in mechanical engineering allows us to simplify kinematics, reduce metal consumption, increase accuracy, reliability, and automation of technological equipment [1, 2]. The achievement of arbitrary kinematics of the working body and the possibility of implementing the optimal laws of its movement [3, 4] are ensured by using automatic electrohydraulic drives with volume regulation in equipment with a capacity of more than 5 kW [5, 6].

The advantages of the volume regulation method over the throttle [7, 8] are significantly less energy loss and more stringent load characteristics. The disadvantages are the structural complexity and increased cost of adjustable hydraulic machines [9, 10]. These factors have led to the predominant use of hydraulic drives with volume regulation

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at medium equipment powers (10–25 kW) and mandatory use at high power (more than 50 kW).

In this regard, the urgent task is to develop methods for the design calculation of automatic electrohydraulic drives for technological equipment with volume regulation.

2 Literature Review

In the general case, there are various hydraulic drives with volume regulation, which differ in the circulation of the working fluid, volume regulation, and branching of energy flows [11, 12].

Known hydraulic drives with the closed and open circulation of the working fluid [13, 14]. The hydraulic drive velocity can be regulated through the adjustable pump, adjustable hydraulic motor, or two adjustable hydraulic machines. Notably, there is smooth and stepwise regulations of the working volume of the hydraulic machine. Along with single-flow hydraulic transmissions, dual-flow ones are used to simultaneously operate hydraulic and mechanical transmissions [15, 16].

Volumetric hydraulic drives with the working fluid's closed circulation have comparatively smaller overall dimensions and weight, all other things being equal. Closed circulation of the working fluid is used when using hydraulic motors with the same effective areas of the working chambers [17, 18]. The essential properties of volumetric hydraulic drives with the closed circulation of the working fluid are the possibility of breaking the operating mechanism and resistance to the associated load using driving motor instead of throttling the fluid flow, which significantly reduces the heating of fluid and ensures the recovery of electric energy in the indicated operating modes [19, 20].

According to the method of implementing the volume method of speed regulation, three structural schemes of hydraulic drives are distinguished: with adjustable pump and uncontrolled hydraulic motor, unregulated pump and adjustable hydraulic motor, and both adjustable hydraulic machines. Volumetric hydraulic drive with adjustable pump and the unregulated hydraulic motor is the most common. Hydraulic drives with such a structure are used in many types of technological equipment and various mechanisms [21, 22]. Under consideration, the hydraulic drive provides a smooth start-up and stepless velocity regulation of the equipment working body through a single control unit [23, 24].

This work aims to develop an engineering method for the design calculation of automatic rotary motion electrohydraulic drive for technological equipment with volume regulation, allowing the values of the maximum load moment and rotation frequency of the hydraulic motor to evaluate the main parameters and to choose elements and devices of the drive, to predict its static and dynamic characteristics.

3 Research Methodology

Based on the analysis of the issue's status, we can propose the following engineering method to calculate the automatic rotary motion electrohydraulic drive for technological equipment with volume regulation.

To calculate the hydraulic drive with the rotational movement of the output link, the next parameters should be taken as input data: M_{max} – maximum load moment (N.m); n_{max} – maximum rotation frequency (rpm); J – reduced inertia moment of the rotating parts (kg.m^2).

3.1 Construction of the Settlement and Principal Scheme for Hydraulic Drive

In the settlement scheme, the drive's principal elements and devices are reflected, the relationships between them are formed, and the main drive parameters are presented. When developing the principal scheme, analogues of the designed equipment and the developers' experience are considered.

3.2 Choice of the Working Fluid and the Nominal Working Pressure

In addition to the main function of transferring energy from pump to hydraulic motor, the working fluid performs a number of essential functions: lubricating the surfaces of the rubbing parts; removal of wear products of rubbing pairs; protecting them from corrosion; cooling of the hydraulic system. Therefore, the correct choice of the working fluid determines the performance and durability of hydraulic equipment. As a rule, the working fluid is selected based on the technical requirements for equipment or the recommendations in the main hydraulic equipment's technical data (i.e., the pump and the hydraulic motor) and considering the operating mode of hydraulic drive, climatic and temperature conditions.

The hydraulic system's pressure depends on the pump type and the hydraulic drive's purpose on the equipment under consideration. The pump pressure should be greater, the greater the load or power of the driven working mechanism. Small pressures lead to an increase in size and weight but contribute to smooth and stable operation; high pressures lead to a reduction in dimensions and weight, complicate the design and operation of hydraulic systems, and reduce hydraulic durability equipment [25, 26]. The working pressure's nominal value in the hydraulic system p_{nom} is a set from the standard series, MPa: 6.3; 10; 12.5; 16; 20; 25; 32; 40.

3.3 Determination of the Working Volume and Choice of the Hydraulic Motor

The working volume of the hydraulic motor q_m considering hydraulic losses in the system, is estimated by the expression

$$q_m \geq (1,2\ldots 1,5)\frac{2\pi M_{max}}{p_{nom}}. \tag{1}$$

According to the parameters q_m and p_{nom}, taking into account n_{max}, the hydraulic motor is selected from the range of series-produced hydraulic equipment. In hydraulic drives of medium and high power (more than 10 kW), rotary-piston hydraulic machines are used mainly, which have a fairly high efficiency coefficient (0,85 … 0,92) and acceptable weight and size indicators (0.5–10 kg/kW) [8, 25].

In the absence of a suitable series-produced engine, the technical assignment is drawn up to develop the original hydraulic motor. In further calculations, the technical data for the value of the working volume for the hydraulic motor q_m is considered.

3.4 Choice the Pump

When assessing the maximum working volume $q_{p.max}$ of the adjustable pump, the volumetric losses in the hydraulic system (leakage) should be considered, and the nominal rotary velocity of the pump shaft, which can be taken from the technical data pumps used for this type of equipment.

Therefore, it is recommended to evaluate the maximum working volume of the pump according to the expression

$$q_{p.\max} \geq (1{,}1\ldots1{,}2)q_m \frac{n_{\max}}{n_{p.nom}}, \tag{2}$$

where $n_{p.nom}$ – nominal rotary frequency of the pump shaft.

According to the parameters $q_{p.max}$ and p_{nom}, the pump is selected from the range of series-produced hydraulic equipment. It should be noted that when choosing pumps, they are also mainly oriented to rotary-piston hydraulic machines. In further calculations, the technical data for the value of the maximum pump working volume $q_{p.max}$ is considered.

3.5 Determination of the Parameters for Mathematical Model of Hydraulic Drive Power Unit

Assuming a rigid load characteristic, the structural diagram of the mathematical model can be represented in the form shown in Fig. 1, where the following parameters are indicated: T_{rp} – time constant of the regulation process for pump working volume; T_{pd} – time constant of the drive power part; $k_{\gamma U}$ – transfer coefficient for the inclination angle γ of the titling washer (cylinder block) by the control voltage U; $k_{\Omega\gamma}$ – transfer coefficient of the drive power unit (transfer coefficient for the rotary velocity Ω by the inclination angle of the titling washer); α – rotation angle of the motor shaft; s – Laplace variable [27, 28].

Fig. 1. The structural scheme of the mathematical model.

The transfer coefficient for the inclination angle of the pump washer by the control voltage

$$k_{\gamma U} = \frac{\gamma_{nom}}{U_{nom}} \approx \frac{\gamma_{max}}{U_{max}}, \tag{3}$$

where $\gamma_{nom}, U_{nom}, \gamma_{max}, U_{max}$ – nominal and maximum values for the inclination angle of the washer (cylinder block) and the control voltage.

The transfer coefficient of the drive power unit

$$k_{\Omega\gamma} \approx \frac{\Omega_p}{\gamma_{max}\frac{q_{p.max}}{q_p}}, \tag{4}$$

where Ω_p – nominal rotation velocity of the pump shaft (*rad/s*), which is related to its rotation frequency (*rpm*) by the dependence

$$\Omega_p = \frac{\pi n_{p.nom}}{30}. \tag{5}$$

If the mathematical model of the power unit is considered for dimensionless variables

$$\overline{\gamma} = \frac{\gamma}{\gamma_{max}} \bar{\Omega} = \frac{\Omega}{\Omega_{max}} \tag{6}$$

where $\Omega \frac{\Omega_p q_{p.max}}{q_m}{}_{max}$ – maximum rotation speed of the hydraulic motor shaft;

It is easy to see that the transfer coefficients (3), (4) in this case are equal to unity

$$k_{\gamma U} = 1;\ k_{\Omega\gamma} = 1. \tag{7}$$

The time constant of the process control of the pump's working volume T_{rp} can be directly set in the passport data of the pump, or indirectly determined from the passport data of dynamic characteristics [25, 29] such as response time with a sharp change in oil flow, time of reversal of oil flow and other.

The time constant of the drive power part T_{pd} can be estimated from the values of the relative damping coefficient ζ_m for the hydraulic motor and its time constant T_m

$$T_{pd} \approx 2\zeta_m T_m. \tag{8}$$

According to the calculated dependence [25, 30], the hydraulic motor's relative damping coefficient is difficult. Therefore, at the preliminary calculation stage, it is recommended to set

$$\zeta_m \approx 0.4 - 1.2. \tag{9}$$

The expression can estimate the time constant of the hydraulic motor

$$T_m \approx (6 - 14)\sqrt{\frac{J}{q_m E_f}}. \tag{10}$$

where E_c – elastic modulus of the working fluid.

Thus, the rotary motion electrohydraulic drive's mathematical model parameters with volume regulation as automatic control objects are determined.

3.6 Assessment of the Static Characteristics for Hydraulic Drive

Usually of practical interest is the velocity static characteristic - the dependence of the rotation velocity on control voltage $\Omega(U)$ for the unloaded drive, the load characteristic – the dependence of the rotation velocity on the load moment $\Omega(M)$ at the nominal working volume of the adjustable pump, and the dependence of power consumption on rotation velocity $N(\Omega)$ and the efficiency coefficient on regulation depth $\eta(\Omega)$. The methods for calculating the static characteristics of hydraulic drives with volume regulation are quite fully described in the technical literature [11, 25] and differ in the degree of accepted assumptions.

3.7 Synthesis of the Automatic Control System

Methods for developing the automatic control system (ACS) by hydraulic drives for technological equipment are presented in papers [28, 29]. For rotary motion electrohydraulic drive, the ACS can be recommended, which considers the observation noise and stochastic disturbance of the control object. The structural scheme of this ACS is shown in Fig. 2.

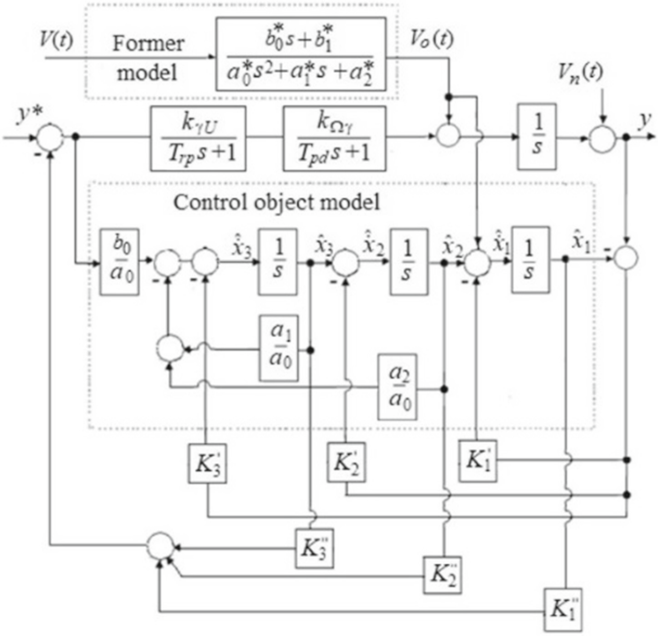

Fig. 2. The structural scheme of the ACS.

On the diagram are indicated: α* – given control law for the rotation angle of the hydraulic motor shaft; x_1, x_2, x_3 – phase variables; K_1', K_2', K_3' – gain coefficients of the Kalman-Bucy filter; K_1'', K_2'', K_3'' – feedback gain coefficients of the controller; $V_0(t)$ – color noise of the control object; $V_n(t)$ – white observation noise; $b_0^*, b_1^*, a_0^*, a_1^*, a_2^*$ – coefficients for the transfer function of the color noise former for the control object;

$$a_0 = T_{rp}T_{pd};\ a_1 = T_{rp} + T_{pd};\ a_2 = 1;\ a_3 = 0; \tag{12}$$

$$b_0 = k_{\gamma U}k_{\Omega\gamma}. \tag{13}$$

4 Results

We show an example of calculating the parameters of an automatic hydraulic drive of the rotational movement of equipment for machining materials for the following input data: maximum load moment $M_{max} = 120$ N.m; maximum rotation frequency $n_{max} = 2100$ rpm; reduced inertia moment of the rotating parts $J = 0.8$ kg.m^2.

Below are the main results of the calculation.

We accept the scheme for a volumetric hydraulic drive with the working fluid's closed circulation with an adjustable pump and unregulated hydraulic motor. The hydraulic drive's settlement and principal scheme are shown in Fig. 3 (P1 – main pump; P2 – auxiliary pump; HM – hydraulic motor; CV1, CV2 – check valves; SV1 – SV4 – safety valves; F – filter; T – tank).

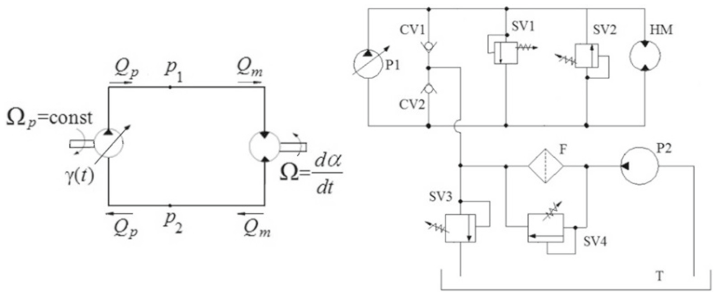

Fig. 3. The structural scheme of the ACS.

We choose the industrial oil IGP-30. We accept the nominal working pressure in hydraulic system $p_{nom} = 20$ MPa.

The working volume of the hydraulic motor

$$q_m \geq (1,2\ldots1,5)\frac{2\pi M_{\max}}{p_{nom}} = 1,3\cdot\frac{2{\cdot}3,14{\cdot}120}{20{\cdot}10^6} = 49{\cdot}10^{-6}m^3 = 49\text{sm}^3. \tag{14}$$

We select the unregulated axial-piston hydraulic motor with titling washer MFS 52 (PJSC "Hydrosila APM", Ukraine), which has the following main technical data parameters: working volume 51.6 cm^3; nominal pressure 22.5 MPa; maximum rotary frequency 3100 rpm; nominal rotary frequency 1500 rpm; the nominal power 29 kW. Further, we consider the working volume's technical data value for the hydraulic motor $q_m = 51.6.10^{-6}$ m^3.

The maximum working volume of the pump

$$\begin{aligned} q_{p.\max} \geq (1,1\ldots1,2)q_m\frac{n_{\max}}{n_{p.HOM}} &= 1,15{\cdot}51,6{\cdot}10^{-6}{\cdot}\tfrac{2100}{1500} \\ &= 83,08{\cdot}10^{-6}m^3 \approx 83\text{sm}^3. \end{aligned} \tag{15}$$

We select the axial-piston adjustable pump PVS 90 EP with electric proportional control (PJSC "Hydrosila APM", Ukraine), which has the following main technical data parameters: maximum working volume 89 cm^3; nominal pressure 22.5 MPa; nominal rotary frequency 1500 rpm; maximum inclination angle of the washer ±18°; the maximum control voltage ±24 V; the nominal power 63.3 kW. Further, we consider the maximum working volume's technical data value for the pump $q_{p.max} = 89.10^{-6}$ m^3.

We consider the automatic drive's mathematical model for dimensionless variables (6), (7). Therefore, we have

$$k_{\gamma U} = 1; k_{\Omega\gamma} = 1. \tag{16}$$

Further,

$$\zeta_m = 1{,}0;\ \mathrm{T}_m = 10\sqrt{\frac{0,8}{51,6{\cdot}10^{-6}{\cdot}1,0{\cdot}10^9}} \approx 0{,}04\,\mathrm{s};\ \mathrm{T}_{rp} = 2\cdot 1,0\cdot 0,04 = 0,08\,\mathrm{s}. \tag{17}$$

To control the drive, we use the ACS with the structural scheme according to Fig. 2. Transient processes in the ACS using the Kalman-Bucy filter and without it are shown in Fig. 4. The perturbing effect on the control object was considered in the form of white noise with spectral density $S_v(\omega) = 1$ and transfer function $W_f(s) = 0{,}02$ for the former model (Fig. 2). Researches have shown that the Kalman-Bucy filter performs optimal filtration and provides the ability to achieve the required quality of control by drive. In particular, it significantly reduces the duration of the transient process.

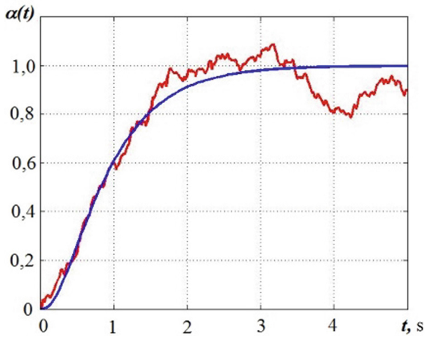

Fig. 4. The transient processes in the ACS.

5 Conclusions

Thus, the engineering method for the design calculation of an automatic electrohydraulic rotary motion drive with volume regulation is presented. The method evaluates parameters and choices that drive elements and devices using the maximum load moment and predicts hydraulic motor rotation velocity. The distinctive feature of the proposed engineering method is determining the transfer coefficients and time constants of the mathematical model and constructing a structural scheme of the ACS by drive. The recommended ACS by the electrohydraulic drive of the technological equipment considers the observation noise and stochastic disturbance of the control object.

The example of design calculation for the automatic electrohydraulic drive parameters for technological equipment for the following input data has been performed: maximum load moment $M_{max} = 120$ N.m; maximum rotation velocity $n_{max} = 2100$ rpm; reduced moment inertia of the rotating parts $J = 0.8$ kg.m^2. The possibility of using a serially produced axial piston regulated pump with an inclined disk and an unregulated hydraulic motor with an inclined washer is shown. Based on hydraulic machines' passport data, the mathematical model parameters for the drive as object of automatic control are determined. To control the drive, ACS is used, taking into account the observation noise and stochastic perturbation of the control object. The research of the system's dynamic characteristics is carried out. It was shown that the Kalman-Bucy filter performs optimal filtering and provides the ability to achieve the required quality of drive control.

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