Simulation of the hydraulic system of a device with self-adaptation by power and kinematic parameters on the working body

T Khinikadze¹,², V Pershin¹, and Y Karagodskaya¹

¹ Don State Technical University, Gagarin sq., 1, Rostov on Don, 344003, Russia
E-mail: ²2130373@mail.ru

Abstract. At present, Russia has adopted a course towards the creation of intelligent machines and equipment. This also applies to mobile technological machines for road construction and municipal purposes, the difficult operating conditions of which and the complexity of the proposed technical solutions hinder the implementation of this project in practice. Therefore, the design and creation of executive devices with a self-adaptation function for this class of technology is an urgent task. Materials and methods. A device with a hydraulic drive function with self-adaptation to load and coordination of kinematic and power parameters of the main movement and feed movement of the working body of a rock drilling rig is presented. For research and design of the device based on the methods of mathematical modeling of the hydraulic drive and adaptive systems, its mathematical model is proposed. Discussion and conclusion. The mathematical model presented in the article shows the fundamental possibility of the proposed device for implementing the principle of self-adaptation in terms of load under external and internal disturbing influences during its operation.

1. Introduction
At present, Russia has adopted a course towards the creation of intelligent machines and equipment. This also applies to mobile technological machines for road construction and municipal purposes, the difficult operating conditions of which and the complexity of the proposed technical solutions hinder the implementation of this project in practice. Therefore, the design and creation of executive devices with a self-adaptation function for this class of technology is an urgent task.

The self-adaptation property is possessed by drives with differential connections of the elements of the internal structure [1]. This class of technical systems includes a device for implementing the method of drilling rock with variable properties. The self-adaptation property is realized by the device of negative indirect and positive direct connections [2].

The quality of the self-adaptation process is influenced by external and internal influences (variability of the load of the resistance of the medium, dry and viscous friction, volumetric stiffness of the fluid and pipelines, adaptive connections).
2. Materials and methods

2.1. Formulation of the problem
In recent years, due to the rapid development of computer technology and its software, as well as in view of the rise in the cost of production of experimental samples and the requirement to reduce the time required to master the production of new products, the modeling of a new product and its theoretical study have become more widespread [3-9].

The development of a special model for calculations and a computational experiment to determine the parameters and indicators and a reasonable choice of the standard size of the device with self-adaptation of a specific application is an urgent task.

The model is developed to solve the problem of designing a device in the environment of dynamic modeling of technical systems SimInTech (Simulation In Technic) [10]. This software product allows you to simulate technological processes occurring in various industries with simultaneous simulation of control systems.

2.2. Description of the device
The device (Figure 1) contains: a constant displacement pump (1), a safety valve (2), a filter (3), adjustable throttles (5) and (10), a flow regulator (9), a feed cylinder (11) and a hydraulic motor of the main movement (6), hydraulic valves (4), (7) and (8), pressure gauges (12), (13) and (14), tank (15) and pipelines.

Figure 1. Schematic diagram of a device for implementing the self-adaptation function in conditions of power resistance on the working body.

The device is designed to implement the function of self-adaptation to the load (in order to stabilize it) and coordinate the output motions of the working body of technological machines and equipment, as well as the functions of the power drive itself. Therefore, the device provides multi-position distributors for the formation of flows and directions of the working fluid in the implementation of these functions. These additional functions of the device include: heating the oil in the hydraulic system at the beginning of its operation; "Weighing" of moving parts (idle load) of the feed mechanism during adjustment to the technological mode; accelerated lifting (retraction) of the tool
with rotation, but without regulation of its speeds; tool feed "to the object of action" or "from the object of action" with rotation and regulation of tool speeds.

3. Results of the research

3.1. Mathematical modeling of internal adaptive connections of the device

The mathematical dependence for the internal negative connection of the device is established by jointly solving the original equations in accordance with Figure 1:

\[
\Delta P_{dr1} = \frac{1}{w_{mol}} M_{gd} + \frac{1}{\ell_{s}} F_{dp}
\]

\[
\Delta P_{dr1} = \frac{2\pi}{\eta_{gd} \eta_{gd}} \left( M_{e_{gd}} + \Delta M_{e_{gd}} \right) + \frac{1}{\ell_{sgd} \eta_{sgd}} \left( F_{cdp} + \Delta F_{cdp} \right)
\]

\[
\nu = \frac{1}{\ell_{s}} \left[ \left( \mu_{dr1} \ell_{dr1} \ell_{dr1} \frac{2\Delta P_{dr1}}{\rho} \right) - \mu_{dr1} \ell_{dr1} \frac{2\Delta P_{dr1}}{\rho} \right]
\]

Considering that the oil flow through the flow regulator (item 9, Fig. 1) is constant, i.e. \( Q_{\text{rp}} = \text{const} \), then the flow through the drain throttle \( D_{r10} \) will also be a constant value. Therefore, the dependence for accelerating the feed rate on the total load on the hydraulic motors of the main movement and the feed movement has the form:

\[
\frac{dv_{dp}}{dt} = \frac{1}{\ell_{sp}} \left[ -A \frac{\text{sign} \left( \frac{\Delta M_{e_{gd}}}{\Delta F_{cdp}} \right) - \lambda_{vn} \omega_{gd}}{\left( \Delta M_{e_{gd}} + \Delta F_{cdp} \right)} \right]
\]

Direct positive relationship between the speeds and accelerations of the shaft of the hydraulic motor of the main movement and the rod of the hydraulic cylinder of the feed movement:

\[
\nu_{dp} = \omega_{gd} \frac{Q_{pr}}{2\eta_{sp} \ell_{sp}} \frac{Q_{pr}}{2\eta_{sp} \ell_{sp}}
\]

3.2. Mathematical modeling of movements of the device elements

\[
\left( J_{gd} + \frac{\rho_{gd}}{\ell_{gd}} \frac{\rho_{gd}}{\ell_{gd}} \frac{d\omega_{gd}}{dt} \right) = \Delta P_{gd} \frac{w_{mgd}}{\ell_{gd}} \frac{M_{e_{gd}} + \text{sign} \left( \Delta M_{e_{gd}} \right) }{\ell_{gd}} - \lambda_{vn} \omega_{gd} \frac{\omega_{gd}}{\ell_{gd}}
\]

\[
\left( J_{dp} + \frac{\rho_{dp}}{\ell_{dp}} \frac{d\omega_{dp}}{dt} \right) = \Delta P_{dp} \frac{1}{\ell_{stp}} - \frac{F_{cdp} + \text{sign} \left( \Delta F_{cdp} \right) }{\ell_{cdp}} \frac{F_{cdp}}{\ell_{cdp}} - \lambda_{vn} \frac{F_{cdp}}{\ell_{cdp}}
\]

In equations (1) - (8), the following designations are adopted: \( v_{dp}, \omega_{gd}, \Delta P_{i} \), \( w_{mgd}, J_{i}, M_{e_{gd}}, \Delta M_{e_{gd}}, i_{sgd}, F_{i}, Q_{pr},, x_{i},, p_{i},, p_{i_{+}}, \rho_{i_{pid}}, \lambda_{sgd}, E_{i} \) - respectively, linear and angular velocities of movements, pressure drop in the i-th section of the hydraulic system, characteristic volume of the hydraulic motor, moment of inertia of gears, elements, moment on the hydraulic motor shaft and deviation of the moment of resistance relative to the nominal value, force on the cylinder rod, friction, medium resistance, consumption of oil on the i-th element, section, pressure on the i-th sections, density, oils, elastic moduli, gear ratio of the i-th gear, the amount of hydraulic friction.

With values \( Q_{pr} = \text{const}, Q_{gd} > Q_{cdp} \), the module operates in the mode of direct feed of the working body with self-adaptation according to the load and the implementation of a direct positive
connection according to the speeds and accelerations of the shaft of the hydraulic motor of the main movement and the hydraulic cylinder of the feed.

From the above, it follows that a change in the speeds of movements of the output links of hydraulic motors (hydraulic motor shafts, hydraulic cylinder piston) occurs when the nominal values of the power technological parameters of the medium resistance, perceived by the working bodies of technological machines, change.

3.3. Mathematical description of the model of technological parameters

It is known that for various technological machines with two coordinated movements of the working body, theoretical or experimental relationships have been established between the power and kinematic output parameters: speeds of movements, torques, feed forces. For example, for rock drilling rigs such dependencies are [4]:

\[ V_m = K_i F^a, \]

\[ F_i = F_0 + \Delta F_0 = F_{00} + k_{yd} \Delta M_{ydd}, \tag{9} \]

where: \( \Delta M_{ydd} \) – change in the specific moment of drilling when drilling rocks with different moment capacity, \( v_m \) – drilling penetration rate, \( k_i \) – transmission coefficient for specific moment; \( F_i, F_{00}, \Delta F \) – respectively, axial i-th, nominal load and its increment.

Considering together equations (1) - (9), it can be concluded that a change in the specific moment when the values of the strength parameters of the drilled rock change leads to a change in the value of the specific moment and axial force on the working body. In accordance with the dependence for negative feedback, this will lead to a change with the opposite sign of the velocities of the main movement and the feed movement and, consequently, to a decrease in the magnitude of the increment of the force parameters of the movements.

4. Modeling the properties of a hydraulic system

The mathematical model of the hydraulic system of the device was developed using the theory of volumetric stiffness [11], which allows taking into account the elastic properties of the working fluid and hydraulic elements of the system. The use of the theory of volumetric stiffness allows to use the method of partial synthesis [12], which significantly speeds up the process of theoretical analysis of the system and increases its accuracy [13 .. 17].

The model of the hydraulic system of the device includes:

– pressure increment equations at any point in the hydraulic system

\[ dp = C_{pe} \left( \sum Q_{axx} \cdot \sum Q_{ixx} \right) dt, \tag{10} \]

– the equations of the flow rates of the working fluid required for calculating the pressures

\[ Q_i = \mu f \sqrt{\frac{2}{\rho}} \left| p_i - p_{i+1} \right| \cdot \text{sign}(p_i - p_{i+1}), \tag{11} \]

where the flow coefficient of the corresponding section of the hydraulic line \( \mu \) is determined depending on the length of the section according to the formula

\[ \mu = \mu_i = \frac{1}{\sqrt{\lambda_i}}, \tag{12} \]

– equations for the reduced coefficients of volumetric stiffness of sections of metal pipelines

\[ C_i = \frac{4}{\pi d_i'^2} \frac{E_i}{E_i'}, \tag{13} \]

– pump flow equation, determined taking into account the volumetric losses that occur in the pump during its operation (its volumetric efficiency)
the equation of the flow rate of the working fluid through the hydraulic motor of the main movement is determined taking into account the volumetric losses that occur in the motor during its operation under load (its volumetric efficiency)

\[ Q_{\text{mot}} = \frac{q_{0,m}}{2\pi \eta_{0,m}} \]  

(15)

the equation of the intensity of the change in the actual flow rate of the working fluid in the inlet-outlet section of the hydraulic cylinder from the side of the rod cavity is determined by the formula

\[ \frac{dQ}{dt} = f_{\text{st}} \cdot \frac{dV}{\rho} \cdot \text{sign}(p) \]  

(16)

– equation for determining the current value of the volumetric efficiency of the pump and motor

\[ \eta_0 = 1 - \left(1 - \eta_{0,\text{nom}}\right) \cdot \frac{p}{p_{\text{nom}}} \]  

(17)

where \( \sum Q_{\text{in}} \) and \( \sum Q_{\text{out}} \) – respectively, the sums of all flow rates of the working fluid entering and leaving from the considered (i-th) volume of the system during the time \( dt \); \( C_{\text{prl}} \) – reduced coefficient of volumetric stiffness at the nodal points of the selected section of the hydraulic system.

The proposed mathematical model of the device for implementing the method of drilling rock with variable properties allows high-precision theoretical studies of its operational capabilities when drilling rock even at the design stage.

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