Simulation of adaptive drill machines with hydraulic drive

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Abstract. In a number of technological machines, the drive performs two related working movements. As you know, most of the machines used for Metalworking, also have a drive with one or two engines, which provides a working process with two movements of the cutting tool relative to the workpiece or part. As a rule, this is rotational and translational motion. The ratio of the speeds of these movements, or the ratio of the two movements, determines the modes and indicators of the cutting process. This ratio is often optimal. The article deals with the method of modeling the adaptive drilling machine, as an example of studying and analyzing the automatic process of maintaining rational cutting conditions with two related working movements. In this case, the feed force can be greater than the nominal value within the power and strength limitations, or be negative, providing reverse movement of the drill in case of jamming. What is new is that the simulation of the adaptive machine operation process is performed, showing the features of the adaptation process, self-adjustment of the drive to rational cutting conditions, with a change in the strength of the drilled material. In particular, it is possible to configure the adaptive scheme to the required degree of adaptation. Equations and the developed method of the analysis of the adaptive drive executed on the basis of two differentials are given.

1. Problem statement
The complexity of solving the problem of optimal control of the drilling machine operation modes is associated with the need to change the drilling modes in accordance with the change in the physical and mechanical properties of the drilled material and taking into account the wear of the cutting part. Relatively new and little known is the issue of development and application of adaptive control of the drilling process, which provides automatic change of drilling modes adequately change the working conditions of the drilling machine, without the use of electronics. Control of drilling modes includes changing the speed of the \( n_t \) rod and changing the feed force \( F_t \), which should be close to the theoretically optimal \( n_p \) and \( F_p \) and be within the limits of strength and technological limitations [2].
2. Analysis of research and publications.
There are known machines for drilling, for loading rock material, which use the principles of adaptation [3]. The essence of the principle of adaptation is to self-tune to a mode of operation that is close to the optimal one.

Features of these machines and the results of their research devoted to a number of scientific publications, for example [4,5]. Currently not sufficiently studied the regularities of formation of loads in the machines with properties of adaptation based on two differential drives [6,7]. The concept of adaptive devices and adaptive machines for workflows with two related movements is substantiated by well-known scientists of Drovnkov A. N., Vodyanik, M. G. [8,9], their students and other scientists [10]. Known studies have revealed the effectiveness and usefulness of the developed principles to achieve adaptation, including drilling machines with hydraulic or Electromechanical drive.

A number of new studies have supplemented and deepened knowledge in the field of adaptation in the drilling process [11,12,13]. However, not all issues of optimization of the drilling process by adaptive drilling machines are solved taking into account the relationship of loads and characteristics of the adaptive drive.

3. Materials and results of research.
To consider the features of such a drive in its structure, two hydraulic differentials are distinguished, on which an adequate change in the parameters of each engine operation depends in response to changes in drilling conditions. Hydraulic and structural diagrams of such a machine are shown in figures 1A and 1B.

![Figure 1](image-url)  
**Figure 1.** Hydraulic two-differential drive of the drilling machine: (A) hydraulic circuit of the drilling machine, (B) representation of the hydraulic circuit in the form of a "bridge": 1-hydraulic cylinder, 2-hydraulic motor, 4,5,6-throttles settings for operating modes, 7-hydraulic pump.

To develop a model of the adaptive drive operation process, the structure of which includes two hydraulic differentials, which connects the ratio of the characteristics of the two engines through the drilling process. The first hydraulic differential is a flow divider from the hydraulic pump line to the line, through the throttle 5 and the second line with the hydraulic motor 2.
The fluid flow from the pump $Q_p$ is divided into flow $Q_5$ and flow $Q_2$. When the flow through the hydraulic motor 2 changes, the flow through the throttle 5 will change. The flow through these lines is related by the expression

$$Q_p = Q_5 + Q_2.$$ 

The second differential is implemented on a two-way hydraulic cylinder 1, the amount of force on the rod of the hydraulic cylinder and the direction of its movement are determined by the pressure difference in its rod and piston cavities. Otherwise, this differential can be characterized by the connection of pressures in the cavities of the hydraulic cylinder with the force on its rod. Equation of the second differential:

$$F_t = F_1 - F_2,$$

where: $F_t$ - is the rod feed force into the bore (feed force); $F_1$ - force determined by the pressure in the piston cavity of the hydraulic cylinder; $F_2$ - force determined by the pressure in the rod cavity of the hydraulic cylinder;

The drive scheme of the drilling machine in Fig. 1A is converted into a closed circuit of the connection of hydroelectric elements and is presented for analysis as a bridge scheme in Fig. 1B. Hydraulic diagrams in Fig. 1A and Fig.1B correspond to the same drilling machine.

In Fig. 1 In the diagram is represented as a bridge. This allows for determining the dependence of the pressure piston (main) cylinder cavity, the flow through the hydraulic motor, the pressure in the piston cavity of the hydraulic cylinder depends on the feed force on the cutting drilling tool. The amount of fluid flow through the hydraulic rotation motor depends on the rotation frequency of the drill rod. Which, in turn, is determined by the resistance to rotation.

Thus, the essence of adaptation is explained: the moment of rotation on the drill rod controls the force of pressing it to the face. In a situation when the rotation moment is less than the calculated one, the rod pressure force on the face increases, and Vice versa, if the resistance moment is too large, the feed force decreases.

It is necessary to find out the dependence of the feed force on the rotation moment. It is necessary to determine the impact of throttle settings. These questions are the purpose of these studies.

These questions can be answered by simulating the process of redirecting the hydraulic fluid in the hydraulic actuator having the properties of adaptation. It is necessary to consider the influence on this redistribution and the characteristics of gidrobiontov: pump, rotation motor, throttles and hydraulic cylinder. Simulation of the adaptive drilling machine is performed using the well-known method of electro-hydraulic analogy.

It is known that in applying this analogy, one has to resort to some inaccuracies in the analogy. In particular, the influence of the Reynolds criterion on the hydro-resistance of throttles is not taken into account. This makes quantitative modeling results not very accurate, especially when studying dependencies over a large range of drilling conditions. However, a qualitative assessment of such adaptive drive schemes is also useful.

In the simulation, we will use a method known in electrical engineering for calculating bridge circuits using the Kirchhoff equation, which allows us to find connections between the currents in the circuits (analog - fluid flows through hydroelectric elements) and the voltages on the resistors (analog - pressure differences on each hydroelectric element), at different values of resistances (flow sections of the chokes).

Using the diagram shown in Fig. 1B draw up a design scheme in which we replace the hydraulic analogues with electric ones.

To create equations, we use the method of contour currents. Let's denote the directions of currents in the branches, and make a system of equations for each contour (Figure 2). Further for the analysis of the investigated dependencies we use the following notations: hydraulic resistance of throttles
Thrott \( t = R_i \), hydraulic resistance of the hydraulic motor = \( R_0 \); hydraulic resistance of the hydraulic cylinder = \( R_5 \), \( E = \) EMF (pressure pump).

\[
\begin{align*}
I_1(R_1 + R_3) - I_2R_1 - I_3R_3 &= E \\
-I_1R_1 + I_2(R_1 + R_5 + R_0) - I_3R_5 &= 0 \\
-I_1R_3 - I_2R_5 + I_3(R_2 + R_3 + R_5) &= 0
\end{align*}
\]

Then we solve the system of equations obtained by the known method and calculate the values of contour currents:

\[
\begin{align*}
F_0(R_0) &= \begin{bmatrix} R_1 + R_3 & -R_1 & -R_3 \\ -R_1 & R_1 + R_5 + R_0 & -R_5 \\ -R_3 & -R_5 & R_2 + R_3 + R_5 \end{bmatrix} \quad \Rightarrow \quad F_0(R_0) = \begin{bmatrix} E & -R_1 & -R_3 \\ 0 & R_1 + R_5 + R_0 & -R_5 \\ 0 & -R_5 & R_2 + R_3 + R_5 \end{bmatrix} \\
F_1(R_0) &= \begin{bmatrix} R_1 + R_3 & E_1 & -R_3 \\ -R_1 & 0 & -R_5 \\ -R_3 & 0 & R_2 + R_3 + R_5 \end{bmatrix} \quad \Rightarrow \quad F_1(R_0) = \begin{bmatrix} R_1 + R_3 & -R_1 & E \\ -R_1 & R_1 + R_5 + R_0 & 0 \\ -R_1 & -R_5 & 0 \end{bmatrix} \\
F_2(R_0) &= \begin{bmatrix} R_1 + R_3 & E_1 & -R_3 \\ -R_1 & 0 & -R_5 \\ -R_3 & 0 & R_2 + R_3 + R_5 \end{bmatrix} \quad \Rightarrow \quad F_2(R_0) = \begin{bmatrix} R_1 + R_3 & -R_1 & E \\ -R_1 & R_1 + R_5 + R_0 & 0 \\ -R_1 & -R_5 & 0 \end{bmatrix}
\]

Next, using the values of contour currents, we calculate the currents in each branch of the bridge circuit, as well as the voltage at each resistance:

Current in branch 1 (flow in branch 1) = \( i_1 \) \( i_1(R_0) = \frac{F_0(R_0)}{F_1(R_0)} \)

Current in branch 2 (flow in branch 2) = \( i_2 \) \( i_2(R_0) = \frac{F_0(R_0)}{F_1(R_0)} \)

Figure 2. Design scheme of modeling of the drilling machine.
Current in branch 3 (flow in branch 3) - $i_3$  
$$i_3(R_0) = \frac{F_3(R_0)}{F_0(R_0)} - \frac{F_1(R_0)}{F_0(R_0)}$$

Current in branch 4 (flow in branch 4) - $i_4$  
$$i_4(R_0) = \frac{F_2(R_0)}{F_0(R_0)} - \frac{F_1(R_0)}{F_0(R_0)}$$

Current in branch 5 (flow in branch 5) - $i_5$  
$$i_5(R_0) = \frac{F_2(R_0)}{F_0(R_0)} - \frac{F_3(R_0)}{F_0(R_0)}$$

Current in branch 0 (flow in branch 0) - $i_0$  
$$i_0(R_0) = \frac{F_2(R_0)}{F_0(R_0)}$$

By analogy: the current in the electric circuit ($i$) is similar to the flow in the hydraulic circuit ($Q$), the resistance voltage is equivalent to the pressure difference between the input and output of the hydraulic element. The relationship between the torque resistance to rotation, the feed force with the values of pressure and flow in the hydraulic circuits of the drilling machine was modeled on the basis of the above equations in Mathcad.

Using these connections, the analysis of the adaptive drilling machine in different modes. As an example, we present an analysis of the influence on the control characteristics of one of the most important in the scheme of the throttle "R1" – which is the "plech" of the first hydraulic differential.

The value of the flow section of the throttle determines the degree of sensitivity of the adaptation scheme.

For figure 3 example of the flow dependence on the torque resistance to rotation at the nominal value of the throttle resistance «thrttl1"is given.
At the nominal position of the throttle regulator (opening at 40%), the value of its hydraulic resistance equal to 400 units is conditionally accepted.

![Figure 3](image_url)

**Figure 3.** Flows dependent, from the moment of resistance to rotation, at the nominal value of the resistance of inductor 1, R1=400 units.
The minimum value of the hydraulic resistance of this choke is conventionally assumed to be 10 units. Closing the throttle 80% corresponds to the hydraulic resistance equal to 800 units (Figure 4).

The working area with this setting of the throttle 1 and other chokes of the system corresponds to the range of torque resistance from "0" to "200" KGM. At values of torque resistance to rotation of more than 180 kg m, there is a reverse motion of the feed cylinder rod. As can be seen in the above graph, with the increase of the torque resistance to rotation by hyperbolic dependence, the feed force decreases. This creates a balance between the load on the hydraulic motor and the feed force. For example, with a change in the strength of the drilled material, the feed force automatically changes, maintaining the torque at values close to the optimum.

![Figure 4](image)

**Figure 4.** Flows dependence on the torque resistance to rotation, with increased hydraulic resistance of the throttle 1, R₁=800 units.

As can be seen in the graph, from the throttle setting 1, significantly depends on the limit value of the torque resistance to rotation, in excess of which, the automatic feed reverse is performed.

4. Conclusions
A feature of the above connection elements of the hydraulic circuit is the formation of hydraulic and hydromechanical differentials.

Such a connection provides the property of adaptation of the drilling machine in changing operating conditions: With an increase in the torque resistance to rotation on the hydraulic motor, the feed force will automatically decrease, up to the reverse of the movement. What is necessary, for example, when jamming the rod during drilling.

The increase in the fortress are drilling rocks, for the model of the drill machine would be to reduce the specific flow and reduce torque, but in this control scheme, the decrease in torque will increase the thrust and stabilization of the drilling speed.

Most drilling machines of domestic and foreign production of rotary drilling have the so-called "free" supply provided by hydraulic cylinders. For a "free" feed, an increase in the strength of the drilled material leads to a decrease in the specific feed and, consequently, to a decrease in the drilling speed.
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