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AUTOMATED CONTROL OF DRIVES FOR OPEN-PIT DRILLING RIGS

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Physical and moral aging of mining equipment, in particular drilling rigs is one of the main problems of the open method of mineral extraction in the quarries of Ukraine. The modernization of the existing park and the creation of a new generation of drilling rigs is an important scientific and applied problem, the success of which depends on the efficiency of the domestic mining industry. The teams of special design bureau of research institutes of Ukraine are engaged in the creation of domestic core drilling rigs. Along with the improvement of the hydromechanical equipment of drilling rigs, it is necessary to improve the drive systems, which must correspond to the achieved level in the global electrical engineering industry. Only in this case, it is possible to create a competitive drilling roller-cone bit at a whole. The issue of finding and choosing a rational way of controlling interconnected drive systems of rotation and feeding rod in the hole button zone is considered. An important issue in the development of rotation and feed drives is the choice of a method of mutual control. The control methods are analyzed in which one of the parameters is maintained at a constant level: the rotation frequency of the roller-cone bit, the moment of resistance on the roller-cone bit, the linear speed of the drilling rod movement, the axial pressure on the drilling rod, the power consumed by the rotation drive. Based on the energy criterion of stability of the roller-cone bit, the most rational way of controlling the drive of drilling rod rotation of the drilling rig was chosen. The roller-cone bit will have the greatest stability when its energy load is uniform, i.e. when maintaining a linear growth of rock destruction energy or when maintaining at a constant level the power released in the roller-cone bit and hole bottom contact zone. The proposed working ability criterion generalizes the known criteria because it automatically considers the strength and abrasiveness of the rock that is destroyed by the roller-cone bit. In the proposed method of controlling the feed drives and rotation of the drilling rod in the process by the roller-cone bit drilling, rigid mechanical characteristics are formed on the roller-cone bit when penetrating rocks with a strength of 10-13 units on the scale of Prof. M.M. Protodiakonov and soft mechanical characteristics – in stronger rocks. When drilling different strength of the rocks of physical and mechanical properties, the control method provides automatic selection of mechanical characteristics depending on the strength of the rock.

Key words: *drilling rod, rotation drive, feed drive, control method.*

Хілов В.С. Автоматизоване керування приводами кар'єрного бурового станка

Фізичне і моральне старіння гірничого устаткування, зокрема бурових верстатів, є одної з основних проблем відкритого способу видобутку корисних копалин на кар'єрах України. Модернізація наявного парку і створення нового покоління бурових верстатів є важливою науково-прикладною проблемою, від успішного вирішення якої залежить працездатність вітчизняного гірничорудного виробництва. Створенням вітчизняних верстатів шарошкового буріння займаються колективи спеціальних конструкторських бюро науково-дослідних інститутів України. Разом з удосконалюванням гідромеханічного устаткування бурових верстатів необхідно покращувати і приводні системи, які повинні відповідати досягнутому рівню у світовій електротехнічній промисловості. Тільки так можна створити конкурентоспроможний буровий верстат загалом. Розглянуто питання пошуку та вибору раціонального способу керування взаємопов'язаними приводними системами обертання та подачі поставу в зону вибою. Проаналізовано способи керування, за яких підтримується на постійному рівні один з параметрів: частота обертання поставу, момент опору на долоті, лінійна швидкість пересування поставу, осьовий тиск на постав, потужність, що споживається приводом обертання. Виходячи з енергетичного критерію стійкості долота, розроблено раціональний спосіб управління приводом обертання поставу верстата шарошечного буріння. Найбільшу стійкість долото матиме за його рівномірного енергетичного навантаження, тобто за підтримки лінійного зростання енергії руйнування породи чи за підтримки на постійному рівні потужності, яка виділяється у зоні контакту «долото – вибій». Запропоновано критерій працездатності, який узагальнює відомі критерії, тому що автоматично враховує міцність та абразивність породи, яка руйнується шарошковим долотом. За запропонованого способу керування приводами подачі та обертання постави в процесі шарошкового буріння формуються жорсткі механічні характеристики на шарошковому долоті під час проходження в породах з міцністю в межах 10–13 одиниць за шкалою проф. М.М. Протодьяконова і м'які механічні характеристики – в більш міцних породах. Під час буріння перемежованих за фізико-механічними властивостями гірських порід спосіб керування забезпечує автоматичний вибір механічних характеристик залежно від міцності породи.

Ключові слова: *буровий верстат, привод обертання, привод подачі, спосіб керування.*

The SBShS-250N and SBSh-250/270-32 drilling rigs created by OJSC NKMZ are equipped with two adjustable rotation systems for uphill and downhill operation, which use modern digital AC and DC drives. Such electromechanical systems are fully controllable and expand the possibilities of automating the drilling process, allowing to take into account the technological features of the drilling rigs, which was impossible to achieve when using non-adjustable drives for the feed drilling rod in the SBSh-250MN-32 machines [1; 2].

An essential issue in the development of a control system for rotary and feed drives is the choice of control method. Control methods are known that maintain one of the following parameters at a constant level: rotational speed of the bit, torque on the bit, linear speed of the bit, axial pressure on the bit, and power consumed by the rotary drive. Based on the energy criterion of bit stability, let's choose a rational way to control the rotary drive of the rotary rod of a ball drilling rig.

The operation of a drilling rig is characterized by the conversion of electromagnetic energy coming from the power supply system into mechanical energy, which is released in the form of unproductive losses and converted into useful work used to destroy rock and transport drill cuttings to the wellhead [3; 4]. Energy flows are formed and directed through the following channels: axial force – the power of linear movement of the bit; rotation frequency – the power of rock destruction; compressed air pressure and flow rate – the power of drill cuttings (mud) removal. Each channel has an individual energy type converter, including: an adjustable electro-hydro-mechanical drive for feeding the drill bit; an adjustable electromechanical drive for rotating the roller cutter bit; an unregulated electromechanical drive for the compressor to remove drill cuttings from the surface of the bottom-hole face [5].

The energy flows are directed to the surface of the bottom hole, with the axial force tending to crush the surface, creating a stress state in the rock mass; the rotational energy is used to penetrate the pins into the surface layer of the bottom hole, destroy the rock and crush it, which is then carried to the wellhead by the air flow.

The drilling process is carried out in two mutually exclusive directions: the largest number of drilled wells in the shortest operating time; the lowest wear of drilling tools (rods and bits) during drilling.

The most worn parts of a roller cutter bit are its tooling and supports. During operation, the bit is subjected to high static and dynamic loads, as well as intense fatigue and abrasive wear. The flow of rotational energy is aimed not only at destroying the rock, but also at destroying the bit itself.

The pins of the roller cutter are subjected to a cyclic impact load, which leads to the accumulation of fracture energy from fatigue of the tooling material and bit supports. Penetration of the pin into the rock layer occurs upon impact, and the stored kinetic energy of the rotation of the bit is converted into potential fracture energy of the rock. A stress state is created on the face with subsequent destruction of its surface layer. As the rock strength increases, the potential energy increases, while maintaining the intensity of the fracture process at a constant level. At the same time, there is a significant wear of the bit, as its destruction due to fatigue of the grit material increases.

The durability of the bit's drill bit material depends on the overcome torque, the current rotational speed of the bit and the power generated in the area of contact between the bit and the rock face, which can change its strength according to an unknown law. In the case of uneven power generation in the face zone, the load is unevenly distributed over the surface of the roller, which causes the appearance of zones with different stresses. This results in uneven wear of the tooling and bit supports and a decrease in its service life, which negatively affects the bit penetration in general.

The following criteria for determining bit durability are proposed: penetration per bit, bit service life, conditional bit wear [6].

The criterion of the durability of a roller cone bit, which objectively controls the current mode of operation (wear), should take into account both the strength of the rock and the duration of the bit in contact with the massif, which has a changing strength and abrasiveness. The strength and abrasiveness of the rock can be objectively assessed by the value of the moment of resistance on the roller (with increasing strength and abrasiveness of the rock, the moment of resistance increases, and the wear of the tooling and bit supports increases at the same time). The amount of bit wear can be estimated by the angle of rotation of the bit at the current moment of resistance, i.e. as [7]:

$$dW = M_c(\alpha) \cdot d\alpha ,$$

where dW – power differential, which characterizes the wear of the bit; $M_c(\alpha)$ – the current torque of the resistant on the roller; $d\alpha$ – differential angle of rotation of the bit.

Complete wear of the tooling and bit supports, according to the proposed bit stability criterion, is defined as:

$$W = \int_0^{\alpha_K} M_c(\alpha)\, d\alpha ,$$

where α_K – bit rotation angle due to full (permissible) wear of the tooling and supports.

Moreover, with an increase in rock strength (resistance torque), the allowable angle of rotation decreases and, conversely, increases when the roller cutter is used in less strong rocks. The dependence of the permissible angle of rotation on the moment of resistance with a limited bit service life is hyperbolic.

To move from the permissible angle of rotation α_K of the bit to its service life T_K, we use the integral dependence of the form:

$$W = \int_0^{\alpha_K} M_c(\alpha) \frac{d\alpha}{dt} dt = \int_0^{T_K} M_c(t)\,\omega \cdot dt ,$$

where t, dt – current time and its differential; ω – roller-cone bit rotation speed; T_K – time corresponding to the maximum wear of the roller cutter bit.

Consider that the product of the torque and rotational speed is the power of rock destruction by the bit $P(t)$, and the integral of the current power over time is the energy E, then:

$$W = \int_0^{T_K} M_c(t)\,\omega \cdot dt = \int_0^{T_K} P(t)\,dt = E ,$$

thus, the allowable wear of the bit is uniquely determined by the amount of energy that the roller converts during drilling in the bottom hole zone. The more energy is spent on drilling in the bottom hole zone, the greater the bit wear.

Then we have that to determine the uniform wear of the bit during in time, it is necessary that the energy flow generated through the channel of the rotation speed of the bit – the rock fracture power, grows linearly as a function of time, i.e. the rate of energy consumption through this channel should be constant. Therefore, to maintain the dependence of the fracture rate on material fatigue at a constant level, the rate of energy input into the face zone should be regulated. It is necessary to change the rotational speed of the bit in inverse proportion to the moment of resistance on the bit. This is possible only by maintaining a constant level of power coming through the rotational speed – rock destruction power channel.

The characteristics of rotary and feed drives should be adjusted in accordance with the strength of the rocks [8]. Therefore, the technological parameters of drilling should change according to the following dependencies: when the strength of the drilled rock increases, the axial pressure on the tool increases, its rotation frequency decreases, which will lead to a decrease in the linear rate of drilling a borehole, i.e.:

$$G = G_0 + a \cdot f; n = n_0 + b / f; V_M = V_0 + c / f,$$

where G, n, V_M, G_0, n_0, V_0 – current and initial axial force, rotational speed and mechanical drilling speed; a, b, c – constant coefficients that depend on the characteristics of the rocks being drilled, the type of bit, etc.; f – strength of the rock being drilled, according to the Protodeacon’s scale.

The graphical interpretation of the above equations is in the form of dependencies (Fig. 1), which define the control law when drilling rocks of varying strength: the stronger the rock, the lower the rotational speed of the roller cutter bit and the greater the axial force on the bit. This algorithm is implemented by the operator in the manual control mode. The strength of the rock cannot be measured directly, so the driller estimates it by the moment of resistance on the roller cutter. Drilling is based on averaged data, as the operator is not able to process the current values of rock strength changes.

The proposed method of controlling the drive systems for feeding and rotation is based on the task of increasing bit stability by improving the method of controlling the drilling process by forming “hard” mechanical characteristics of the rotation drive when drilling in soft and fractured rocks and “soft” mechanical characteristics when drilling in strong unbroken rocks [9]. When drilling rocks that vary in physical and mechanical properties, automatic switching from one drive system operation mode to another allows to increase bit stability.

This task is solved by distributing the operating modes of the drilling rigs drive systems in accordance with the strength of the rock being destroyed, which ensures a rational load on the roller-cone bit.

In addition, the drilling process control method considers the possibility of limiting the appearing vibration vibrations of the drill bit, which excite self-oscillations in the electromechanical system. If the natural and forced frequencies coincide, emergency resonance phenomena occur in the machine. With an increase in the power consumed for rock destruction, at a constant fracture resistance torque, the rotational frequency of the tool and its vibration oscillations increase. Therefore, in the proposed control method, vibration oscillations are limited by influencing the set fracture power: with an increase in vibration oscillations, the power consumed for rock fracture should decrease.

Drilling hard, intact fractured rocks is due with significant peak drag moments on the bit. The value of the drag torque can exceed the maximum possible value of the rotary drive torque, which leads to the bit “sticking” on the bottom hole. Since the

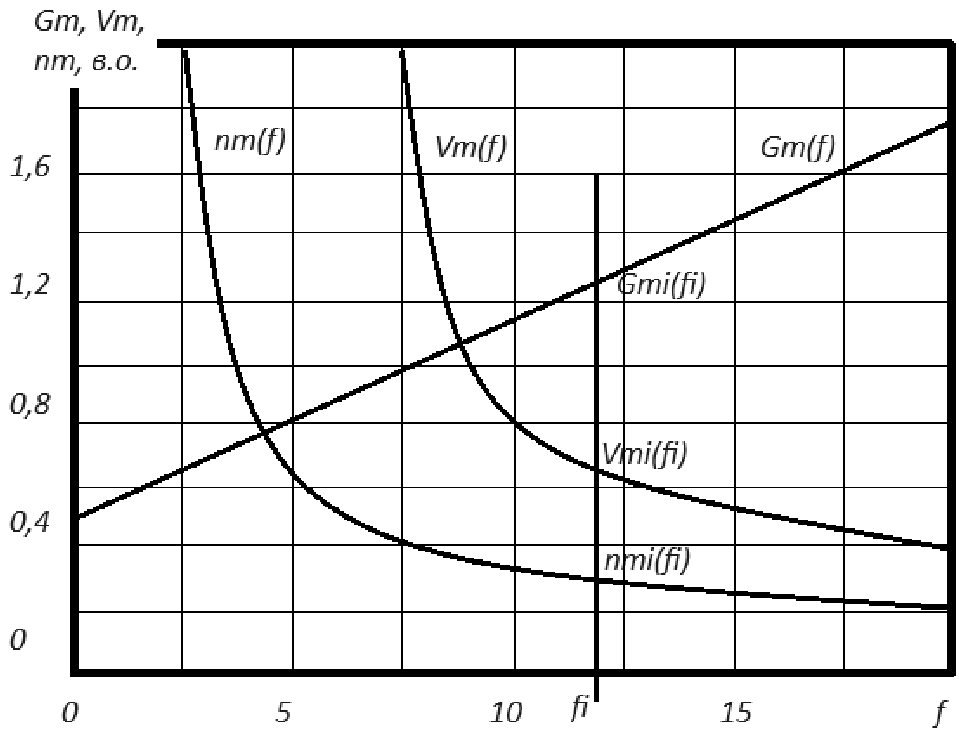

Fig. 1. Static mechanical characteristic realized on the bit (n_m – bit rotation frequency, V_m – linear velocity of the bit, G_m – axial force on the bit, f – rock strength factor)

drag torque depends on the axial pressure, if it is exceeded during drilling, the setpoint limit should be reduced to an acceptable value by adjusting the bit pressure. The lower the bit pressure, the lower the resistance torque.

If the current power value required to fracture the rock is less than the set value, then drilling is carried out in non-energy-intensive rocks, such as fractured or soft rocks. In this case, it is rational to drill in the mode that maintains a constant rotational speed and adjust the pressure on the bit. In this drilling mode, the linear speed of the bit should be limited to eliminate dynamic impacts of the bits when passing through rock with higher strength.

As the bit moves into stronger or undisturbed rock, the power required to drill in the rock mass increases. Therefore, in order to maintain greater durability of the bit equipment, it is necessary to switch to the drilling mode with constant pressure on the bit and adjust its rotation speed. To improve the bit operating conditions in this control mode, it is necessary to maintain a constant power flow in the bottom hole zone, i.e., with an increase in the moment of resistance on the bit, its rotation speed should be reduced accordingly.

Fig. 2 shows the static mechanical characteristic realized on the bit with this method of controlling the drive systems for feeding and rotating the posture (ω – bit rotation speed, M_c – resistance moment).

When drilling with a bit in fractured or soft (non-energy-intensive) rocks, low fracture power is required. In this mode of drilling, it is rational to limit the bit speed to the maximum specified level and control the axial force on the bit so that the linear speed of the bit does not exceed the maximum specified value (section 1–3 in the mechanical characteristic). As the axial pressure increases, the power required to fracture the rock and the static torque on the bit increase.

As the bit moves into undisturbed, hard rock, the power consumed by the rotary drive increases, meaning that drilling is performed in energy-intensive rocks. In this case, the drilling rig's productivity is limited by its power capacity. The drilling rig moves to the mechanical characteristic 3–4 (Fig. 2), where the rig's energy resources are controlled to maintain a constant power flow required to fracture the rock. In this mode of drilling, as the strength of the drilled rock increases, the static moment of resistance on the bit increases and its rotation speed decreases.

The linear speed of the bit movement will be unstable and depends on the physical and mechanical properties of the drilled rock. In the section of the mechanical characteristic 3–4, the axial pressure on the bit is maintained constant.

On the section of mechanical characteristics 4-6, the following parameters are kept constant: static torque, rock fracture power flow. The

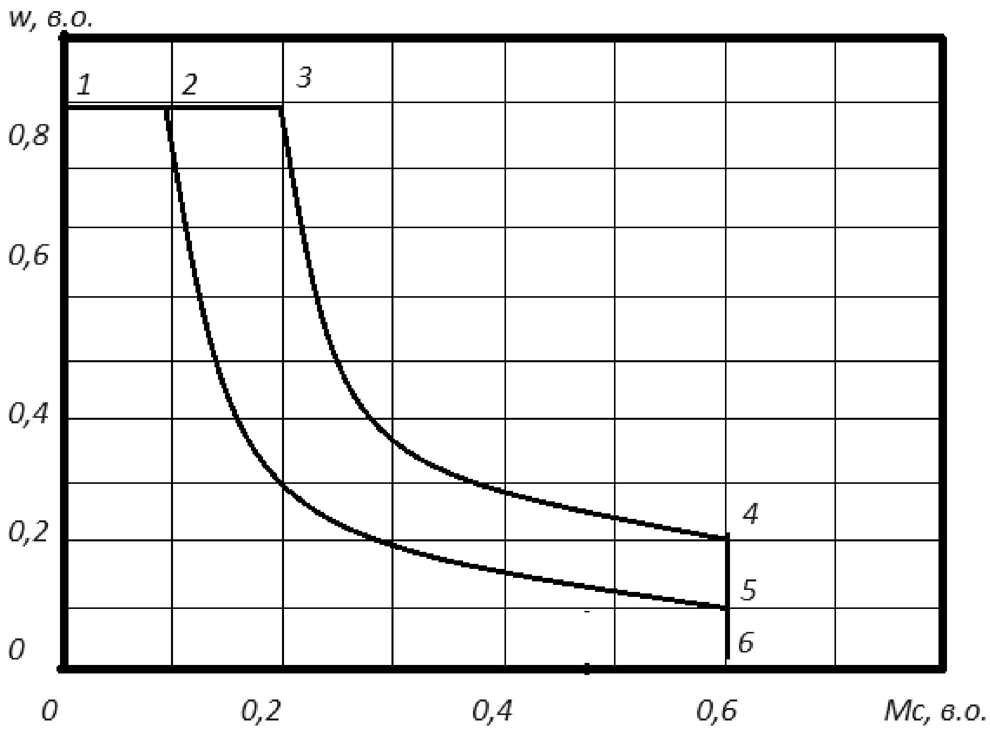

Fig. 2. Static mechanical characteristic of the drive system realized by the proposed method of controlling the drive systems for feeding and rotating the bit (*ω* – bit rotation frequency, M_c – resistance moment)

elimination of vibration vibrations during drilling is achieved by reducing the set fracture power. The static characteristics for the mode of operation with reduced fracture power in Fig. 2 are shown by the section 1–2–5–6.

Thus, based on using the energy criterion of bit stability, it can be concluded that the bit will have the greatest stability under a uniform energy load, i.e., when maintaining a linear increase in the energy of rock destruction or when maintaining a constant level of power released in the bit-head contact zone. The considered bit performance criterion summarizes the previously proposed criteria (bit penetration, bit service life, conditional bit wear), since it automatically takes into account the strength and abrasiveness of the rock being destroyed by the bit.

As a result of the analysis of the state of the roller cutter method of blast drilling and theoretical and experimental studies of ways to improve the drive systems of the drilling rig.

1) Currently, one of the main problems of open-pit mining in Ukraine is the physical and moral obsolescence of mining equipment, including drilling rigs. Therefore, modernization of the existing fleet and creation of a new generation of drilling rigs is an important scientific and applied problem, the successful solution of which determines the competitiveness of domestic mining production in the global market.

2) The teams of special design bureaus of the institutes of OJSC Novo-Kramatorsk Machine-Building Plant (Kramatorsk), OJSC KryvorizhNIPIrudmash, OJSC Kryvyi Rih Mining Engineering Plant (Kryvyi Rih) are engaged in the development of domestic ball drilling machines, which improve the mechanical and hydraulic equipment of the drilling rigs, but continue to use traditional thyristor drive systems with DC motors.

3) Along with the improvement of the hydromechanical equipment of the drilling rig, it is necessary to improve the drive systems, which must be in line with the level achieved in the global electrical industry. Only then can a competitive drilling rig be created.

4) In order to increase the stability of the roller cutter bit by maintaining the power flow in the bottom hole zone, a drilling process control method with control of the drives of the mechanisms of downhole operations, feeding and rotation was developed, which forms hard mechanical characteristics on the roller cutter bit when drilling in rocks with strength f≤10-13 according to the scale of Prof. M.M. Protodyakonov and soft mechanical characteristics in stronger rocks. When drilling intermixed rocks with different physical and mechanical properties, the control method provides automatic selection of mechanical characteristics depending on the rock strength.

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