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ИССЛЕДОВАНИЕ ЭНЕРГОЭФФЕКТИВНОГО УПРАВЛЯЕМОГО ЭЛЕКТРОМЕХАНИЧЕСКОГО РЕЗОНАНСА ДЛЯ ПРОЦЕССОВ РЕЗАНИЯ И РАЗРУШЕНИЯ ГОРНОГО МАССИВА

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Аннотация: Представлена математическая модель ТП-Д электропривода, адаптированная для исследования энергоэффективных резонансных режимов электромеханической системы органов резания горных машин. Энергоэффективность достигается за счет рационального закона движения органа резания с учетом динамического процесса резания, имеющего возвратно-вращательную траекторию координаты скорости в области контакта режущего инструмента с горным массивом. Такой процесс можно обеспечить за счет резонансного режима в электромеханической системе при использовании внешнего возмущающего воздействия. При совпадении частоты колебания внешнего возмущающего воздействия с частотой собственных колебаний электромеханической системы достигается резонансный режим функционирования. Система управления должна обеспечивать настройку на резонансную частоту и ограничивать амплитуду вынужденных колебаний тока и скорости электродвигателя. В качестве регулятора управляемого резонансного режима функционирования предложен ПИД-регулятор. Аналитические исследования посредством математической модели позволили получить зависимости частоты собственных колебаний электромеханической системы и коэффициента динамичности тока электродвигателя (амплитуды колебаний тока) от параметров регулятора, которые показали, что настройка на резонансную частоту достигается за счет дифференциальной части ПИД-регулятора. Ограничение амплитуды вынужденных колебаний тока возможно пропорциональной частью регулятора.

Ключевые слова: электромеханическая система, структура управления, энергоэффективный резонансный режим, пропорционально-интегрально-дифференциальный режим управления, коэффициенты динамичности по току и скорости, повышение производительности бурения.

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Development of energy-efficient controlled electromechanical resonance for processes of cutting and shattering of rock massif

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Abstract: Mathematical model of TP-D electric drive is presented. The model is adapted for investigation of energy-efficient resonant modes of electromechanical system of cutting body of mining

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machines. Energy saving is achieved at the cost of rational law of motion of cutting tool taking into account dynamic cutting process of having reverse rotational trajectory of velocity coordinate in the contact area of cutting tool with rock massif. Such a process can be provided by means of resonant mode in electromechanical system using external disturbances. Resonant mode of functioning is achieved at matching of oscillation frequency of external disturbances with natural oscillation frequency of electromechanical system. Control system must support adjustment on resonant frequency and restrain amplitude of forced oscillation of current and electric motor speed. PID controller was proposed .as regulator of controlled resonant mode of functioning. Analytical studies by means of mathematical model has allowed to obtain dependences of natural oscillation frequency of electromechanical system and dynamic response factor of electric motor current (amplitude of current oscillation) upon parameters of controller, which has shown that adjustment on resonant frequency is achieved by means of differential part of PID controller. Limitation of force oscillations of current is performed by proportional part of controller.

Key words: electromechanical system, control structure, energy-efficient resonant mode, proportional-integral-differential control mode, dynamic coefficient of current and speed, increase in performance of drilling.

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Introduction

The theory of controlled electromagnetic resonance is presented in [1—3, 6—10]. Basic concepts of the theory lie in the fact that electromechanical system is considered as object of regulation in which synthesis of mechanical and electrical resonance is implemented. It is proved theoretically that such electromechanical resonance provides energy-saving effect at operation of cutting tools of mining machinery and mechanisms. One more effect was fixed during pilot testing: increase in performance of mining machine with cutting body. This effect still has no theoretical validation.

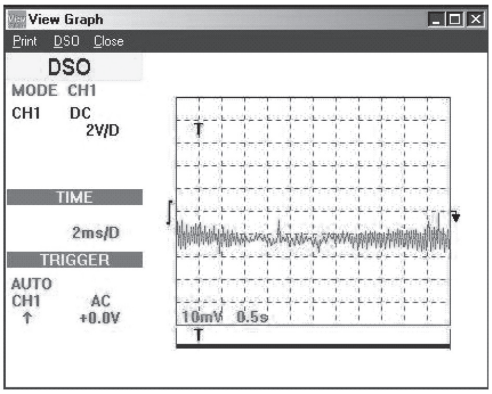

Fig. 1. Current response of electric motor at drilling by SBSh-250MN drill rig

Рис. 1. Токовая реакция электродвигателя при бурении станком СБШ-250МН

As is known resonance occurs in case of matching of natural oscillation frequency and frequencies of external disturbances [11—15]. This can be realized by two methods: by generation of control signal corresponding to natural oscillation frequency of electromechanical system or by adjustment of natural oscillation frequency to bottom reaction frequency. The second method is more practical, because the application of the first method requires usage of generator of control action with variable frequency, which complicates implementation of adjustment on resonant frequency. In further researches method of adjustment on resonant frequency by regulation of natural oscillation frequency of electromechanical system of cutting body which corresponds to frequency of bottom reaction (Fig. 1). During investigation of damping capabilities of electromechanical systems it was fixed that it's natural oscillation frequency depends upon transfer factor of flexible feedback on current. This

property was used for adjustment on resonant frequency.

Besides adjustment on resonant frequency it is necessary to restrict oscillation amplitude in resonant mode, because it can reach large values [4, 5]. The studies have shown that amplitude limitation can be achieved by means of direct feedback on speed of electromechanical system or current. Direct feedback on speed provides amplitude limitation in limited frequency band. There are no such limitations for direct feedback on current. Therefore, regulating system by electromechanical resonant mode contains flexible feedback on current and direct feedback on current.

Pilot testing of controlled electromechanical resonance were carried out at Lebedinsky MPP. The system was installed on electric drive of swivel head of SBSh-250MN drill rig. Test results has shown that throughput performance rised by 22%, power consumption reduced by 31.6%, and reduction of a power intensity was 46% at dynamic response factor of current equal to 1.4. Computer-Aided Process Control System of Lebedinsky MPP was used for recording of drilling indicators.

Main Part

Analysis of structure of resonance mode control of electromechanical system operation has shown that this structure can be significantly simplified if PID controller is used in place of flexible and direct feedback. In PID controller the proportional part (*P*) implements analogue of direct feedback, and the differentiating part (*D*) implements analogue of flexible feedback. The integrating part (*I*) of controller is redundant and is not used. At the same time, it is necessary to develop a theory of controlled electromechanical resonance when using PID controller.

Mathematical model of electromechanical system with control structure based on PID controller is written as (Fig. 2).

Mathematical model is adapted to electric motor of body of rock mass cutting and shattering. This body represents single-loop control system on motor electromagnetic torque on PID controller. Frequency converter has built-in PID controller. Estimation of control error as a result of that assumption is performed by means of computer simulation. To simplify derivation of analytical dependences, lets reduce spectrum of external disturbances from cutting body to fundamental ($\upsilon = 1$) harmonics. If necessary, the spectrum may be expanded and taken into account in final analytical dependences.

The following symbolic designations are used in mathematical model on Fig. 2: u_z — signal on electromagnetic torque; P — proportional part of controller; I/s — integral part of controller; sD — differentiating part of controller; u_y — control voltage of frequency converter; k_p — static coefficient of frequency converter; T_p — time constant of frequency converter; e_p — voltage of converting device; k_m — static transfer factor of motor electromagnetic torque; T_e — elect-

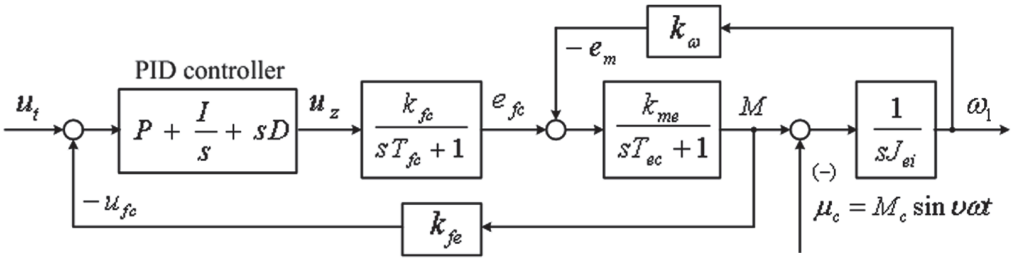

Fig. 2. Mathematical model of electromechanical system with control based on PID controller
Рис. 2. Математическая модель электромеханической системы с управлением на базе ПИД-регулятора

romagnetic time constant of «frequency converter — asynchronous electric motor» system; M — motor electromagnetic torque; J_{np} — equivalent moment of inertia in «motor — body of rock mass cutting and shattering»; ω_1 — phase rate of motor shaft; k_ω — transfer factor of self-feedback on motor EMF; e_ω — motor EMF; k_m — direct feed back factor on electromagnetic torque; u_{om} — feedback factor signal on electromagnetic torque; μ_c — static resistance torque in steady-state process mode at external disturbance; M_c — amplitude of static resistance torque; ω — pulsatance of external disturbance oscillations.

Transformations of structure of mathematical model presented in Fig. 2 has shown that transfer function

$$\frac{M(S)}{\mu(S)} = \frac{1}{s^2\left(kT_\mu D + T_e T_\mu\right) + s\left(kT_\mu P\right) + \left(kT_\mu + 1\right)}, \quad (1)$$

where $k = k_p k_m k_{om}$ — parameter of feedback on electromagnetic torque; $T\mu$ — electromechanical time constant.

On the basis of transfer function (1), second-order differential equation is obtained

$$\left[s^2\left(kT_\mu D + T_e T_\mu\right) + s\left(kT_\mu P + T_\mu\right) + \left(kT_\mu I + 1\right)\right]M = H_\mu \sin\omega t, \quad (2)$$

where $H_\mu = M_c$ — static offset on motor torque.

Solution of differential equation (2) is found in the form:

$$tg\varepsilon_\mu = \frac{2n\omega\left(kP+1\right)}{\left[\Omega^2 - \omega^2\left(2nkD+1\right)\right] + 2nkI} \quad (3)$$

$$k_{d.\mu} = \frac{A_\mu}{H_\mu} = \frac{\Omega^2}{\sqrt{\left[\Omega^2 - \omega^2\left(2nkD+1\right) + 2nkI\right]^2 + \left[2n\omega\left(kP+1\right)\right]^2}}, \quad (4)$$

where ε_μ — phase shift angle of forced oscillations of electromagnetic torque with respect to phase of disturbing oscillations; $k_{d.\mu}$ — dynamic response factor on motor electromagnetic torque of electromechanical system; A_μ — amplitude of forced oscillations of motor electromagnetic torque; n — damping coefficient; Ω — pulsatance of natural oscillation frequency of electromechanical system.

As was validated in [1], energy-efficient operation mode of electromechanical system of body of rock mass cutting and shattering depends on dynamic response factor of electromagnetic torque (current) of electric motor. At that it is ascertained that dependence of electric motor power consumption is in inverse proportion to dynamic response factor of electromagnetic torque.

Resonance of electromechanical system occurs at the fulfillment of the condition:

$$\Omega = \omega\sqrt{2nkD+1}\,. \quad (5)$$

For provision of resonant mode, it is required to bring to equality value of natural oscillation frequency and value of force oscillations frequency by means of adjustment of PID controller. In this case expression (5) is written as

$$\omega = \nu = \frac{\Omega}{\sqrt{2nkD+1}}\,. \quad (6)$$

where ν — adjusted value of pulsatance of natural oscillation frequency.

In accordance with (6), differentiating part of PID controller is calculated using formula

$$D = \frac{\Omega^2 - \omega^2}{2nk\omega^2}\,. \quad (7)$$

For resonant mode, we get:

• tangent of phase shift angle of forced oscillations with respect to disturbing oscillations, according to (3),

$$tg\varepsilon_{\mu} = \frac{\omega(kP+1)}{kI}; \tag{8}$$

• dynamic response factor of motor electromagnetic torque according to (4)

$$k_{d.\mu} = \frac{\omega^2(2nkD+1)}{2n\sqrt{k^2I^2+\omega^2(kP+1)^2}}, \tag{9}$$

where ω — resonant pulsatance of external disturbances.

For limitation of amplitude of forced oscillations of electromagnetic torque in resonant mode, analysis of dynamic response factor of this electric drive coordinate on expression (9) is required. As was found in [1], dynamic response factor of current (electromagnetic torque) for energy-efficient mode lies within the range of $k_{rez.\mu}$ = 1,1 — 1,4. At larger values of dynamic response factor, a threat of disruption of kinematic chains of electromechanical system arises.

Analysis of expression (9) shows, that limitation of amplitude and, therefore, of dynamic response factor of electromagnetic torque is possible by one of two adjustment methods. These are adjustment of proportional or integral parts of PID controller.

If adjustment of proportional part of PID controller (I = 0) is applied, then parameter of adjustment is determined in accordance with (9):

$$P = \frac{\omega(2nkD+1) - 2nk_{t.rez.\mu}}{2nkk_{t.rez.\mu}}, \tag{10}$$

where $k_{t.rez.\mu}$ — given value of dynamic response factor of electromagnetic torque of motor in resonant mode.

Integral part of PID controller is redundant on condition limitation of forced oscillations limitation, therefore at controller adjustment it is accepted that I = 0.

Analysis of expression (10) shows that adjustment of proportional part of controller is restricted. For normal operation of PID controller, it is required, that adjustment parameter has positive value. Do this requires observance of inequality

$$\omega(2nkD+1) > 2nk_{t.rez.\mu}.$$

Analysis of expression of phase shift angle of forced oscillations with respect to phase of disturbing oscillations (8) shows that it does not influence energy efficiency, as in the case of study of behavior of electric motor speed in resonant mode.

In result of transformations of structure of mathematical model shown in Fig. 2, we get transfer function of motor speed on static torque without including integral part of controller

$$\frac{\omega_1(s)}{\mu_c(s)} = \frac{1/k_m k_{\omega}\left[s(kD+T_e)+(kP+1)\right]}{s^2\left(kT_{\mu}D+T_eT_{\mu}+s(kP+1)T_{\mu}+1\right)} \tag{11}$$

On the basis of transfer function (11), we get second-order differential equation

$$\left[s^2\left(kT_{\mu}D+T_eT_{\mu}\right)+s(kP+1)T_{\mu}+1\right]\omega_1 = H_{\omega}\sin\omega t, \tag{12}$$

where $H_{\omega} = M_c/k_m k_{\omega}$ — static offset on motor speed.

Solution of differential equation (12) we seek for dynamic response factor of electric motor speed:

$$k_{d.\omega} = \frac{A_\omega}{H_\omega} = \frac{\sqrt{\omega^2\left(T_\mu\Omega^2 kD+1\right)^2 + T_\mu^2\Omega^4\left(kP+1\right)^2}}{T_\mu\sqrt{\left[\Omega^2-\omega^2\left(2nkD+1\right)\right]^2 + 4n^2\omega^2\left(kP+1\right)^2}} \quad (13)$$

where A_ω — amplitude of electric motor speed.

Since value angle shift of phase of forced oscillations of motor speed with respect to phase of disturbing oscillations does not affect adjustment of controller, providing energy-efficient operation of electromechanical system, then derivation of that entity is omitted.

Resonance of electromechanical system takes place upon condition, that is at change of natural oscillation frequency of electromechanical system due to impact of control system. Modified natural oscillation frequency is determined by (5).

In this case, resonance occurs at $\omega = \nu$, that is numerical value of external disturbance should match to frequency determined by (6). So it is required, in accordance with (11), that value of differential part of PID controller was calculated by formula (7).

For resonant mode, dynamic response factor of motor speed is equal, according to (13), to

$$k_{rez.\omega} = \frac{\sqrt{\omega^2\left(T_\mu\Omega^2 kD+1\right)^2 + T_\mu^2\Omega^4\left(kP+1\right)^2}}{2nT_\mu\left(kP+1\right)}. \quad (14)$$

Adjustment to resonant frequency is performed by implementation of relation (5), and limitation of amplitude of forced oscillations is performed by implementation of condition (10). Therefore, dynamic response factor of motor speed in resonant mode determined by (14), is not controllable and depends upon given parameters of energy efficiency of processes of rock mass cutting and shattering.

Let's carry out verification of received theoretical relations by their comparison with experimental data recorded at simulation on the basis of MatLab/Simulink application program package. Comparison is carried out for open-loop and closed-loop control systems for electromechanical resonance. For open-loop control systems we consider $D = 0$, $I = 0$ и $P = 0$. The results of comparative study are presented in the form of characteristic curves in Fig. 3 and Fig. 4.

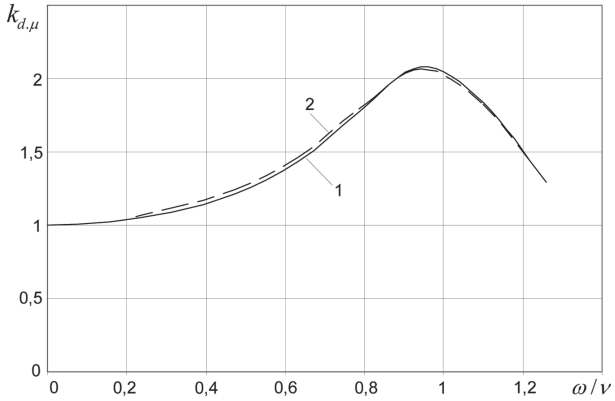

Fig. 3. Characteristic curve «dynamic response factor of electromagnetic torque — vs — pulsatance of external disturbances» for open-loop system: 1 — theoretical; 2 — experimental

Рис. 3. Графическая зависимость коэффициента динамичности электромагнитного момента от угловой частоты внешних возмущающих воздействий для разомкнутой системы: 1 — теоретическая; 2 — экспериментальная

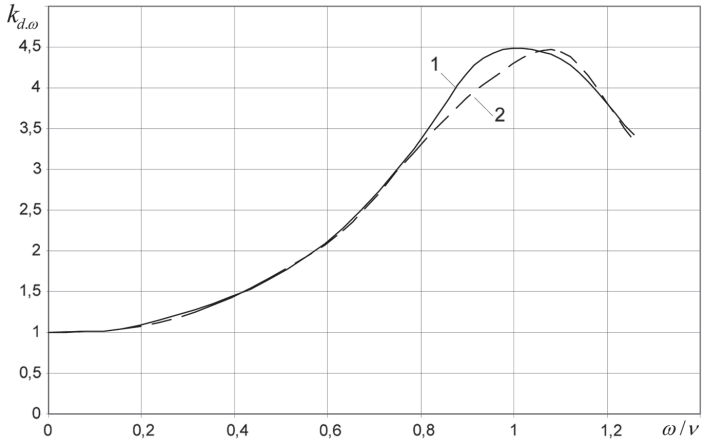

Fig. 4. Characteristic curve «dynamic response factor of motor speed — vs — pulsatance of external disturbances» for open-loop system: 1 — theoretical; 2 — experimental

Рис. 4. Графическая зависимость коэффициента динамичности скорости двигателя от угловой частоты внешних возмущающих воздействий для разомкнутой системы: 1 — теоретическая; 2 — экспериментальная

As is seen from graphical dependences of dynamic response factor of motor electromagnetic torque (Fig. 3) and motor speed (Fig. 4) upon pulsatance of external disturbances, extreme value of a function is shifted with respect to resonant frequency ($\omega/\nu = 1$). This fact corresponds to oscillation theory.

Graphical dependences of dynamic response factors of electromagnetic torque and motor speed upon pulsatance of external disturbances for closed-loop system are presented in Fig. 5 and Fig. 6, correspondingly. As is seen from graphical dependences in Fig. 5, the difference of theoretical and experimentasl values of dynamic response factor of motor electromagnetic torque. The difference at resonant frequency ($\omega/\nu = 1$) amounts to 13%, which is permissible for engineering calculations.

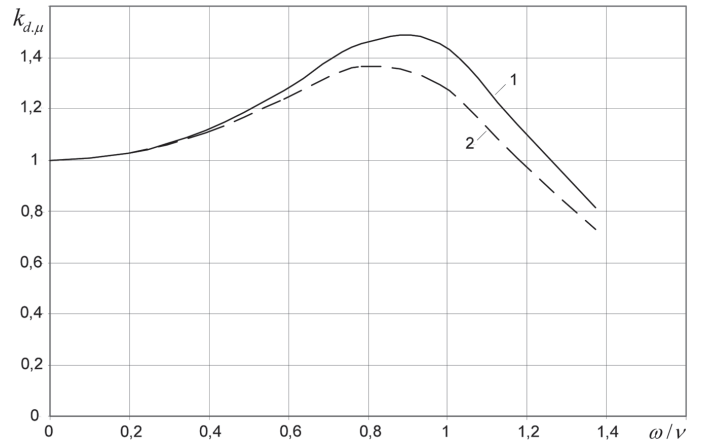

Fig. 5. Characteristic curve «dynamic response factor of electromagnetic torque — vs — pulsatance of external disturbances» for closed-loop system: 1 — theoretical; 2 — experimental

Рис. 5. Графическая зависимость коэффициента динамичности электромагнитного момента от угловой частоты внешних возмущающих воздействий для замкнутой системы: 1 — теоретическая; 2 — экспериментальная

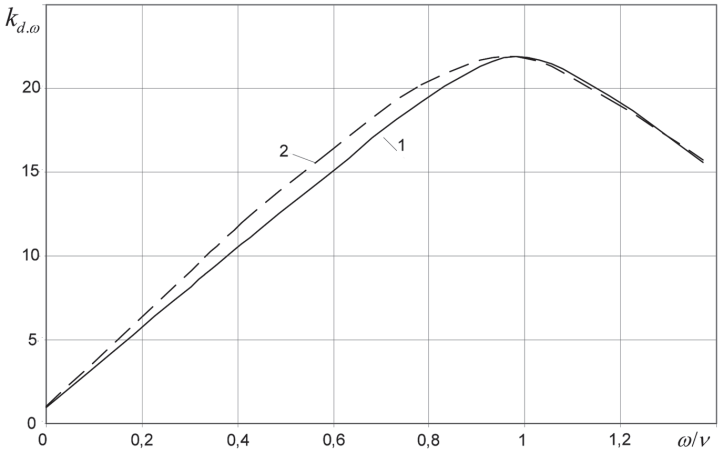

Fig. 6. Characteristic curve «dynamic response factor of motor speed — vs — pulsatance of external disturbances» for closed-loop system: 1 — theoretical; 2 — experimental

Рис. 6. Графическая зависимость коэффициента динамичности скорости двигателя от угловой частоты внешних возмущающих воздействий для замкнутой системы: 1 — теоретическая; 2 — экспериментальная

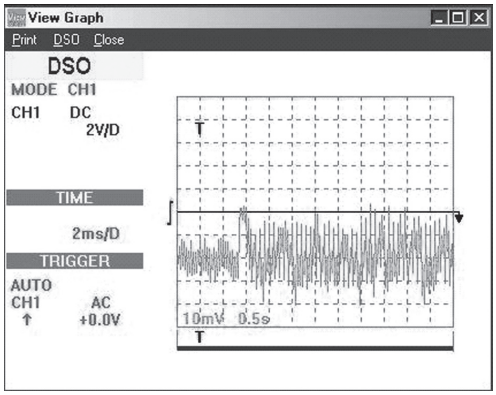

Fig. 7. Oscillogram of electric motor current (electromagnetic torque) during transition from normal mode tor resonant mode

Рис. 7. Осциллограмма тока (электромагнитного момента) электродвигателя при переходе от нормального режима к резонансному

As is seen from experimental graphical dependence dynamic response factor of motor speed upon pulsatance of external disturbances, there is a close agreement with theoretical data in the area of resonant frequency ($\omega/\nu = 1$).

It is noteworthy approximately 5-time-increased value of dynamic response factor of motor speed for closed-loop system (Fig. 5) in comparison with open-loop control system (Fig. 4).

Increase of motor speed stipulates increase in productivity of electromechanical system in resonant mode. This fact was found in pilot testing on Lebedinskiy MPP. Nevertheless, this aspect requires further theoretical evidences.

When performing pilot testing control systems for electromechanical resonance on Lebedinskiy MPP, oscillograms of resonant mode (Fig. 7) were received. Differences between theoretical and experimental data were determined on the basis of these oscillograms — they amounted to 11%.

Conclusion

Development of theory of controlled electromagnetic resonance showed expediency of usage of proposed method of energy-efficient shattering of rock massif by means of electromechanical systems with cutting bodies. This method is classified as groundbreaking technology in the field of mining, provides opportunities for increase of throughput performance of mining machinery and mechanisms, boosts energy efficiency of drilling processes.

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РАЗРАБОТКА И ЭКСПЛУАТАЦИЯ ГОРНЫХ МАШИН И ОБОРУДОВАНИЯ В УСЛОВИЯХ ГОРНО-ОБОГАТИТЕЛЬНОГО ПРОИЗВОДСТВА

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Рассмотрены вопросы эксплуатация водоотливных установок в условиях шахт и рудников. Перекачивание вод с содержанием абразивных примесей руд и горных пород приводит к гидроабразивному износу деталей проточной части и уплотнений центробежных насосов, а значит, к росту радиальных зазоров и объемным утечкам через них. При дальнейшей работе в этих условиях происходит снижение подачи, напора и КПД насосов, что снижает энергетические характеристики водоотлива и ведет к угрозе затопления шахт и рудников. При технико-экономическом анализе работы водоотливной установки с утечками приходится решать задачи по определению влияния объемных утечек на величину удельного расхода электроэнергии насосной установкой при откачивании воды из шахты на поверхность и определению потерь электроэнергии. С ростом стоимости электро-энергии появляется острая потребность разработки новых энергоэффективных технологий шахтного водоотлива, например, применение высокооборотных насосов. Стоимость жизненного цикла комплексов шахтного водоотлива следует определять по структурным составляющим. В первую очередь необходимо оценить стоимость жизненного цикла ЦНС как наиболее энергоемкого элемента комплекса. Проведена сравнительная оценка ремонтопригодности существующих центробежных секционных однопоточных насосов типа ЦНС и разрабатываемых двухпоточных насосов типа ЦНСД. Оценка ведется относительно наличия разгрузочного устройства в насосах ЦНС и его отсутствия в насосах ЦНСД. В ряде работ разработан принцип имитационного моделирования при расчете предельно допустимых отклонений трасс скважин от проекта. Использование описанной методики в комплексе с программой расчета трассы «снизу-вверх» и затрат на бурение по данному варианту трассы дает возможность осуществлять выбор рациональных углов скважин в точке подсечения на основе обеспечения допустимого уровня погрешности и минимума соответствующих затрат.

DEVELOPMENT AND OPERATION OF MINING MACHINERY AND EQUIPMENT IN THE CONDITIONS OF MINING AND PROCESSING PRODUCTION

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The issues of operation of drainage systems in mines and mines. Pumping water containing abrasive constituents of ores and rocks leads to hydroabrasive wear of wetted parts and seals of centrifugal pumps and hence an increase in the radial gaps and volume leaks through them. Further operation under these conditions reduces the supply, pressure and efficiency of pumps, which reduces the energy characteristics of drainage and leads to the threat of flooding of mines and mines. In the technical and economic analysis of the drainage system with leaks have to solve the problem of determining the effect of volume leaks on the value of the specific electricity consumption of the pumping unit when pumping water from the mine to the surface and determine the loss of electricity. With the increase in the cost of electricity, there is an urgent need to develop new energy-efficient technologies for mine drainage, for example, the use of high-speed pumps. The cost of the life cycle of mine drainage systems should be determined by the structural components. First of all, it is necessary to assess the cost of the life cycle of the Central nervous system as the most energy-intensive element of the complex. Comparative evaluation of the maintainability of existing single-threaded centrifugal sectional pumps CNS and develop two in-line pumps SNSD. The assessment is conducted regarding the presence of the discharge device in the pumps of the Central nervous system and its absence in the pumps of the Central NERVOUS system. A number of works have developed the principle of simulation when calculating the maximum permissible deviations of well tracks from the project. Using the described technique in conjunction with the program calculating the route bottom-up and drilling costs on the route option enables the choice of rational angles of the wells at the point of podsahania on the basis of ensuring the acceptable level of error and low costs.

НАУЧНО-МЕТОДИЧЕСКОЕ ОБЕСПЕЧЕНИЕ ОПТИМАЛЬНОГО ПРОЕКТИРОВАНИЯ ТЕХНОЛОГИЧЕСКИХ СИСТЕМ ГОРНОДОБЫВАЮЩИХ ПРЕДПРИЯТИЙ

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Представлены результаты аналитических исследований в области развития научно-методической базы обеспечения оптимального проектирования и обоснования основных проектных решений технологических систем горнодобывающих предприятий. С учетом анализа прикладных и теоретических исследований в сфере горной науки показано, что немалая роль в этой области отводится и аспекту создания высокоэффективных и прогрессивных технологических схем горнодобывающих предприятий, адаптированных для функционирования в рыночных условиях с учетом сложившихся тенденций и закономерностей. В настоящее время основу методологии проектирования горнодобывающих предприятий должны составлять линейные и нелинейные дискретные экономико-математические модели, которые реализуются с помощью одного или нескольких методов, например, комплексной оптимизации, имитационного моделирования, прогнозирования, теории и приложений нечетких множеств, когнитивных и динамических алгоритмов, анализа и параметрического синтеза стохастических систем, гибридных методов моделирования общего экономического равновесия с использованием агент-ориентированных моделей, энтропийного анализа сложных систем, структурного системного анализа IDEFO и др.

SCIENTIFIC AND METHODOLOGICAL SUPPORT OF OPTIMAL DESIGN OF TECHNOLOGICAL SYSTEMS OF MINING ENTERPRISES

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The results of analytical researches in the field of development of scientific and methodical base of providing optimum design and justification of the basic design decisions of technological systems of mining enterprises are presented. Taking into account the analysis of applied and theoretical research in the field of mining science, it is shown that a significant role in this area is given to the aspect of creating highly efficient and progressive technological schemes of mining enterprises, adapted to operate in market conditions, taking into account the current trends and patterns. Currently, the basis of the methodology of design of mining enterprises should be linear and nonlinear discrete economic and mathematical models, which are implemented using one or more methods, for example, complex optimization, simulation, forecasting, theory and applications of fuzzy sets, cognitive and dynamic algorithms, analysis and parametric synthesis of stochastic systems, hybrid methods of modeling General economic equilibrium using agent-oriented models, entropy analysis of complex systems, structural system analysis IDEFO et al.