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Mathematical Model of the Dynamics of the Armament of the Tricone Drill Bit

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ABSTRACT
This study presents a mathematical model of the dynamics of tricone drill bits, which remain widely used in open-pit mining due to their reliability and versatility. Despite their extensive application, improving their efficiency and durability remains a relevant issue. The main operational challenges are identified, including insufficient knowledge of the stress–strain state of rocks in the contact zone and the effect of tooth geometry on kinematics and rock-breaking efficiency. Analytical dependencies are proposed to account for bit geometry, trajectory motion, transmission ratios, and tooth–rock interaction. Based on the principles of theoretical mechanics, performance criteria are formulated through specific contact and volumetric work of rock destruction, enabling an objective assessment of energy consumption. The model demonstrates the potential of analytical methods for optimizing drill bit design and kinematics, reducing energy consumption, increasing productivity, and extending tool life. The results can be applied in the design of next-generation drill bits and in engineering software for selecting rational drilling parameters under specific geological conditions. The proposed approach provides a foundation for further studies in mathematical modeling of rock destruction dynamics and the advancement of open-pit mining technologies.

Keywords: rock, drilling, drill bit, kinematics, work, design, model, equation.

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Indroduction

In global open-pit mining practice, well drilling is mainly performed using roller bits, which are the key tools in this production process. This type of work is characterized by high labor intensity and high costs. At the same time, about 80-85% of all drilling operations are carried out using three-cone bits. Drilling accounts for 25-40% of the total cost of production, therefore, the tasks of increasing the service life of bits and reducing the costs of their use are of paramount importance [1].

Despite the accumulated experience in the field of design and operation of roller bits, many aspects of their operation have not been fully studied. In particular, questions remain open regarding the stress-strain state of the rock in the contact zone with the teeth, an accurate description of the dynamics of the interaction of the rollers with the rock, as well as taking into account the forces of penetration of the rock-destroying tool when determining the kinematic parameters. Existing approaches are often empirical in nature and do not allow for a full consideration of the influence of the geometric parameters of the teeth on the efficiency of rock destruction [2].

The modern development of drilling theory and tool design requires a transition to mathematical models that allow the real dynamics of the interaction between the drill bit structure and the rock to be described. This approach provides not only a fundamental understanding of the destruction process, but also the ability to optimize the design of drill bits for specific operating conditions.

In the conditions of the mining industry of Uzbekistan, where large-scale open-pit mining is carried out, the issues of improving the design and increasing the durability of drill bits are of particular importance. The use of mathematical modeling allows solving the problems of optimizing the structure of roller cutters, choosing rational drilling modes and developing new tools that can reduce costs and increase the reliability of the production process.

However, to date, the stress–strain state of rocks in contact with the working parts of drill bits, as well as the dynamics of roller drilling tools and the modeling of their interaction, have not been fully investigated. There are unresolved problems due to the failure to take into account the forces of penetration of the teeth of the rock-cutting tool into the rock when determining the kinematic parameters of the drill bits [3].

The purpose of this work is to develop and analyze a mathematical model of the dynamics of three-cone drill bits, taking into account the geometric parameters of their weapons, gear ratios, and features of the trajectories of the teeth. Based on the model, criteria for the tool's performance are formed, allowing not only to evaluate its effectiveness, but also to use the obtained results in the design and implementation of new designs of drill bits [4].

Materials

The main objective of the studies described in this and the following chapters is to establish the relationship between the obtained criteria for assessing the performance of the roller cutter structure and the classical criterion for the cost of drilling per linear meter, known as the Bingham criterion [5]. It should be noted that the kinematic criteria in the form of relatively specific contact work and volumetric destruction work were obtained on a deterministic basis. We need to determine the possibilities of efficient manufacturing of such structures in the conditions of Uzbekistan.

Today, the goal of increasing the efficiency of three-cone bits is viewed through optimization of the process of rock destruction during drilling. This requires a corresponding mathematical model that describes the mechanism of interaction of the cutting tool adequately to their real dynamics in the well bottom [6].

Rock destruction by drilling bits can be assessed by determining two parameters, such as specific contact and specific volumetric work of destruction, and are presented as follows [7]:

$$A_s = \frac{A_{gen}}{S}, \tag{1}$$

where: A_s - specific contact work of destruction, kgs.mm/mm^2;

A_{gen} - total work expended on deformation and destruction of rock when pressing the stamp, kgs.mm;

S - area of the flat base of a cylindrical stamp, mm^2;

$$A_v = \frac{A_{gen}}{V}, \tag{2}$$

where: A_v - specific volumetric work of destruction, kgs.mm/mm^3;

V - volume of deformed rock, mm^3.

Next, it is necessary to show that the criteria for specific contact work and volumetric destruction work are functions of the geometric parameters of drill bits, by varying which it is possible to solve optimization problems to improve the dynamics of tricone bit armament [8].

How the criteria for specific contact work and volumetric destruction work depend on the geometric parameters of the bit is easiest to trace in the process of constructing their analytical structures. All this is based on the method for calculating the main parameter of these criteria - the contact path of the teeth of the roller cutters at a given depth of their immersion in the rock [9].

To calculate the technological criteria for the performance of three-cone bits, it is necessary to construct two-parameter equations of the trajectories of the movement of the tooth tip of the roller cutter in the form [10]:

$$\left.\begin{aligned} x &= x(G, \varphi, \psi) \\ y &= y(G, \varphi, \psi) \\ z &= z(G, \varphi, \psi) \end{aligned}\right\}, \tag{3}$$

or

$$\left. \begin{aligned} x &= R\sin\varphi - r\sin\psi\cos\varphi - r(1-\cos\psi)\sin\varphi\cos\alpha, \\ y &= R\cos\varphi + r\sin\psi\sin\varphi - r(1-\cos\psi)\cos\varphi\cos\alpha, \\ z &= r(1 \quad \cos\psi)\sin\alpha; \end{aligned} \right\}, \tag{4}$$

where Γ is a set of geometric parameters, and ϕ and ψ are the angles of rotation of the bit and roller around their axes.

R is the radius of the circle at the bottom of the well along which the crown rolls, mm;

r is the radius of the crown, mm;

α is the angle of inclination of the plane of the crown to the plane of the cross section of the well, deg.;

Next, we consider the transformations of two-parameter equations (3) to one-parameter ones

$$\left. \begin{aligned} x &= x(G, i, \psi) \\ y &= y(G, i, \psi) \\ z &= z(G, i, \psi) \end{aligned} \right\} \tag{5}$$

The gear ratio of the roller cutter i, which determines how many revolutions the roller cutter will make around its axis in one revolution of the bit, can be calculated using a special method [11].

The transformation of two-parameter equations of motion trajectories in the form (5) to one-parameter equations is carried out by substituting [12]:

$$\varphi = \frac{\psi}{i}, \tag{6}$$

where *i* - gear ratio of the bit. Then we have:

$$\left. \begin{aligned} x_j &= R_j \sin\frac{\ }{i} - r_j \sin\psi \cos\left(\frac{\psi}{i} - \ _j\right), \\ y_j &= R_j \cos\frac{\psi}{i} + r_j \sin\psi \sin\left(\frac{\psi}{i} - \ _j\right), \\ z_j &= r_j(1 \quad \cos\psi). \end{aligned} \right\}, \tag{7}$$

where R_j, r_j, *and i* - constant parameters that determine the external appearance (geometry) of a tricone drill bit;

ψ – variable parameter.

On the basis of theoretical mechanics, it is possible to construct analytical structures of dynamic criteria for assessing the performance of three-cone bits [13].

The speed of movement of the teeth of the drill bit rollers must be integrated and have the form of a function of the parameter *ψ*.

Let's find it using the well-known formula of theoretical mechanics [14]

$$V(\psi) = \sqrt{\left(\frac{dx}{\psi}\right)^2 + \left(\frac{dy}{d\psi}\right)^2 + \left(\frac{dz}{d\psi}\right)^2} \tag{8}$$

Further

$$V(\psi) = \sqrt{A_j + B_j \cos\psi + C_j \sin\psi + D\cos^2\psi}, \tag{9}$$

Where:

$$A_j = \frac{R_j^2 + r_j^2}{i^2} + r_j^2,$$
$$B_j = -\frac{2R_j r_j}{i}\cos\gamma,$$
$$C_j = \frac{2R_j r_j}{i}\sin\gamma,$$
$$D_j = -\frac{r_j^2}{i^2},$$
$$\gamma_j = \arcsin\left(\frac{k}{R_j}\right). \ .$$

Here, it should be noted that the offset angle γ_j refers to the *j*-th crown, and is determined through the magnitude of the offset of the roller cutter axis in the plan *k* and through the radius of the circle at the well bottom R_j, along which this crown rolls.

Expressions for calculating the path of contact of a roller cutter tooth with displaced axes of rotation in the plan are found using the well-known formula of theoretical mechanics:

$$S = \int_{\psi_0}^{\psi_1} V(\psi)\, d\psi, \tag{10}$$

where: ψ_0 and ψ_1, respectively, the lower and upper limits of integration, depending on a given or certain depth of immersion of the contact paths into the rock.

The expression we are looking for is:

$$S_j = \int_0^{\psi_j} V_j(\psi)\, d\psi + \int_{2\pi-\psi_j}^{2\pi} V_j(\psi)\, d\psi \tag{11}$$

Where is $\psi_j = \arccos\left(1 \quad \frac{H_j}{r_j \sin\alpha}\right);$

$H_j = h_j$ - calculated height on the toroid belt if the crown is in contact with the rock on the periphery, mm;

$H_j = \delta_j$ - Specified height of the trajectory on the toroid belt, if the crown contacts the face not on the periphery, mm.

Here it is necessary to consider two cases of assigning the limits of integration:

1. If the *j-th* crown is not rolled on the periphery of the face, then

2.
$$S_j = \int_0^{\psi_{j(\delta)}} V_j(\psi)d\psi + \int_{2\pi-\psi_j(\delta)}^{2\pi} V_j(\psi)d\psi \quad (12)$$

3. If the crown is peripheral (first, calibrating), then

4.
$$S_j = \int_0^{\psi_{j(\delta)}} V_j(\psi)d\psi + \int_{2\pi-\psi_j(h)}^{2\pi} V_j(\psi)d\psi\,. \quad (13)$$

In general, the integration of the contact paths of the teeth of the cutters with the offset axes of rotation in the plan is since the contact and contact paths are not equal to the contact paths of the exit from the contact, even with equal values of their immersion in the rock.

Results

Next, let's look at the calculation of the cutter ratio of a tricone drill bit *i*, which is the main parameter for calculating contact paths when embedded in rock. The gear ratio of the cutters can be determined by the ratio of the radius of the net rolling ring r_0 and the radius of the circle at the bottom of the hole along which it rolls R_0 in the form:

$$\frac{R_0}{r_0} = i = \frac{\psi}{\varphi} \quad (14)$$

To determine the performance assessment of tricone drill bits, the following criteria should be considered:

- analytical structure of the criteria;
- The physical meaning of the criteria;
- Possibilities of Criteria for Evaluating the Performance of Tricone Bits in Solving Optimization Problems.

Criteria (1) and (2) are objective energy criteria for the static destruction of rock under a stamp in the study of the physical and mechanical properties of rocks [[16], [17]].

Energy criteria for the physical and mechanical properties of rocks during their static fracture are the criteria for assessing the performance of drill bits in the form of relative specific contact and volumetric fracture work, the analytical structure of which is presented below in the formulas.

It is proposed to take the following functional dependencies as criteria for assessing the performance of drilling tricone bits:

$$A'_{q,j} = \frac{F_{q,j} i}{3 \cdot \Delta S} T_{q,j} I_{q,j} \sin 2\psi + \frac{I_{q\,j}}{2} \sin 4\psi\,, \quad (15)$$

$$A''_{q,j} = \sum_{q=1}^{3} \frac{\left(\frac{h}{d}\left(cos\left(\frac{\theta}{2}-\beta\right)\frac{a}{b}\right)\right)\left(Fz_{q,j} i_q\right)}{3\left(2\pi R_{q,j} D_{q,j}\left(r_t - \sqrt{r_t^2 - \frac{Pax}{\pi p_h(1+tg\varsigma)}}\right)\right)} T_{q,j} I_{q,j}\, sin\, 2\,\psi + \frac{I_{q,j}}{2} sin\, 4\,\psi, \quad (16)$$

Where is

$$T_{q,j} = 4 \cdot \left[\frac{1}{i_q^2} \left\{ \left(R_{q,j} - 2r_{q,j} \cos\gamma_{q,j} \cos\alpha \right) + r_{q,j}^2 \left[\cos\alpha \left(\cos\alpha - 2i_q \right) + (1+j) \right] \right\} \right] +$$

$$+2 \cdot \left[\frac{2r_{q,j}}{i_q^2} \left(r_{q,j} \cos\alpha - R_{q,j} \cos\gamma_{q,j} \right) \left(i_q - \cos\alpha \right) \right] +$$

$$+2 \cdot \left[\frac{2R_{q,j} r_{q,j}}{q} \left(r_{q,j} \cos\alpha - R_{q,j} \cos\gamma_{q,j} \right) \left(i_q - \cos\alpha \right) \right] - \left(\frac{r_{q,j}^2}{i_q^2} \sin^2\alpha \right);$$

$$I_{q,j} = \frac{1}{2} \left(\begin{array}{l} 8 \cdot \left[\frac{1}{i_q^2} \left\{ \left(R_{q,j} - 2r_{q,j} \cos\gamma_{q,j} \cos\alpha \right) + r_{q,j}^2 \left[\cos\alpha \left(\cos\alpha - 2i_q \right) + (1+j) \right] \right\} \right] - \\ -8 \cdot \left[\frac{2R_{q,j} r_{q,j}}{{}^{2}_{q}} \left(r_{q,j} \cos\alpha - R_{q,j} \cos\gamma_{q,j} \right) \left(i_q - \cos\alpha \right) \right] - 3 \cdot \left(\frac{r_{q,j}^2}{i_q} \sin^2\alpha \right) \end{array} \right);$$

q, j – The index that determines the number of the cutter and the number of the crown;

R – Crown rolling radius at the bottom of the well, mm;

r –radius of crown, mm;

i – drill bit gear ratio;

α – Corner of the Axis of cone bits, deg;

$\gamma = \arcsin\left(\frac{K}{R}\right)$ – offset angle, deg;

ψ – variable parameter of the cone bit, deg;

β – Tooth sharpening angle, deg;

ϑ – Angle of inclination of the axis of the crown, deg;

a – Tooth cross-section length, mm;

b – Tooth cross-section width, mm;

F – Tooth movement resistance force, N;

z – Number of teeth, pcs;

P_{ax} – Axial load on the tooth, kN;

P_h – Rock hardness, Pa;

ς - Angle of internal friction, deg;

r_t – radius of the cutting part of the tooth, mm.

The assessment of the performance of drill bits is the kinematic parameters, for the kinematic passport of the tricone bit, tabular and graphic forms are presented [18,19,20].

Without the use of computer technology, calculations and analysis of the dynamics of tricone bit armament based on these formulas are ineffective [21].

Discussion

As can be seen, formulas (15) and (16) show the set of geometric parameters of drill bits.

The implicit dependence of these criteria lies in the specified value of insertion (immersion) of the teeth of the cutters into the rock. This dependence is associated with the geometric parameters of the drill bits, on the shape of the teeth, on the energy parameters transmitted to the teeth, on the physical and mechanical properties of rocks in certain conditions (constrained, lightweight) at the bottom of the well, i.e.:

$$\delta = \delta(D, P, E). \quad (17)$$

To date, this function has not been built in an explicit form. But this fact is not an obstacle for studying the performance of tricone bits under other equal conditions, i.e., at a given value of tooth insertion. At the same time, we also know the limits of change in this value

$$0 \le \delta \le h_t, \quad (18)$$

where: h_t - the height of the tooth departure from the body of the ball, mm.

Thus, it can be argued that the criteria for assessing the performance of tricone bits in the form (15) and (16) are functions of the triad: bit – rock – energy.

The physical essence of kinematic criteria and their obvious dependence on the geometric parameters of drill bits serve as an objective basis for the development of a methodology for improving the dynamics of new structures and their modifications.

Conclusion

The conducted research has resulted in the development of a mathematical model describing the dynamics of the armament of tricone drill bits, taking into account their geometric parameters, gear ratios, and the kinematics of tooth movement in the rock contact zone. Analytical dependencies have been obtained that make it possible to quantitatively assess the specific contact and volumetric work of rock destruction, which serve as objective criteria for evaluating drilling efficiency.

The proposed model provides a theoretical framework for determining the relationship between the structural parameters of drill bits and their operational performance, thereby enabling optimization of bit geometry and operating modes under various geological conditions. The results demonstrate that improving the dynamic characteristics of tricone bits through mathematical modeling can significantly reduce energy consumption, increase drilling productivity, and extend tool life.

The formulated energy and kinematic criteria can be effectively used in the design of next-generation drill bits and in computer-aided engineering systems for simulating drilling processes. Further research should focus on experimental verification of the developed model and on the integration of the obtained results into practical design and optimization methodologies for rock-destroying tools in open-pit and deep drilling operations.

Conflict of interest. On behalf of all the authors, the corresponding author declares that there is no conflict of interest.

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Үш қашау тісті бұрғыларды жабдықтау динамикасының математикалық моделі

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ТҮЙІНДЕМЕ
Мақалада сенімділігі мен әмбебаптылығына байланысты ашық карьерлік тау-кен жұмыстарында кеңінен қолданылатын үш қашау тісті бұрғыларды жабдықтау динамикасының математикалық моделі ұсынылған. Ұзақ мерзімді пайдалану тәжірибесіне қарамастан, олардың тиімділігі мен беріктігін арттыру мәселелері өзекті болып қала береді. Негізгі пайдалану мәселелері, соның ішінде жанасу аймағындағы тау жыныстарының кернеу-деформация күйі және бұрғылау қашауының тістері геометриясының кинематика мен қирату тиімділігіне әсері туралы білімнің жеткіліксіздігі анықталды. Жасалған аналитикалық тәуелділіктер қашаудың геометриясын, қозғалыс траекториясын, беріліс қатынастарын және тістердің жыныспен өзара әрекеттесуін ескеруге мүмкіндік береді. Теориялық механикаға сүйене отырып, энергия шығындарын объективті бағалауды қамтамасыз ететін меншікті жанасу және көлемдік бұзу жұмыстары арқылы өнімділік критерийлері тұжырымдалды. Ұсынылған модель қашаулардың құрылымын және кинематикасын оңтайландыруға, энергия шығынын азайтуға, өнімділікті арттыруға және қызмет ету мерзімін ұзартуға мүмкіндік береді. Алынған нәтижелерді жаңа буын қашауларды жобалауда және нақты тау-кен және геологиялық жағдайларда ұтымды бұрғылау параметрлерін таңдауға арналған инженерлік бағдарламалық жасақтаманы жасауда пайдалануға болады. Ұсынылған тәсіл тау жыныстарының бұзылуы динамикасын модельдеу және ашық карьерлік өндіру технологияларын жетілдіру саласындағы одан әрі зерттеулердің негізін құрайды.

Түйін сөздер: тау жынысы, бұрғылау, бұрғы қашауы, кинематика, жұмыс, жобалау, модель, теңдеу.

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Математическая модель динамики вооружения трехшариковых долот

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АННОТАЦИЯ

В работе представлена математическая модель динамики трёхшарошечных буровых долот, которые сохраняют широкое применение в условиях открытых горных работ благодаря своей надёжности и универсальности. Несмотря на длительный опыт использования, вопросы повышения их эффективности и долговечности остаются актуальными. Уточнены ключевые эксплуатационные проблемы, включая недостаточную изученность напряжённо-деформированного состояния пород в зоне контакта и влияние геометрии зубьев на кинематику и эффективность разрушения. Предложены аналитические зависимости, учитывающие геометрию вооружения, траекторию движения, передаточные отношения и взаимодействие зубьев с породой. На основе теоретической механики сформулированы критерии работоспособности через удельные контактные и объёмные работы разрушения, что обеспечивает объективную оценку энергетических затрат. Модель демонстрирует возможности аналитических методов для оптимизации конструкции и кинематики долот, снижения энергопотребления, повышения производительности и увеличения срока службы. Полученные результаты могут быть использованы при проектировании долот нового поколения и создании инженерного программного обеспечения для выбора рациональных параметров бурения в конкретных горно-геологических условиях. Предложенный подход формирует основу для дальнейших исследований в области моделирования динамики разрушения пород и совершенствования технологий открытых горных работ.

Ключевые слова: порода, бурение, буровое долото, кинематика, работа, проектирование, модель, уравнение.

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