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ANALYTICAL STUDY OF ROCK CUTTING MECHATRON VIBRATION SYSTEM BY FLAT AUGER TOOLS

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АНАЛІТИЧНЕ ДОСЛІДЖЕННЯ ПРОЦЕСУ МЕХАТРОННОЇ ВІБРАЦІЙНОЇ СИСТЕМИ РІЗАННЯ ГІРНИЧОЇ ПОРОДИ ПЛОСКИМИ РІЗЦЯМИ ШНЕКОВОГО БУРА

Purpose. To create a mechatron model of vacuum tube vibration system for rock cutting by flat auger tools based on physical and mechanical properties of processed array and kinematic characteristics of the instrument.

Methodology. The analytical model of the fracture process of rock cutting by tool vibration considering plastic properties of the massif was developed. The main technological parameters of massif vibrating cutting with normal variations were modelled: dependences of normal and tangential pressure in the zone of working body interaction with the medium, normal and shear stresses in the zone of destruction, rock characteristics of the medium, vibration parameter dependences on the characteristics of mechatronic system geometry of the contact area of flat chisel treated with medium.

Findings. The choice of the computational model of the vibration rock cutting with the normal to the direction of movement of the working body fluctuations was substantiated considering the processes arising from destruction: the occurrence of compressive and tensile stresses. The main stages and interconnection options in the simulation of vibration cutting were established.

Originality. Scientific novelty lies in the development of a method of analysis of contact interaction of roller working body molding machine with an array taking into account the changes in the stabilization process of physical and mechanical properties of the treated medium, the aim of which is to predict the required voltage and depth of the formed layer.

Practical value. The theoretical basis of rock cutting by flat auger tool taking into account the normal component of the vibration with regard to the movement direction allowing for the deformation of the rock mass and the contact interaction with the working body was established, that allows improving the technology of drilling wells by reducing the power consumption of the cutting process. The results enable us to determine the parameters of power and kinematic conditions for the occurrence of the vibration cutting.

Keywords: *mechatrone vibration system, massif, cutting, drilling*

Introduction. Drilling the wells while constructing structure foundations and exploratory wells of all kinds of mineral resources, including oil and gas, is a specific type of capital construction of complex technical facilities under unique geological and geoclimatic conditions; it is characterized by high material costs throughout their construction facilities cycle. However, drilling is one of the most popular ways of foundation construction and geological Earth surveys, and exploration of virtually all minerals deposits. The volume of drilling operations, both in the world and in Ukraine are increasing and require new technical and technological tools and solutions to reduce the cost of their implementation [1, 2].

Unsolved problems. Modern technology of drilling operations, used in the formation of wells for various purposes, involves a mechanical destruction of rocks. In this regard, the construction of modern drilling, boring-crane machines and equipment were developed using mostly mechanical methods of rock destruction. The most common way for well construction is a rotary method of drilling equipment using a rotational action of drilling tool equipped with a cutting type. Mechanical destruction of rocks is achieved with tools with cutting action. That is why they play a very important and sometimes decisive role as a means of influence on the environment that is destroyed. Currently, drilling equipment is produced which lacks advanced design, leading to significant cost and overruns of material resources, energy in particular, reduced productivity of machinery and equipment as well as to the increased cost of drilling.

One of the promising areas of drilling equipment power consumption reduction is the creation of innovative cutting technology by analyzing patterns of their interaction with the developed soil. Creation of special conditions, where vibration cutting during drilling operations appears, eliminates the above drawbacks with significantly reduced energy costs.

Significant contribution to the creation and development of the foundations of the theory of dynamical destruction of rocks has been made by such famous scholars of the research and higher education institutions as M. Dombrovskii, A. Zelenin, V. Balovniev, W. Baumann, Yu. Vetrov, V. Baladinskii, R. Poderni and others. In their works most authors take into account the application of dynamic loading in the normal direction to the surface of the mountain massif with the emergence of compression stress. However, the process of rock destruction occurs with minimal energy power costs while creating tensile stresses in the array. That is why the development and introduction of new resource-saving technologies of rock destruction, including a vibrating cutting, will significantly improve specific indicators of energy according to which Ukraine lags behind developed countries by 2–5 times.

Analysis of the recent research. Research of vibration action due to rocks drilling can be divided into two groups: the first group examines the dynamic behaviour of the drilling column; the second group considers the interaction of working bodies with the rock. The main idea of the first studies is to minimize oscillatory processes of the drilling column to stabilize the cutting process. Among the second group works, great interest in terms of disclosure of vibrating mechanism while rock cutting is evoked by inquiries in rock destruction with chisel of PDC [3, 4]. In these works urgent issues of interaction mechanism of cutting elements of modern rock cutting tools with a rock steady are considered. The peculiarities of geometry and dynamics of chisels impact in the cutting process were established. However, application of these results in terms of the main vibration parameter (frequency and amplitude) choice and the definition of cutting forces is complicated because of the lack of calculation models considering mechanics of contact interaction element of the rock separated from the working body and the array direction at different vibrations tools.

Unsolved aspects of the problem. Rock vibration cutting can be divided into two main types of tool vibrations when cutting directions and vibrations are parallel or perpendicular. Most vibration technologies and research studies consider the first type as the preferred process of destruction. The basis of the research of the first type of oscillation is the hypothesis for reducing strain during dynamic destruction that would reduce the energy intensity of the process. However, intensification of this type of cutting is limited by emerging higher loads on the contact surface of the tool which leads to its intensive wear. Research and application of the second type of oscillation by setting magnetostrictive vibrators, together with the drilling column and destroying tool that form mechanotronic oscillating tool system, will change the characteristic of the static cutting stress distribution and deformation in the zone of destruction. Changing the direction of the rock movement with regard to the instrument in the process of destruction would reduce the contact pressure and stress, and as a result will reduce energy-power parameters.

Objectives. To install the main technological parameters of vibrating cutting normal to the direction of cutting vibrations, it is important to create a process model for contact interaction of flat chisel screw drill with the processed environment, taking into account the characteristics of the distribution of stresses and strains that occur in the mountain range.

Presentation of the main research. Screw drills are equipped with boring crane machines for well drilling cycle. Bore blade design consists of a body, to which cutting elements (cutters) and intake are attached. Intake *1* (Fig. 1) in a screw auger, is an element which allows lining up the drill on the axis of the drill hole during drilling. Most of the rocks, and as a result, energy costs account for cutting elements – flat chisels *2*. To create vibrations that are oriented normal (perpendicular) to the direction of the chisel, boring machine is equipped with a magnetostrictive vibrator which expanding and contracting with high frequency under alternating magnetic field takes the drill towards the face.

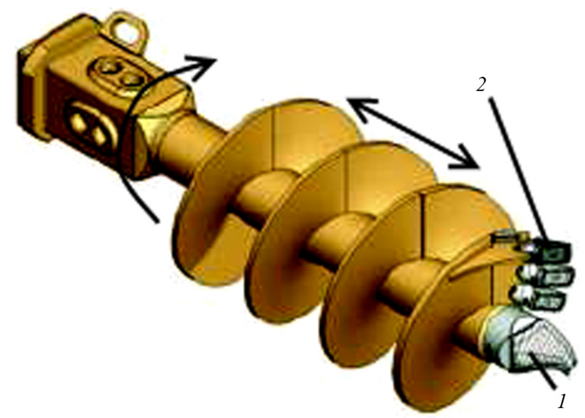
Kinematics of the screw borer is the combination of two movements: a rotational one and a translational one along the axis. Thus, with the rotation of the borer by the drill angle of θ, the cutter travels a distance equal to the product of the angle of rotation by the radius, which determines the position of the tool with the rotation by the angle of θ. Due to this phenomenon, to achieve full compliance with computational models it is appropriate to consider a shift of rock perpendicular to the direction of the cutting edge, which will quite complicate the calculations. Moreover, this phenomenon reduces its influence on the contact area with increasing radius of the screw borer, which allows applying a plane orthogonal model while describing the process of cutting. To confirm the theoretical efficiency of vibration effects on massif let us compare the results of static and vibrating rock destruction with flat chisel (Fig. 2, *a, b*).

Let us consider the balance of the discharge from array rock element of thickness t and height h. The action of the tool on the breed causes normal p and tangential pressure τ for the interaction of which Coulomb's law of friction should be used. Detachment of element is caused by its relative shift along the plane of the array, which is characterized by inclination to horizontal ψ, length $h/\sin\psi$, and the maximum shear stress τ_S.

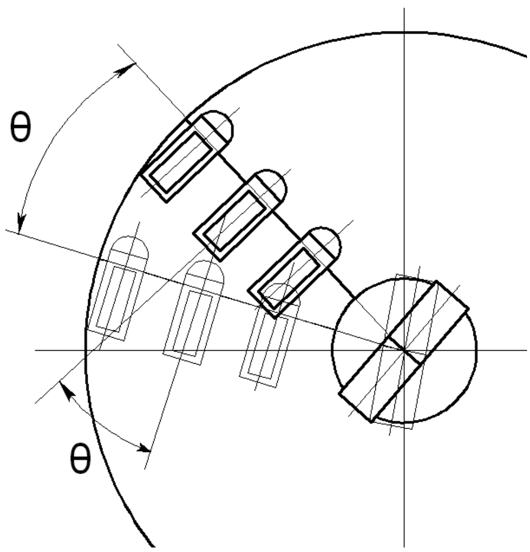
Limiting the shear stress τ_S in the case of rock destruction while using Coulomb-Mohr model depending on the conditions is of the following form:

in the case of compression: $\tau_S = p_S \tan\varphi + c$;

in the case of stretching: $\tau_S = c - |p| \tan\varphi$,



a



b

Fig. 1. Exterior (a) and scheme of screw borer repositioning (b)

where p_S is normal pressure that occurs at the site of displacement; φ is the angle of internal friction; *c* is cohesion.

The equilibrium equation of discharge static element when cutting (Fig. 2, *a*) is

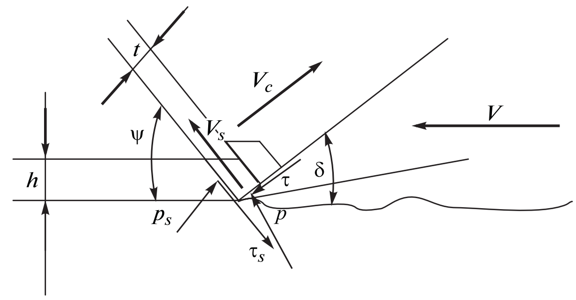
$$\sum X = 0;\ p_s \frac{h}{\sin\psi}\sin\psi + \tau_s \frac{h}{\sin\psi}\cos\psi - $$
$$- pt\sin\delta - \tau t\cos\delta = 0;$$
$$\sum Y = 0;\ p_s \frac{h}{\sin\psi}\cos\psi - \tau_s \frac{h}{\sin\psi}\sin\psi + $$
$$+ pt\cos\delta - \tau t\sin\delta = 0,$$

where δ is a cutting angle of.

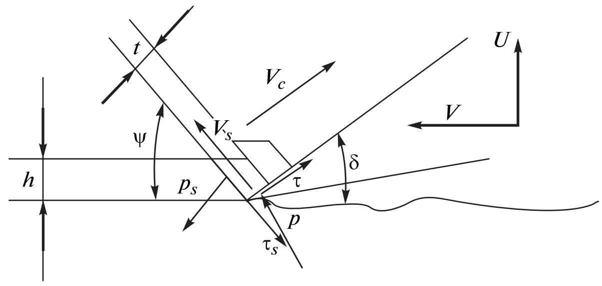
Normal pressure on the basis of equality of friction and shear angles $\psi \approx \varphi$ is

$$p = \frac{hc(\mathrm{tg}(2\phi)\mathrm{tg}(\phi)+1)}{\mathrm{tg}(\phi)t(\sin(\delta)+\mu\cos(\delta)+\mathrm{tg}(2\phi)\cos(\delta)-\mu\,\mathrm{tg}(2\phi)\sin(\delta))}.$$

Let us determine the parameters of vibration action when element separation occurs with the least effort,



a



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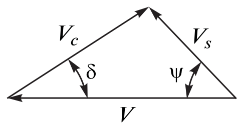

c

Fig. 2. Scheme to output ratio of contact pressures and velocities at vibrocutting, h and t are the height and thickness of the array element separated from the rock; ψ and δ are shift angles and sharp rocks; p and τ are normal and tangential components of the contact pressure between the rock and a chisel; p_s and τ_s are normal and tangential components of the contact pressure between the array and the discharge element; V and U are tangent and normal components of the speed of the chisel; V_S and V_c are the relative speeds of the element in regard to array and a chisel

and, as a consequence, with lower energy efficiency. The condition of vibrocutting effect is the direction of the tangential component of the complete contact pressure changing (Fig. 2, *b*). This is possible while creating a vibration velocity, when its tangential component *U* along the plane of contact of rocks with a tool is higher than the chip velocity V_c in relevance to speed of the chisel

$$V_c < U_{\text{в/с}}. \qquad (1)$$

According to the triangle of velocities (Fig. 2, *c*), let us find the speed of the chips relating to the tooth V_c

$$V_c = V\frac{\sin(\psi)}{\sin(\pi-\delta-\psi)}. \qquad (2)$$

From the expressions (1) and (2) the condition of vibration velocity for vibrocutting regime setting is

$$af \geq V\frac{\sin(\psi)\sin(\delta)}{2\pi\sin(\delta+\psi)} = Vk_в,$$

where a and f are amplitude and frequency of vibration; $k_в$ is the coefficient of vibration.

Dependence of the vibration coefficient on the cutting angle δ at different angles ψ appears close to a linear relationship with increasing inclination and curvature of the rocks with a large shear angle (Fig. 3). The shearing angle for the soil increases with the degree of compression (20–35°); as for rocks, it increases with increasing of strength (18–35°). Thus, to provide the vibration cutting regime with normal vibrations to the direction of tool at which will reverse the relative motion of the tool relatively to the chip, it is necessary to create fluctuations of higher vibrovelosity for more compacted soils and hard rocks.

By providing the condition for vibrovelocity (1) with the purpose of ensuring the vibrocutting regime, pressure tangential component changes its direction (Fig. 2, *b*). Under conditions of equilibrium of discharge element (in the case of vibration cutting with the normal direction of fluctuations)

$$\sum X = 0; \quad -p_s\frac{h}{\sin\psi}\sin\psi + \tau_s\frac{h}{\sin\psi}\cos\psi - $$
$$-pt\sin\delta + \tau t\cos\delta = 0;$$
$$\sum Y = 0; \quad -p_s\frac{h}{\sin\psi}\cos\psi - \tau_s\frac{h}{\sin\psi}\sin\psi + $$
$$+pt\cos\delta - \tau t\sin\delta = 0.$$

Similarly, normal pressure p in the course of the tool moving up is

$$p_в = \frac{hc(\tau\gamma(2\phi)\mathrm{tg}(\phi)+1)}{\mathrm{tg}(\phi)t(\sin(\delta)\text{-}\mu\cos(\delta)+\mathrm{tg}(2\phi)\cos(\delta)+\mu\,\mathrm{tg}(2\phi)\sin(\delta))}.$$

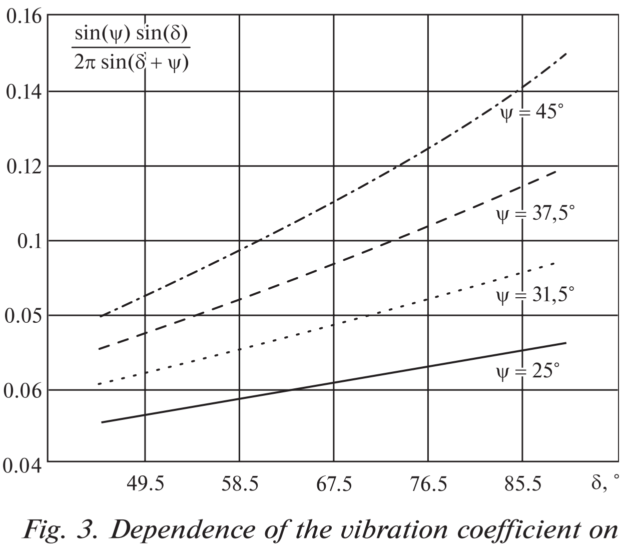

Fig. 3. Dependence of the vibration coefficient on the cutting angle δ at different angles of splitting ψ

Comparison of the obtained dependences of normal pressure values p, $p_в$ (Fig. 4) appearing at static and vibration cutting and with normal fluctuations in the direction to the tool movement when cutting geometrical parameters are different, shows the effectiveness of the proposed method of rock destroying (for the next conditions: $h = 0.1$, m $t = 0.1$ m, $\mu = 0.4$). Average cutting resistance decreases due to the fact that the massif during one oscillation cycle will be under the influence of variable stretching and compression forces. The variable cutting force might be obtained if large sinusoidal oscillations are put on a normal component of the mentioned force. Thus, the cutting force will involve impulses of maximum values corresponding to normal pressures p, $p_в$. So the average value of the pressures and cutting forces will decrease. Pressure reducing by 57 % during the move of the chisel at the top as a whole will reduce pressure by 30 % on average and will result in decrease in strength and power necessary for the implementation of the cutting process. With the change of direction and speed of the separate element of rock V_c, tribotechnical properties of surfaces in contact with the reduction coefficient of friction will vary significantly during the cycle, which, in turn, will lead to reductions in cutting forces.

However, it should be noted that the implementation process of drilling vibration requires a rather complex system of energy-electromechatronic additional source of high-frequency vibration (magnetostrictor) to create the necessary vibrovelosities that provide the reverse direction of movement of rocks on the surface of the chisel, which will reduce the energy efficiency of the proposed method.

Besides, a significant shortcoming that will increase energy costs and reduce the stability instrument

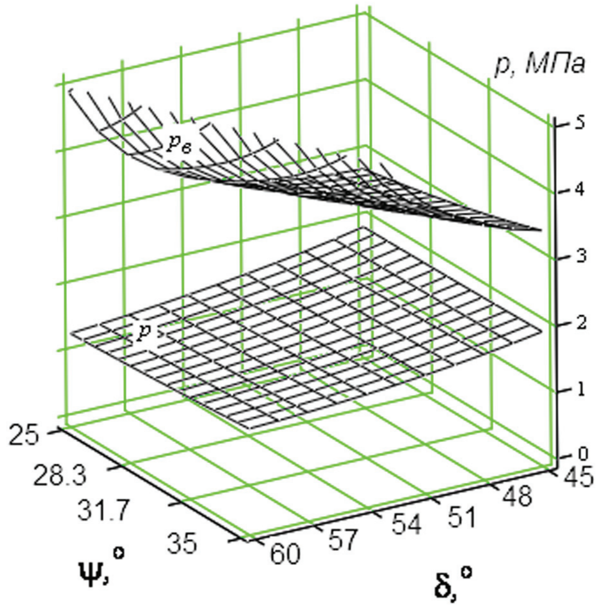

Fig. 4. Dependence of normal pressures p, $p_в$ arising under static and cutting vibration with normal fluctuations to the direction of the tool movement from cutting and chipping angles

includes intensive force interaction of back chisel surfaces with rock at vibration borer motion in the direction of the face.

Conclusions and recommendations for further research. The proposed approach to the vibropower impact of mechatronic vibration drilling system when obtaining wells allows establishing the interaction between the stress and contact pressures in the zone of destruction, which is the basis for calculating the energy-power cutting process. The reduction (up to 57 %) of contact pressures was defined which will significantly increase the stability of the front surface of the tool and reduce energy costs at the destruction.

The conditions for the process of vibration cutting were established with normal fluctuations to the direction of cutting; the fluctuations determine the dependence of major vibration mechatronic system parameters (frequency and amplitude) on the geometric parameters of drilling chisel.

In addition, the authors proposed principles and patterns of rock fracture with normal fluctuations to the direction of cutting which will allow application in modelling of other technological and mining geotechnical processes requiring power consumption reducing and chisel life increasing.

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Мета. Створення моделі процесу мехатронної вібраційної системи різання гірської породи пласкими різцями шнекового бура з урахуванням фізико-механічних властивостей масиву, що обробляється та кінематичних характеристик інструмента.

Методика. Розроблена аналітична модель процесу руйнування гірської породи вібраційним ріжучим інструментом з урахуванням пластичних властивостей масиву. Змодельовані основні технологічні параметри процесу вібраційного різання гірського масиву з нормальними коливаннями: залежності нормальних і дотичних тисків у зоні взаємодії робочого органу із середовищем, нормальні й дотичні напруження в зоні руйнування гірської породи, характеристики середовища, залежності вібраційних параметрів мехатронної системи від особливостей зони контакту пласких різців з оброблюваним середовищем.

Результати. Обгрунтовано вибір розрахункової моделі процесу вібраційного різання гірської породи з нормальними до напряму руху робочого органу коливаннями з урахуванням виникаючих процесів при руйнуванні: стискаючих і розтягуючих напружень. Встановлені основні етапи та взаємозв'язки параметрів при моделюванні процесу вібраційного різання.

Наукова новизна. Полягає в розробці методу аналізу контактної взаємодії ріжучого інструменту з гірським масивом з урахуванням зміни під час процесу різання фізико-механічних властивостей оброблюваного середовища, метою якого є прогнозування виникаючих напружень і тисків у зоні контакту та глибини відокремленого шару, а також визначення умов виникнення процесу вібраційного різання.

Практична значимість. Створені теоретичні основи різання гірської породи пласкими різцями шнекового бура з урахуванням дії нормальної складової вібрації відносно напрямку руху з урахуванням особливостей деформації гірського масиву та контактної взаємодії робочого органу із середовищем, що обробляється, які дозволяють удосконалити технологію буріння свердловин шляхом зменшення енергоємності процесу різання. Отримані результати дозволяють визначити силові параметри процесу та кінематичні умови виникнення вібраційного різання.

Ключові слова: *мехатронна вібраційна система, гірський масив, різання, буріння*

Цель. Создание модели процесса мехатронной вибрационной системы резания горной породы плоскими резцами шнекового бура с учетом физико-механических свойств обрабатываемого массива и кинематических характеристик инструмента.

Методика. Разработана аналитическая модель процесса разрушения горной породы вибрационным режущим инструментом с учетом пластических свойств массива. Смоделированы основные технологические параметры процесса вибрационного резания горного массива с нормальными колебаниями: зависимости нормальных и касательных давлений в зоне взаимодействия рабочего органа со средой, нормальные и касательные напряжения в зоне разрушения горной породы, характеристики среды, зависимости вибрационных параметров мехатронной системы от особенностей геометрии зоны контакта плоских резцов с обрабатываемой средой.

Результаты. Обоснован выбор расчетной модели процесса вибрационного резания горной породы с нормальными к направлению движения рабочего органа колебаниями с учетом возникающих процессов при разрушении: сжимающих и растягивающих напряжений. Установлены основные этапы и взаимосвязи параметров при моделировании процесса вибрационного резания.

Научная новизна. Заключается в разработке метода анализа контактного взаимодействия режущего инструмента с горным массивом, с учетом изменения во время процесса резки физико-механических свойств обрабатываемого среды, целью которого является прогнозирование возникающих напряжений и давлений в зоне контакта и глубины обособленного слоя, а также определение условий возникновения процесса вибрационного резания.

Практическая значимость. Созданы теоретические основы резания горной породы плоскими резцами шнекового бура с учетом действия нормальной составляющей вибрации относительно направления движения с учетом особенностей деформации горного массива и контактного взаимодействия рабочего органа с обрабатываемой средой, позволяющие усовершенствовать технологию бурения скважин путем уменьшения энергоемкости процесса резания. Полученные результаты позволяют определить силовые параметры процесса и кинематические условия возникновения вибрационного резания.

Ключевые слова: *мехатронная вибрационная система, горный массив, резание, бурение*

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