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GEOMETRIC MODELLING OF FACE PROCESSING SURFACES BY PLANETARY EXECUTIVE DEVICES OF TUNNELLING MACHINES

Purpose. To identify characteristic surface forms generated by the movement of a cutting tool located on the working disks of a planetary executive device depending on its main parameters in various implementation schemes. This will contribute to a more accurate determination of rational values for the structural and kinematic parameters of the executive device for specific design schemes and operating conditions.

Methodology. A scheme was used to provide a general definition of the surface formed while processing the face with the system of working tools of a planetary executive device, which integrates all the existing and theoretically possible options of a planetary executive device with two rotational motions and a translational one. The generalized model of the planetary executive device is based on an arbitrarily oriented moving working disk which rotates, with a system of working tools positioned on it.

Findings. In the work, modelling and geometric analysis are performed of the characteristic forms of surface carriers (processing surfaces) of the trajectories of the working tool installed on the disks of the planetary executive devices of tunnelling machines. The characteristic peculiarities are revealed of the change in the shape of the processing surface when varying the values of the parameters of the executive device and the nature of the impact of each of them on the shape of this surface, taking into account the peculiarities of the interaction of the working tool with the rocks being destructed.

Originality. Geometric analysis of surface carriers formed by numerous trajectories of movement of working tools of various designs of the planetary executive device shows that, in general, the processing surface is a section of a helical cylindrical helicoidal surface. When simplified, it turns into a section of a toroidal surface, with a second-order closed curve, whose shape depends on the values of the orientation angles of the working disk. To identify the characteristic peculiarities of the face surface formation, assessment was performed of the impact of each of these parameters separately on the shape of the surface carriers of the working sections of the tool trajectories (processing surfaces), considering the case of maximum processing of the face surface with the working disks of the executive device to ensure the commonality of the results.

Practical value. The results of the studies conducted in the work provide the theoretical basis for solving the engineering issues of the interaction of the working tool of planetary executive devices with rocks being destructed, where the geometric parameters of this interaction are of paramount importance.

Keywords: *face, tunnelling machine, planetary executive device, cutting tool, processing surface*

Introduction. The destruction of rocks and minerals using the method of planetary drilling (cutting) is one of the most effective means of separating material from the geological formation. The prospect of this method lies in the ability to combine rotational movements, simultaneously with translational effects including an impact effect, which are transmitted to the cutting tool allowing for the creation of rational structural designs for executive mechanisms under different working conditions. The planetary method of rock destruction has proven to be particularly effective in the extraction of salts and other soft minerals, including rock salt, at the "Artemsil" production association in Soledar. In the mining industry, this method of rock destruction is implemented through mining and tunnelling-cleaning combines, roadheaders and shaft tunnelling machines, while in tunnel construction – through shield complexes (hereinafter referred to as tunnelling machines). The main component of a tunnelling machine, which performs the primary technological operation – rock destruction, is the executive device. Therefore, when designing new machines [1] or upgrading the existing ones, emphasis should be placed on the executive device.

Thus, addressing the task of improving the technical level of mining and cleaning machines [2] equipped with planetary executive devices is highly relevant, both in Ukraine and worldwide.

Literature review. As demonstrated in works [3, 4], a significant number of mining machines and complexes equipped with planetary executive devices are widely used in global mine workings, as well as in the mining and construction industries. These executive devices can perform simultaneous processing of the entire cross-section of the drifting face or work in conjunction with a system of burrowing devices and auxiliary rotational executive devices to achieve the required excavation profile. Depending on the values of structural and kinematic parameters, a classification of executive bodies of this type was previously developed, which includes both implemented structural schemes and theoretically possible ones [5].

Each of the structural schemes of the planetary executive device has its own advantages and disadvantages. Moreover, existing designs of planetary executive devices are inferior to simpler constructions, such as rotary ones, in their ability to break up hard rock and minerals [6].

Most of the disadvantages caused by the peculiarities of the kinematics of motion and other factors involved in the interaction process between the cutting tool of planetary executive devices and the material cannot be eliminated at the design level in the existing schemes [7]. However, it is possible to minimize these disadvantages by identifying the factors that make them occur.

The complexity of choosing rational values for the parameters of the executive mechanism in the planetary destruction method is primarily associated with the complexity and insufficient understanding of the interaction process between the cutting tool and the destructible mass [8]. This, in turn, is caused by the complexity of its kinematics and, as a result, the geometry of cutting (destruction).

The executive mechanisms of continuous destruction, which operate based on the transmission of simple rotational motion to the tool, are proposed in [5] to be considered as a partial case of the planetary mechanism in order to maintain consistency in the research.

All existing schemes of rotary and planetary executive devices, as mentioned, have both advantages and disadvantages. For example, alongside high energy efficiency and the ability to break hard rocks, rotary executive devices feature several significant drawbacks [9]. Firstly, as shown in [5, 10], there is a significant overturning moment that arises because simultaneously, all the working tools are in contact with the material. Eliminating this phenomenon is only possible by increasing the overall weight of the machine. However, this also results in a range of negative factors such as increased cost, decreased transportability, and more complex assembly and disassembly operations. Secondly, there is a zone of low speeds and high forces in the central part of the executive mechanism, which results in uneven wear of the working tools located at different distances from the centre of rotation [11].

However, most of the drawbacks associated with rotary executive mechanisms are absent in schemes with planetary motion of the working tool. In this regard, planetary drilling, as established in [12, 13], differs from simple rotation by requiring less energy for destruction as well as minimal yield of fine particulate fraction, which forms as a result of grinding the rock mass and negatively affects the working conditions for personnel [14]. This is achieved by applying all the advantages of milling method, which is the basis of planetary cutting. However, existing designs of planetary executive devices have complex drive reducer mechanisms, long tool paths, and other drawbacks related to the tool trajectory, and they also have limitations in their ability to break hard rocks.

Thus, in order to use the milling method to full advantage with the transmission of multiple rotational motions to the cutting tool, which is achieved through the use of planetary executive devices, and to minimize the negative impact of factors associated with the peculiarities of tool motion kinematics, it is necessary to conduct a thorough and comprehensive study on their operation process. One direction of such research involves considering the geometric parameters of the interaction process between the cutting tool or its system and the rocks being fractured, as well as analysing the resulting processing surfaces, which have not been extensively examined or analysed in previous studies.

The purpose of this study is to identify characteristic surface forms generated by the motion of the cutting tool located on the working disks of the planetary executive device, based on its main parameters in different implementation schemes. This will contribute to a more precise determination of rational values for the structural and kinematic parameters of the executive devices for specific structural designs and operating conditions.

To achieve the stated purpose, it is necessary to:

1) analyse the generalized model of the kinematics of the cutting tool's motion in the planetary executive device to determine its parameters which define and affect the form of the stope surface processed;

2) determine the influence of each parameter of the planetary executive device, which determines its form, on the geometric properties of the stope surface processed.

Methods. To determine the surface formed while processing the stope with the system of cutting tools of the planetary executive device, we will apply the diagram presented in Fig. 1. This diagram was proposed in the work [5] and integrates all the existing and theoretically possible variations of the planetary executive device with two rotational motions and a translational one.

Applying the structural diagram shown in Fig. 1 as the basic one, let us consider the scheme of formation of stope surface processed when changing the design parameters of the executive mechanism (Fig. 2). The fundamentally generalized model of the planetary executive device, proposed in the previous work [3], consists of one or several movable working disks with a radius *r*, whose planes are arbitrarily oriented in space. Each of these disks is equipped with a system of cutting tools (A_1, A_2, A_3, ..., A_n). Various types of cutters are commonly used in planetary executive mechanisms, but in general, any cutting tool can be employed.

As a result of the geometric composition of the specified components, the working tool performs the resulting planetary motion. Since the rotation plane of the disk (or disk system) can take an arbitrary position in space, this model can be considered as the one combining all the existing and theoretically possible design schemes of a planetary executive device.

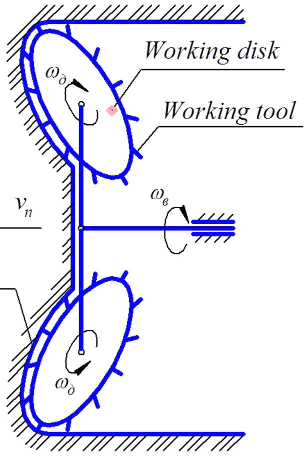

Fig. 1. Generalized diagram of a planetary executive device

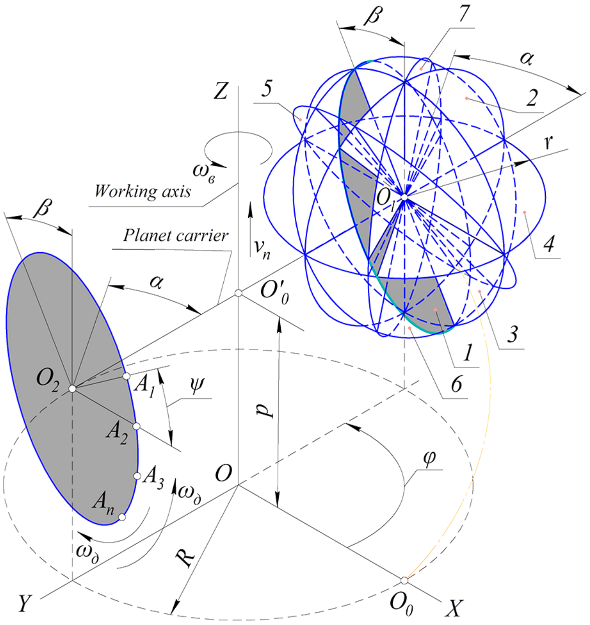

Fig. 2. General diagram of formation of stope surface processed

Results. Let us consider the main structural and kinematic parameters of the general scheme of the planetary executive device affecting its trajectory and determine which ones influence the shape of the stope surface processed. Referring to the diagram shown in Fig. 2, in the coordinate system *OXYZ*, the single working disk starts its motion with its centre located at point O_0. Then the disk moves to another intermediate position, while its centre moves to point O_1. Let us examine all possible variations of the disk's plane orientation in space in this position. The corresponding images of the positions of the working disk are shown in Fig. 2.

The general scheme of the executive device under consideration has the following design parameters: *R* – the radius of rotation of the working disk centre relative to the longitudinal axis of the device (the radius of the helical centroid); *r* – the radius of the working disk (the distance from the axis of disk rotation to the cutting point); α – the angle between the plane of the working disk and the vertical plane *XOZ* in the starting position of motion; β – the angle between the plane of the working disk and the vertical plane *YOZ* in the starting position of motion; ψ – the angle between adjacent cutting tools on the working disc.

To maintain the consistency and for further studying of the influence of the parameter ratio between R and r on the forms of the trajectories of tool motion and processing surface, it is reasonable to establish a relationship between these values as follows: $k = R/r$.

The general scheme of the planetary executive device has the following set of kinematic (operational) parameters: ω_d, ω_B – according to the angular velocities of rotation of the cutting tool positioned on the working disk in relative and translational motions. The relationship between ωд and ω_B is expressed by the gear ratio – $i = \omega_d/\omega_B$); φ is the angle of rotation of the centre of the working disk in translational motion around the axis of the executive device from the initial position. This parameter is related to the angle of rotation of the cutting tool in the plane of the working disk by the equation $\theta = \varphi i + \psi$, where θ is the angle of rotation of the cutting tool in the plane of the working disk from the starting position; h – the discharge rate of the executive device to the face in the direction of its destruction (per one complete revolution).

The working disk, whose rotation plane is in a general position relative to the adopted coordinate system with the centre at point O_2, is shown separately for clarity (Fig. 2).

The trajectory of motion of a single cutting tool in the considered model, depending on the values of design and kinematic parameters, is described by the equations [5]

$$\begin{aligned} x &= R\cdot\cos\varphi + r(\cos(\varphi i+\psi)\cdot\cos(\varphi+\alpha) \mp \\ &\mp \sin(\varphi i+\psi)\cdot\sin\beta\cdot\sin(\varphi+\alpha)); \\ y &= R\cdot\sin\varphi + r(\cos(\varphi i+\psi)\cdot\sin(\varphi+\alpha) \pm \\ &\mp \sin(\varphi i+\psi)\cdot\sin\beta\cdot\cos(\varphi+\alpha)); \\ z &= \frac{h}{2\pi}\varphi \pm r\cdot\sin(\varphi i+\psi)\cdot\cos\beta. \end{aligned} \tag{1}$$

These equations describe the motion of the cutting tool according to two possible schemes – additive and subtractive ones.

If the cutting tool rotates counterclockwise simultaneously in relative and translational rotational motions, the additive scheme of operation is in process (corresponding to the upper signs in front of the equation components (1)). However, if the direction of rotation of the working disk is reversed, the sign of the angle $\varphi i + \psi$ changes from "+" to "–". Consequently, this also causes a change in the sign of individual terms of the equations (1). This working scheme of the executive device is called subtractive (corresponding to the lower signs in front of the equation terms (1).

As shown by previous studies [3, 5], the direction of rotation of the disks and the tubing head adaptor (a planet carrier) significantly affects the nature of the interaction between the cutting tool and the rock mass, but it does not have any influence on the shape of the processing surface.

According to the analysis of the general diagram of the planetary executive device (Fig. 2) and the equations (1), which describe the trajectory of its cutting tool, the generalized parameters are the angles of orientation of the working disk plane, α and β, the value of the ratio $k = R/r$, and the gear ratio – i. However, the specific structural schemes which occur from the model considered can be influenced by both design and kinematic parameters of the executive device.

Specific design schemes (implemented and structurally possible) of the planetary executive device can be obtained by substituting specific values of parameters into the equations (1), the ranges of which are determined in the work [5].

Each of the fundamental schemes of the planetary executive device, can result in various modifications which differ in their design peculiarities and the number of planet carriers (tubing head adaptors), working disks, the availability of burrowing devices and roof processing tools in order to give them a specific profile.

Thus, through analysing the general scheme of forming of the stope surface processed and the kinematic equations of the cutting tool motion (1), it is evident that the shape and nature of the processing surface are influenced by the design angles α and β, the ratio coefficient of the planet carrier and working disk radii $k = R/r$, and the discharge rate of the executive device to the face within one working revolution, h. However, considering the fact that the value of h compared to other design parameters and dimensions of the executive device is sufficiently small, by the order of 0.01 % of the value of these parameters, it can be neglected and not taken into account when modelling.

Therefore, by sequentially substituting the values of parameters α, β, and k from the ranges corresponding to each specific design scheme into the equations (1), we can obtain the corresponding processing surfaces.

Since the operation of most design schemes of the planetary executive device is based on skip cutting, the processing surfaces geometrically consist of discrete line surface carriers, constructed as a family of trajectories of multiple cutting tools installed on the disk of the planetary executive body (Figs. 3–10). In this case, the value of the coefficient k only affects the inner radius of the surface considered. Therefore, to maintain consistency, we will assume that the coefficient k is the same ($k > 1$) for all cases of the modelled surfaces.

The correspondence of the surface carriers of the trajectories of the working tool, shown in Figs. 3–10, to the design

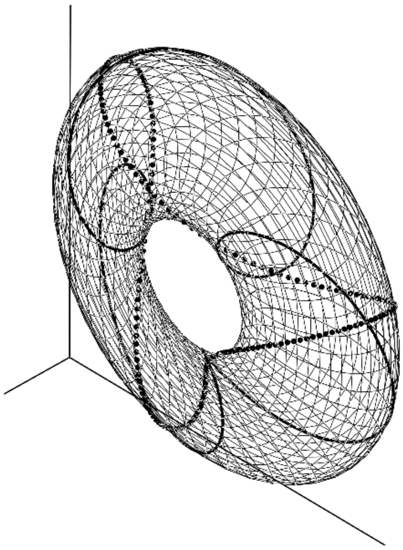

Fig. 3. Surface carrier of the trajectories of the working tools
($\alpha = 40°$, $\beta = 60°$)

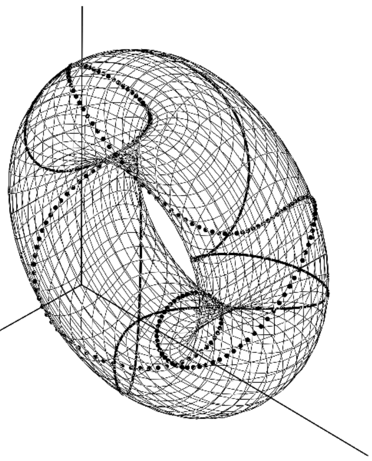

Fig. 4. Surface carrier of the trajectories of the working tools
($\alpha = 45°$, $\beta = 0°$)

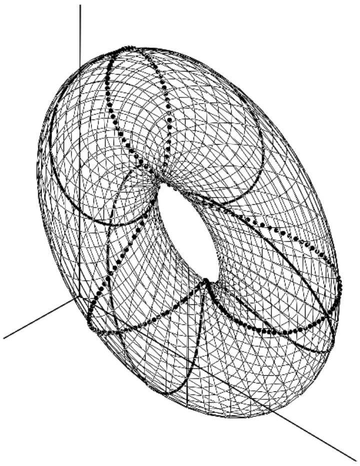

Fig. 5. Surface carrier of the trajectories of the working tools $(\alpha = 0^\circ, \beta = 45^\circ)$

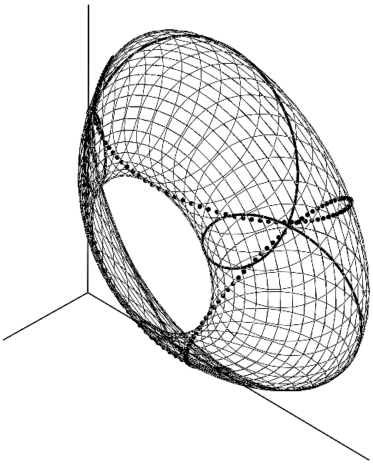

Fig. 6. Surface carrier of the trajectories of the working tools $(\alpha = 90^\circ, \beta = 45^\circ)$

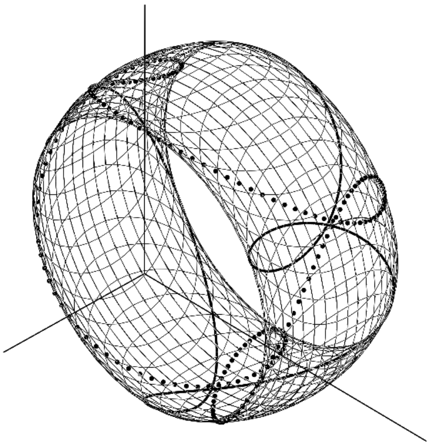

Fig. 7. Surface carrier of the trajectories of the working tools $(\alpha = 90^\circ, \beta = 0^\circ)$

schemes of the planetary executive device is provided in Table (the names of individual cases of design schemes correspond to their working names proposed in the work [5].

The general case of the processing surface formed during one complete revolution of the executive device, taking into account the skip cutting mode characterized by periodic withdrawal of the working tool from contact with the stope surface, is shown in Fig. 11.

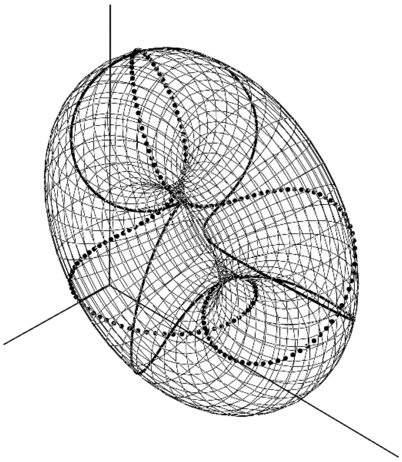

Fig. 8. Surface carrier of the trajectories of the working tools $(\alpha = 0^\circ, \beta = 0^\circ)$

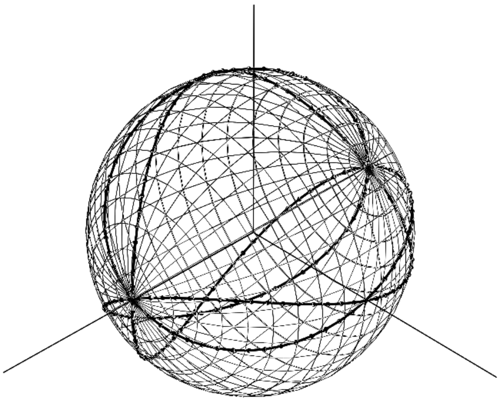

Fig. 9. Surface carrier of the trajectories of the working tools $(\alpha = 0^\circ, \beta = 0^\circ, k = 0\ (R = 0)$

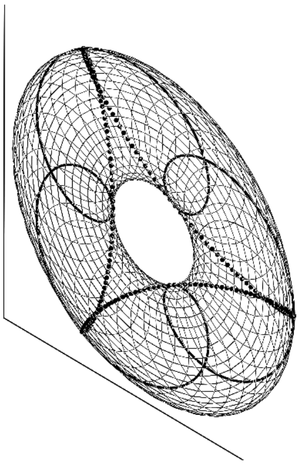

Fig. 10. Surface carrier of the trajectories of the working tools $(\alpha = 0^\circ, \beta = 90^\circ)$

The geometric analysis of the surfaces (Figs. 3–10) formed by the set of motion trajectories of the working tools of different design schemes of the planetary executive device shows that, in general, the processing surface is a section of a helicoidal cylindrical surface. In a simplified case, when $h = 0$, it transforms into a section of a toroidal surface with a generatrix in the form of a closed second-order curve, whose shape depends on the values of the angles of orientation of the working disk – α and β.

Table

Correspondence of the surface carriers of the trajectories of the working tool to the design schemes of the planetary executive device

Constructive scheme name	Figure No.	The range of the scheme's existence parameters		
		k	α, degrees	β, degrees
General scheme	3	> 0	(0; 90)	(0; 90)
Planetary α-toroidal	4	> 0	(0; 90)	0
Planetary β-toroidal	5	> 0	0	(0; 90)
Planetary orthospherical	6	> 0	90	(0; 90)
Planetary circular	7	> 0	90	0
Planetary toroidal	8	> 0	0	0
Planetary spherical	9	0 ($R = 0$)	0	0
Flat-planetary	10	> 0	0	90

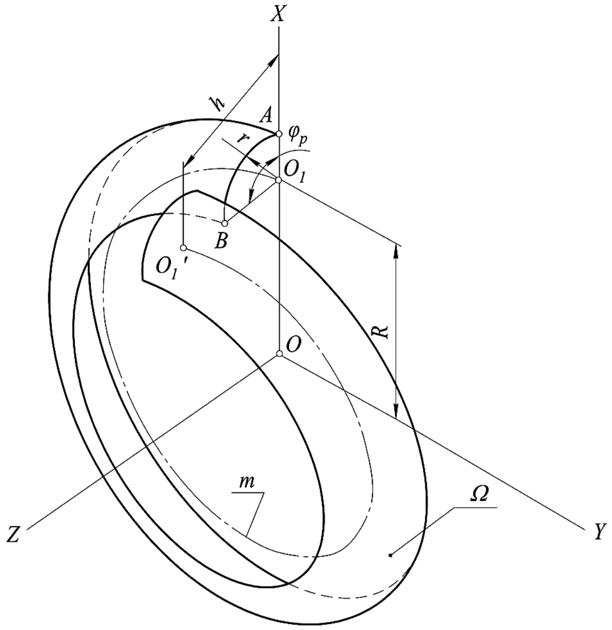

Fig. 11. General case of the processing surface

To identify differential peculiarities of the formation of the slope surface, an assessment of the influence of each of these parameters on the shape of the surface carriers of the working areas of the tool motion trajectory (processing surfaces) was performed. In order to ensure consistency of the results, the case of maximum surface processing with the cutting disks of the executive device, i. e., when $\varphi_p = 90°$, was considered.

Analysing the influence of the coefficient k on the conditions of the formation of the processing surfaces, with constant values of other design parameters, it has been found that when $k \geq 1$, surfaces of transitional ($k = 1$) and open ($k > 1$) helicoidal cylinder are formed. When $k \in (1; 0)$, the trajectory of the working tool lies on a closed helicoidal cylindrical surface. In the limiting case of the flat-planetary executive device scheme (Fig. 11), the generatrix of this cylinder will be a straight line, and the corresponding processing surface will be a helicoid. In terms of design, increasing the value of the coefficient k leads to a corresponding decrease in the area of the stope surface that is to be processed directly with the cutting disks of the executive device, while the area of the surface subjected to processing by the burrowing device increases.

Through analysing the influence of the design angles of orientation of the working disk α and β, it was determined that with an increase in their values within the range of 0° to 90°, the size of the conditional semi-axis of the generatrix of the surface carrier of the trajectories decreases, reaching its minimum value when α and β are both – 90°. In terms of design, this means that increasing the values of α and β results in a corresponding decrease in the area of the slope surface that is to be processed with the cutting disks of the executive device, while the area of the surface subjected to processing with the burrowing device increases.

Conclusions. On account of the theoretical studies on the formation of stope surface processed with the working tool of planetary executive devices in tunnelling machines, the following results have been obtained:

1. In the general case, under steady operating conditions, the processing surface is a section of a helicoidal cylindrical surface. With zero delivery of the executive device to the stope ($h = 0$), it transforms into a section of a toroidal surface with a generatrix in the form of a closed curve of the second order, whose shape depends on the values of the design parameters of the executive device. Under the condition of zero delivery, the form and nature of the stope surface processes are only influenced by the design parameters of the executive device, namely the angles of the working disk's orientation in space α and β, and the ratio of the radii of the planet carrier and working disk, $k = R/r$.

2. The values of the design parameters of the executive device, α, β and k, determine the specific form and corresponding geometric parameters of the resulting processing surface and the limits of its existence. As a result, they also condition the availability or absence of the burrowing device and determine its required diameter. Certain (limiting) values of these parameters define partial cases of design schemes and, consequently, the forms of the stope processing surfaces.

The results of the conducted research provide the theoretical basis for further conducting of more comprehensive studies related to solving issues of the interaction of the working tool of planetary executive devices with the mass being destructed, where geometric parameters of this interaction are of crucial importance. Some of the questions that can be addressed include:

- improving the parameters of the cutting process;
- determining the rational parameters of the skip cutting mode;
- minimizing the friction path between the working tool and the rocks being destructed;
- excluding "critical" areas of the processing surfaces where the working tool can experience significant overloads due to the presence of special geometric elements;
- ensuring harmonious operation of cutter wheels and the burrowing device and resolving a number of other issues that affect the efficiency of the planetary executive device, etc.

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Геометричне моделювання поверхонь обробки вибою планетарними виконавчими органами гірничопрохідницьких машин

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Мета. Виявлення характерних форм поверхонь, що породжуються при русі різального інструменту, розташованого на робочих дисках планетарного виконавчого органу, в залежності від основних його параметрів у різних схемах реалізації. Це сприятиме надалі більш точному визначенню раціональних значень конструктивних і кінематичних параметрів виконавчого органу для конкретних конструктивних схем і експлуатаційних умов.

Методика. Використана схема для загального визначення поверхні, що утворюється у процесі обробки вибою системою робочих інструментів планетарного виконавчого органу, яка узагальнює в собі всі існуючі й теоретично можливі варіанти планетарного виконавчого органу із двома обертальними та одним поступальним рухом. В основу узагальненої моделі планетарного виконавчого органу покладено довільно зорієнтований рухомий робочий диск, що обертається, з розташованою на ньому системою робочих інструментів.

Результати. У роботі виконане моделювання й геометричний аналіз характерних форм поверхонь-носіїв (поверхонь обробки) траєкторій робочого інструменту, установленого на дисках планетарних виконавчих органів гірничопрохідницьких машин. Виявлені характерні особливості зміни форми поверхні обробки при варіюванні значеннями параметрів виконавчого органу та характер впливу кожного з них на форму даної поверхні з урахуванням особливостей взаємодії робочого інструменту з масивом, що руйнується.

Наукова новизна. Геометричний аналіз поверхонь-носіїв, що утворені множиною траєкторій руху робочих інструментів різних конструктивних схем планетарного виконавчого органу, показує, що у загальному випадку поверхнею обробки є відсік гвинтової гелікоїдальної циліндричної поверхні. У спрощеному випадку, вона перетворюється на відсік тороїдальної поверхні, із твірною у вигляді замкненої кривої другого порядку, форма якої залежить від значень кутів орієнтації робочого диску. Для виявлення характерних ознак формоутворення поверхні вибою, була виконана оцінка впливу окремо кожного із цих параметрів на форму поверхонь-носіїв робочих ділянок траєкторій руху інструменту (поверхонь обробки), розглядаючи, для спільності результатів, випадок максимальної обробки поверхні вибою робочими дисками виконавчого органу.

Практична значимість. Результати проведених у роботі досліджень дають теоретичне підґрунтя для вирішення технологічних питань взаємодії робочого інструменту планетарних виконавчих органів із масивом, що руйнується, де вкрай важливе значення мають геометричні параметри цієї взаємодії.

Ключові слова: *вибій, гірничопрохідницька машина, планетарний виконавчий орган, різальний інструмент, поверхня обробки*

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