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DEVELOPMENT OF A METHODOLOGY FOR CALCULATING THE WORKING PROCESS OF THE ROTARY WORKING BODY OF MACHINES FOR EARTHWORKS AND ROAD WORKS

The object of this research is the working process of high-speed separation of soil mass elements by the cutting elements of a rotor. The existing problem is that soil cutting by the rotor occurs during the translational movement of the base machine. This creates a complex trajectory of the cutting edge and leads to continuous changes in chip thickness. Considering the trajectory of the cutting edges and the function of chip thickness variation allows for a more accurate assessment of the energy characteristics of the rotor drive.

Key parameters, such as the torque on the drive shaft, drive power, and energy consumption, were analyzed as functions of the working body's geometry, rotational speed, base machine velocity, and soil properties. The obtained mathematical models account for the actual trajectories of the cutting elements and changes in soil cutting thickness. Additionally, the interaction conditions with the surrounding environment and the physical and mechanical properties of the soil were considered. A methodology for engineering calculation and optimization of the rotary working body's parameters was developed. It considers the rotor's design, size, interaction conditions, and environmental factors. Analysis of the working process of a rotary working body with specified parameters and soil properties led to the following conclusions:

– The power consumption for the drive and the energy intensity of the process in direct and reverse soil cutting are practically equal. The differences do not exceed 5 %.

– In reverse operation, the average horizontal component of soil cutting resistance increases by 1.15–1.25 times compared to direct cutting. However, the resistance force vector is directed toward the working body's movement, reducing the required traction force of the base machine.

– The average value of the vertical component of cutting resistance in reverse operation is 2.0–2.5 times lower than in direct cutting. This reduces the effort required to deepen the working body or adjust the soil development depth.

This study will be useful for machine-building enterprises specializing in the design and manufacture of earthmoving and road construction machines, particularly those with an active rotary working body.

Keywords: *rotary working body, cutting trajectory, cutting knives, cutting thickness, absolute speed, energy consumption.*

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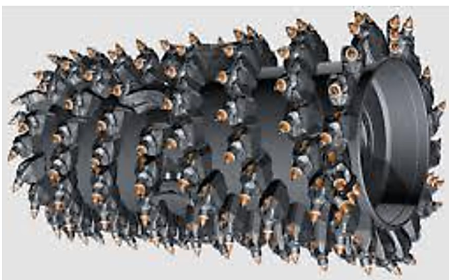
1. Introduction

Rotary working bodies (Fig. 1) are extensively employed across various technological machines, including earthmoving and milling equipment for layer-by-layer excavation of dense soils and coatings, mining in open-pit operations, and as functional components of continuous excavators and recyclers. Their application extends to agricultural and forestry machinery. Rotary working bodies demonstrate superior efficiency compared to other earthmoving machines, particularly for tasks involving the destruction of surface soil layers, concrete and asphalt pavements, open-pit mining, and stripping operations during quarry construction for ore extraction.

A distinctive feature of the rotary working body's operational process lies in the combination of the machine's translational movement with the rotational motion of the working body itself. This combination produces a complex trajectory for the cutting elements and results in variations in cutting thickness as they interact with the working medium. The impact of these features becomes more pronounced with reduced rotor diameter and increased speed of gradual movement. Therefore, it is critical to study the working process of rotary working bodies to develop mathematical models for calculating their geometric, kinematic, and power parameters, optimizing these parameters, and establishing an engineering calculation methodology.

Previous studies, such as [1, 2], have examined the working process of disc rotary working bodies without multi-step cutting elements, exploring variations in cutting depth and design schemes. References [3, 4] provide power parameters for milling-type working bodies based on empirically determined soil cutting resistance for specific ranges of knife width, feed, milling depth, and soil type. Paper [5] presents mathematical models for geometric and kinematic parameters of rotary tillage tools but lacks a methodology for calculating energy parameters. Empirical models for predicting forces on Bilgin disc mills are proposed in [6], while [7] discusses a machine design for trench development and determines drive power and rotational speed.

Further studies [8, 9] examine the effects of cutting parameters on power consumption, including models for oscillating circular saws. Innovations in milling teeth, such as diamond-coated tools, which significantly improve performance and durability, are discussed in [10]. Additionally, [11] introduces a pendulum stand to study asphalt concrete milling, providing insights into cutting work, forces, and the influence of material properties. Although these studies contribute valuable knowledge, they do not fully address the milling process parameters of the working body as a whole.



a

b

c

d

Fig. 1. Rotary working body's: *a* – road milling machine; *b* – excavation and milling working body; *c* – ground cutter; *d* – forest mulcher

Recent research [12, 13] includes methodologies for field and stand tests, wear mechanism identification, and simulation modeling of spiral cutters. These studies emphasize specific aspects of rotary working bodies but underscore the need for a comprehensive approach to analyze and optimize their operational processes. This research aims to address these gaps by developing detailed mathematical models and engineering methodologies for rotary working bodies.

The aim of this research is to address issues in the methodology for calculating the performance of the rotating working body of earthmoving machines. These issues involve refining the calculation schemes of the interaction between the working body and the excavated material during both forward and reverse cutting. Based on this, mathematical models are developed to determine the kinematic, force, and energy parameters of the working process.

2. Materials and Methods

The object of this research is the working process of high-speed separation of soil mass elements by the cutting elements of a rotor. The existing problem is that soil cutting by the rotor occurs during the translational movement of the base machine. This creates a complex trajectory of the cutting edge and leads to continuous changes in chip thickness. Considering the trajectory of the cutting edges and the function of chip thickness variation allows for a more accurate assessment of the energy characteristics of the rotor drive.

The first step is to obtain the trajectory of movement of the cutting elements of the rotating working body. For this, graphic calculation schemes, graph-analytical classical methods, and the basic principles of the theory of machines and mechanisms were used.

The geometric and kinematic parameters of the cutting elements' interaction with the rotating working body were theoretically determined. This analysis was based on the obtained movement trajectory, design features, and geometric characteristics. Classical theoretical methods, including trigonometry and kinematics, were used. Additionally, the study established the limits within which these parameters vary, considering the developed theoretical justification.

The refined geometric and kinematic parameters of the cutting elements' interaction with the rotating working body were analyzed. Additionally, the limits of parameter variation were considered in this analysis. Based on these factors, mathematical provisions were developed using fundamental principles of cutting theory. Furthermore, these provisions determine the drive power as well as the horizontal and normal components of the cutting support for the rotary working body.

Further calculations of the rational parameters of the rotary working equipment according to the developed methodology were performed using the MATHCAD application software package.

3. Results and Discussion

The cutting trajectory of the knife of a rotary working body is formed by combining the gradual movement of the machine with a speed V_m and the rotational movement of the working body with a circular speed ω_0 (Fig. 2). The direction of rotational movement in the lower part of the working body can coincide with the direction of gradual movement of the machine (forward cutting) or have the opposite direction (reverse cutting).

There is a moment of motion determined by a point at a distance $r_0 = V_m / \omega_0$ from the axis of rotation of the working body $(p.O_1)$ upwards (Fig. 2, *a*) or downwards (Fig. 2, *b*), when the speeds of forward and rotational movements are balanced. The successive positions of this point create a straight line parallel to the soil surface at a distance r_0 from the trajectory of the working body axis. Therefore, the cutting trajectories are curves obtained by rolling a circle of radius r_0 along the considered straight line without slipping.

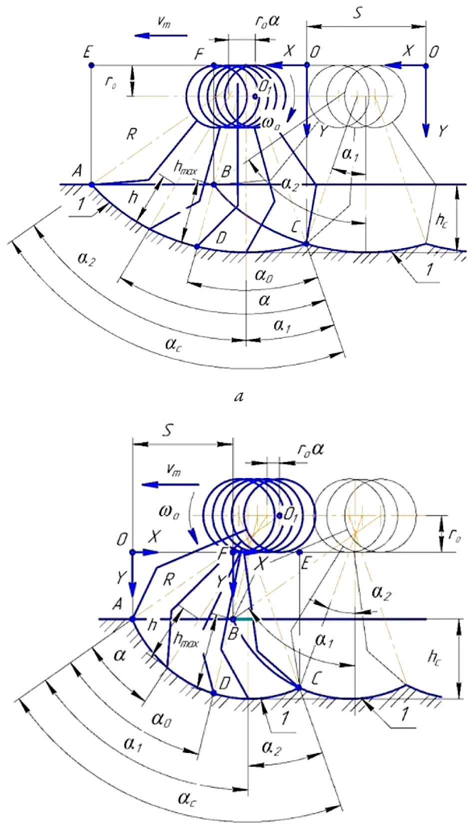


Fig. 2. Calculation diagrams to determine the trajectories of the cutting knives of a rotary working body: *a* – forward cutting; *b* – reverse cutting

The trajectories obtained (line 1) are trochoidal. The equations of the trochoid in XOY coordinate system for forward cutting are:

$$x=\varphi_1(\alpha)=r_0\alpha+R\sin(\alpha-\alpha_1)+R\sin\alpha_1; \quad (1)$$

$$y=\psi_1(\alpha)=r_0+R\cos(\alpha-\alpha_1), \quad (2)$$

where α is the fluid angle of rotation of the cutting blade relative to the point O; R is the radius of the rotary working body.

Accordingly, for reverse cutting, the equations of the trochoid [3, 4] in the XOY coordinate system are as follows:

$$x=\varphi_2(\alpha)=-r_0\alpha-R\sin(\alpha_1-\alpha)+R\sin\alpha_1; \quad (3)$$

$$y=\psi_2(\alpha)=-r_0+R\cos(\alpha_1-\alpha). \quad (4)$$

Step of the cutting paths:

$$S=\frac{2\pi r_0}{z}=\frac{2\pi V_m}{z\omega_0}, \quad (5)$$

where z is the number of turns of the helical lines along the rotary working body where the cutting knives are installed (Fig. 3).

For the design scheme of direct cutting, it is possible to write the equality $0.5S=R\sin\alpha_1+r_0\alpha_1$ from which the equation to determine the angle α_1 is:

$$F(\alpha_1)=R\sin\alpha_1+r_0\alpha_1-0.5S. \quad (6)$$

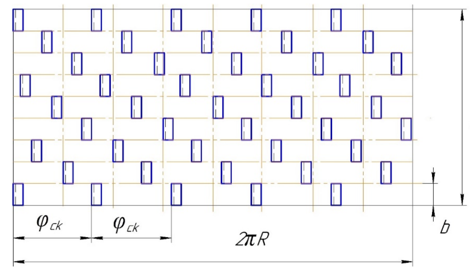


Fig. 3. An example of the cutting knives layout on a rotary working body at $z=5$

The angle α_2 is equal to:

$$\alpha_2=\arccos\frac{R-h_c}{R}, \quad (7)$$

where h_c is the depth of soil cutting by the rotary working body.

The value of the angle α_1 for the calculated reverse cutting pattern:

$$\alpha_1=\arccos\frac{R-h_c}{R}. \quad (8)$$

Also, for this scheme, the equation, $0.5S=R\sin\alpha_2-r_0\alpha_2$, is valid, where the equation to determine the angle α_2 is:

$$F(\alpha_2)=R\sin\alpha_2-r_0\alpha_2-0.5S. \quad (9)$$

Ground cutting angle for both design cases:

$$\alpha_c=\alpha_1+\alpha_2. \quad (10)$$

The equation to determine the angle α_0, which corresponds to the maximum cutting depth for forward soil cutting, is as follows:

$$F(\alpha_0)=r_0(\alpha_c-\alpha_0+\alpha_1)+R[\sin(\alpha_c-\alpha_1)+\sin\alpha_1]-$$
$$-(R-h_c)\tan(\alpha_0-\alpha_1)-1.5S. \quad (11)$$

And for reverse cutting:

$$F(\alpha_0)=r_0(\alpha_1-\alpha_0-\alpha_c)+R[\sin\alpha_1-\sin(\alpha_1-\alpha_c)]-$$
$$-(R-h_c)\tan(\alpha_1-\alpha_0)-1.5S. \quad (12)$$

Maximum depth of cut $h_{\max}$:

$$h_{\max}=\sqrt{\Delta x^2+\Delta y^2}. \quad (13)$$

For forward cutting:

$$\Delta x=x_B-x_D=r_0\alpha_1+R[\sin(\alpha_0-\alpha_1)+\sin\alpha_1]-$$
$$-(R-h_c)\tan(\alpha_0-\alpha_1)-0.5S; \quad (14)$$

$$\Delta y=y_D-y_B=R[\cos(\alpha_0-\alpha_1)-1]+h_c. \quad (15)$$

For reverse cutting:

$$\Delta x=x_B-x_D=S+r_0\alpha_0+R\sin(\alpha_1-\alpha_0)-R\sin\alpha_1; \quad (16)$$

$$\Delta y=y_D-y_B=R[\cos(\alpha_1-\alpha_0)-1]+h_c. \quad (17)$$

Longitudinal cross-sectional area of soil chips cut in case of forward cutting:

$$F_c = F_{AEOC} - F_{FOCB} - F_{AEFB}, \quad (18)$$

where F_{AEOC} is the area of the AEOC shape; F_{FOCB} is the area of the FOCB shape; F_{AEFB} is the area of the AEFB shape.

The corresponding areas are equal to:

$$F_{AEOC} = \int_0^{\alpha_c} \psi_1(\alpha)\varphi_1'(\alpha)\mathrm{d}\alpha = \int_0^{\alpha_c} \left[r_0 + R\cos(\alpha - \alpha_1)\right]^2 \mathrm{d}\alpha; \quad (19)$$

$$F_{FOCB} = \int_{2\alpha_1}^{\alpha_c} \psi_1(\alpha)\varphi_1'(\alpha)\mathrm{d}\alpha = \int_{2\alpha_1}^{\alpha_c} \left[r_0 + R\cos(\alpha - \alpha_1)\right]^2 \mathrm{d}\alpha; \quad (20)$$

$$F_{AEFB} = S(R + r_0 - h_c). \quad (21)$$

Longitudinal cross-sectional area of soil chips cut in case of reverse cutting:

$$F_c = F_{AOEC} - F_{BFEC} - F_{AOFB}, \quad (22)$$

where F_{AOEC} is the area of the AOEC shape; F_{BFEC} is the area of the BFEC shape; F_{AOFB} is the area of the AOFB shape.

The corresponding areas are equal to:

$$F_{AOEC} = \int_0^{\alpha_c} \psi_2(\alpha)\varphi_2'(\alpha)\mathrm{d}\alpha = \int_0^{\alpha_c} \left[R\cos(\alpha_1 - \alpha) - r_0\right]^2 \mathrm{d}\alpha; \quad (23)$$

$$F_{BFEC} = \int_0^{\alpha_1-\alpha_2} \psi_2(\alpha)\varphi_2'(\alpha)\mathrm{d}\alpha = \int_0^{\alpha_1-\alpha_2} \left[R\cos(\alpha_1 - \alpha) - r_0\right]^2 \mathrm{d}\alpha; \quad (24)$$

$$F_{AOFB} = S(R - r_0 - h_c). \quad (25)$$

The length of the soil cutting path L_C is determined by the length of the ADC part of trochoid 1 and is equal to, for forward cutting:

$$L_c = \int_0^{\alpha_c} \sqrt{\left[\varphi_1'(\alpha)\right]^2 + \left[\psi_1'(\alpha)\right]^2} = \int_0^{\alpha_c} \sqrt{\left(r_0^2 + R^2\right) + 2r_0 R\cos(\alpha - \alpha_1)} \cdot \mathrm{d}\alpha. \quad (26)$$

For reverse cutting:

$$L_c = \int_0^{\alpha_c} \sqrt{\left[\varphi_2'(\alpha)\right]^2 + \left[\psi_2'(\alpha)\right]^2} = \int_0^{\alpha_c} \sqrt{\left(r_0^2 + R^2\right) - 2r_0 R\cos(\alpha_1 - \alpha)} \cdot \mathrm{d}\alpha. \quad (27)$$

Average thickness of soil cutting h_{av}:

$$h_{av} = \frac{F_c}{L_c}. \quad (28)$$

The calculation scheme to determine the kinematic parameters of soil cutting is show in Fig. 4.

Absolute speed of the cutting edge of the knife for forward cutting (Fig. 4, *a*):

$$V_a = \sqrt{V_m^2 + V_0^2 + 2V_m V_0 \cos(\alpha_{c.av} - \alpha_1)}. \quad (29)$$

For reverse cutting (Fig. 4, *b*):

$$V_a = \sqrt{V_m^2 + V_0^2 + 2V_m V_0 \cos(\alpha_1 - \alpha_{c.av})}, \quad (30)$$

where $V_0 = \omega_0 R$ is the liner velocity of the knife cutting edge; $\alpha_{c.av} = 0.5\alpha_c$ is average angle of soil cutting.

The angle of inclination of the vector V_a to the horizontal direction:

– forward cutting:

$$\psi = \arcsin\left[\frac{V_0}{V_a}\sin(\alpha_{c.av} - \alpha_1)\right]; \quad (31)$$

– reverse cutting:

$$\psi = \arcsin\left[\frac{V_0}{V_a}\sin(\alpha_1 - \alpha_{c.av})\right]. \quad (32)$$

The direction of action of the tangential component of the soil cutting resistance is opposite to the direction of the absolute speed V_a of the cutting edge of the knife (Fig. 5).

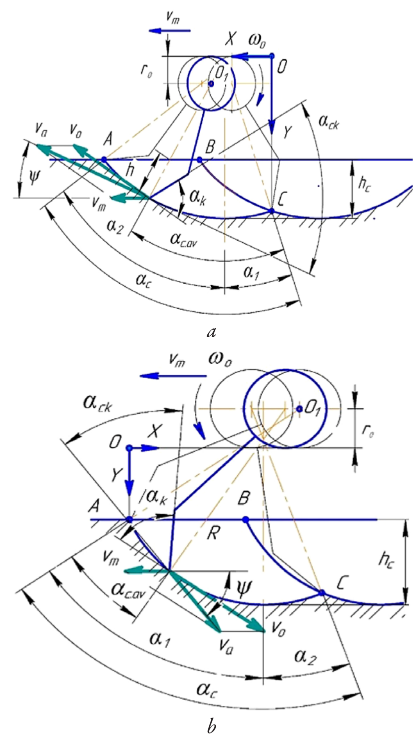


Fig. 4. Calculation scheme to determine the kinematic parameters of soil cutting by a rotary working body: *a* – forward cutting; *b* – reverse cutting

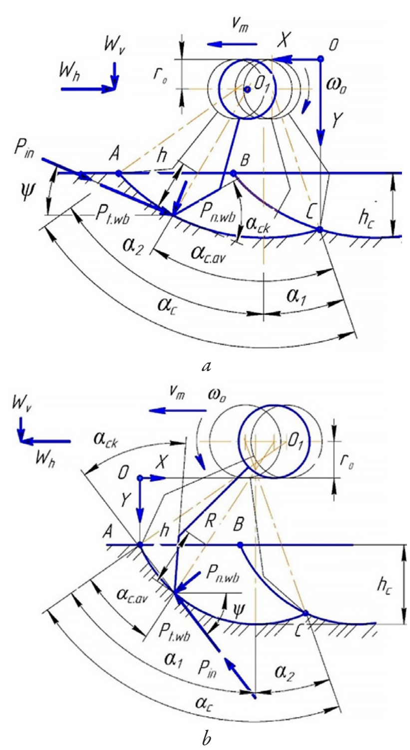


Fig. 5. Calculation scheme to determine the resistance to soil cutting by a rotary working body: *a* – forward cutting; *b* – reverse cutting

The average value of the tangential component of the cutting resistance of a soil-cutting knife based on the theory of the limiting equilibrium of soils [10]:

$$P_{t.ck}=\left(1+\text{ctg}\,\alpha_{ck}\tan\delta\right)A_1bh_{av}\left[\frac{\gamma_s gh_{av}}{2}+c_w\,\text{ctg}\,\rho\left(1-\frac{1}{A_1}\right)\right], \tag{33}$$

where δ is the angle of extremal friction of soil; ρ is the angle of internal friction soil; b is the width of the cutting knife; c_w is cohesion of the soil; α_{ck} is the angle of cutting of the soil by knife; γ_s is the density of the soil in the natural state.

The value of the coefficient A_1 is determined analytically depending on the cutting angle α_{ck}:

– when $\alpha_{ck}\le\frac{1}{2}\arcsin\frac{\sin\delta}{\sin\rho}-\frac{\delta}{2}$,

$$A_1=\frac{1-\sin\rho\cos2\alpha_{ck}}{1-\sin\rho};$$

– when $\alpha_{ck}>\frac{1}{2}\arcsin\frac{\sin\delta}{\sin\rho}-\frac{\delta}{2}$,

$$A_1=\frac{\cos\delta}{1-\sin\rho}\left(\cos\delta+\sqrt{\sin^2\rho-\sin^2\delta}\right)e^{\left(2\alpha_{ck}-\pi+\delta+\arcsin\frac{\sin\delta}{\sin\rho}\right)\tan\rho}.$$

The maximum value of the tangential component of soil cutting with a cutting knife:

$$P_{t.ck.\max}=$$
$$=\left(1+\text{ctg}\,\alpha_{ck}\tan\delta\right)A_1bh_{\max}\cdot\left[\frac{\gamma_s gh_{\max}}{2}+c_w\,\text{ctg}\,\rho\left(1-\frac{1}{A_1}\right)\right]. \tag{34}$$

The angle α_{ck} is equal to:
– for forward cutting:

$$\alpha_{ck}=\alpha_k-\alpha_{c.av}+\alpha_1+\psi; \tag{35}$$

– for reverse cutting:

$$\alpha_{ck}=\alpha_k-\alpha_{c.av}+\alpha_1-\psi, \tag{36}$$

where α_k is the angle of inclination of the cutting knife to its radius.

Operation to overcome the cutting resistance force by a single cutting knife:

$$A_{ck}=P_{t.ck}L_c. \tag{37}$$

During the operation process, all cutting knives cut the soil in one turnover of the rotary working body. Therefore, the total work on cutting the soil by the working body in a turnover is equal to:

$$A_{wb}=\frac{2\pi}{\varphi_{ck}}\cdot\frac{B}{b}\cdot A_{ck}, \tag{38}$$

where φ_{ck} is the angular pitch of the cutting knives; B is the width of the rotary working body.

The average value of the total tangential component of the cutting resistance of the rotary tillage tool is:

$$P_{t.wb}=\frac{A_{wb}}{L_0}, \tag{39}$$

where L_0 is the path of the cutting edges of the working body knives per one turnover of the working body for forward and reverse cutting.

Path L_0 for forward cutting:

$$L_c=\int_0^{2\pi}\sqrt{\left(r_0^2+R^2\right)+2r_0R\cos\left(\alpha-\alpha_1\right)}\cdot d\alpha. \tag{40}$$

Path L_0 for reverse cutting:

$$L_c=\int_0^{2\pi}\sqrt{\left(r_0^2+R^2\right)-2r_0R\cos\left(\alpha_1-\alpha\right)}\cdot d\alpha. \tag{41}$$

The solution of equations (6), (9), (11), (12), as well as the finding of integrals by formulas (19), (20), (23), (24), (26), (27), (40), (41) is carried out using the MATHCAD application package.

Average value of the total normal component of the soil cutting resistance:

$$P_{n.wb}=P_{t.wb}\,\text{ctg}\left(\alpha_{ck}+\delta\right). \tag{42}$$

After the soil is cut, it accelerates to an absolute speed V_a, which leads to resistance in the form of an inertial force P_{in}.

The mass of soil cut per one turnover of the rotary working body is:

$$m_1=\frac{2\pi V_m Bh_c\gamma_s}{\omega_0}. \tag{43}$$

From the equation $\left(m_1V_a^2\right)/2=P_{in}L_0$ the resistance from soil acceleration for a certain design case is equal to:

$$P_{in}=\frac{m_1V_a^2}{2L_0}. \tag{44}$$

The average value of the soil cutting resistance with the rotary working body in the direction of the machine movement in case of forward cutting:
– horizontal:

$$W_h=\left(P_{t.wb}+P_{in}\right)\cos\psi-P_{n.wb}\sin\psi; \tag{45}$$

– vertical:

$$W_v=\left(P_{t.wb}+P_{in}\right)\sin\psi+P_{n.wb}\cos\psi. \tag{46}$$

The average value of the soil cutting resistance with the rotary working body in the direction of the machine movement in case of reverse cutting:
– horizontal:

$$W_h=\left(P_{t.wb}+P_{in}\right)\cos\psi+P_{n.wb}\sin\psi; \tag{47}$$

– vertical:

$$W_v=\left(P_{t.wb}+P_{in}\right)\sin\psi-P_{n.wb}\cos\psi. \tag{48}$$

The average torque value on the drive shaft of the rotary working body:
– for forward cutting:

$$M_{tor.av}=\begin{bmatrix}\left(P_{t.wb}+P_{in}\right)\cos\left(\alpha_{c.av}-\alpha_1-\psi\right)+\\+P_{n.wb}\sin\left(\alpha_{c.av}-\alpha_1-\psi\right)\end{bmatrix}R; \tag{49}$$

– for reverse cutting:

$$M_{tor.av}=\begin{bmatrix}\left(P_{t.wb}+P_{in}\right)\cos\left(\alpha_{c.av}-\alpha_1+\psi\right)+\\+P_{n.wb}\sin\left(\alpha_{c.av}-\alpha_1+\psi\right)\end{bmatrix}R. \tag{50}$$

Power consumption for the drive of the rotary working body:

$$N = M_{tor.av}\omega_0. \quad (51)$$

Energy intensity of the operation process of cutting soil with a rotary working body:

$$E = \frac{N}{Bh_c V_m}. \quad (52)$$

Example of calculation of a rotary working body in case of forward cutting with the following initial data: diameter of the rotary working $D = 0.8$ m; width of the rotary working body $B = 2.0$ m; rotation speed $n_0 = 120\ \text{min}^{-1}$; speed of the machine $V_m = 0.5$ m/s; depth of soil cutting $h_c = 0.2$ m; number of turns of the helical lines of the cutting knives $z = 5$; width of the cutting knives $b = 0.25$ m; angle of inclination of the cutting knives $a_k = 45°$; soil type – loam; angle of internal friction $\rho = 25°$; angle of external friction $\delta = 21°$; soil adhesion $c_w = 0.03$ MPa; soil density in the natural state $\gamma_s = 2100\ \text{kg/m}^3$.

Calculation results: angles $\alpha_1 = 3.3°$; $\alpha_2 = 60°$; $\alpha_p = 63.3°$; $\alpha_0 = 59.5°$; $\psi = 25.9°$; maximum cutting depth $h_{\max} = 0.04$ m; average cutting depth $h_{av} = 0.021$ m; absolute cutting edge speed $V_a = 5.5$ m/s; components of cutting $P_{t.wb} = 2328$ H; $P_{n.wb} = 1160$ H; $W_h = 2711$ H; $W_V = 2605$ H; average torque on the drive shaft $M_{tor.wb} = 1627$ Hm; power consumption for the drive of the rotary working body $N = 20.5$ kWt; energy intensity of the operation process of soil cutting $E = 102.2\ \text{kWt} \cdot \text{s/m}^3$.

Practical significance. The obtained theoretical studies can be used as a methodology for engineering calculation of rotary working bodies in various branches of mechanical engineering.

Research limitations. The research results are limited to the physical and mechanical characteristics of soils, namely, thawed soils of categories I–IV are taken into account, for which a mathematical model for determining the cutting resistance with a straight knife is given in the studies. To apply studies in the interaction of rotary working bodies with other types of environments, it is necessary to take into account the features of their cutting using appropriate mathematical models to determine the cutting resistance of the environment by cutting knives or cutters provided for by the design of the working body.

Influence of martial law conditions. The studies performed can be used to calculate and create active working bodies for demining the area from explosive objects.

Prospects for further research. Further research involves increasing the efficiency of rotary working bodies by developing and calculating means of directional transportation of the soil environment from the cutting zone.

4. Conclusions

Methods were developed to calculate the geometric, kinematic, and power parameters of the rotary working bodies in earthmoving and road construction machines. These calculations consider the actual trajectories of the cutting elements and their quantity.

Additionally, the methods account for variations in soil cutting thickness and the interaction conditions between the working body and the excavation environment. Physical and mechanical properties of the soil are also included in the analysis.

The effectiveness of the methodology is confirmed by a practical calculation of a real rotating working body. The obtained results made it possible to refine its parameters and take a more substantiated approach to the selection and design of the power equipment. As a result of applying the proposed methodology, a comparative analysis of direct and reverse cutting of materials with different physical and mechanical properties showed that the differences in drive power consumption and energy intensity between the cutting methods do not exceed 5 %. The average horizontal component of resistance during reverse cutting is 1.15 to 1.25 times greater than during direct cutting, while the average vertical component of resistance is 2.0 to 2.5 times lower.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship, or other, that could influence the research and its results presented in this article.

Financing

The study was conducted without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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