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TRANSPORTING ABILITY CALCULATION OF THE ROTOR OF SOIL-CULTIVATING LOOSENING AND SEPARATING VEHICLE

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Currently, loosening and separating machines that combine the operations of crumbling and separating of soil according to the treated layer depth have come to the forefront. Interaction of the rotor blade of these machines with the soil comprises three stages: soil core formation; steady movement; and dumping of soil from the separating grid. The article determined the direction and magnitude of soil displacement, parameters and shape of the furrow formed after the ripper passage. Based on theoretical research, a mathematical model of the interaction of working bodies with the soil was developed. The initial data were obtained experimentally, and the model was justified. As a result, it was found that the supplied soil layer thickness and the fracture angle of ripper have the greatest influence on the transporting capacity of rotor ripper. Reducing the rotor blade entry angle into the soil from 45° to 30° made it possible to raise the second soil feed of the loosening and separating machine by more than 40 times. The width of rotor ripper practically does not affect the transporting capacity. Changing the angle of ripper entry into the soil allowed obtaining of the required transporting capacity of ripping and separating machine without changing the rotor design. Practical significance of the study lies in the possibility of increasing the work productivity without increasing its energy indicators.

Keywords: soil layer thickness; tillage quality; energy intensity; ripper fracture angle; soil core

Improving the tillage quality by increasing the energy intensity of tools leads to a decrease in unit productivity and an increase in timing of technological operations (Blednykh, Svechnikov and Troyanovskaya, 2016; Ovchinnikov et al., 2017; Svechnikov and Troyanovskaya, 2019). This has a negative impact on crop yields and the cost of their production (Modolo et al., 2012; Šarauskis et al., 2020).

High-quality crumbling of the surface layer of chernozem soils of medium and heavy mechanical composition is provided by milling working bodies. However, the cutters have a high energy consumption, which limits their use at present (Daraghmeh et al., 2019; Levchenko et al., 2016).

When justifying the geometric shape of a working body, the question of priority of the qualitative and energy performance of tools is inappropriate. These two indicators of a working tool must be evaluated in a complex relationship – as integral elements of a closed cycle of crop cultivation technology (Blednykh, Svechnikov and Troyanovskaya, 2017; Mamatov et al., 2021).

Currently, tillage loosening and separating machines are widely used in the agro-industrial complex (Fig. 1).

The operation principle of working bodies of these machines is grounded on the combination of crumbling



Fig. 1 Soil-cultivating friable-separating machine
Source: Syromyatnikov and Khramov, 2021

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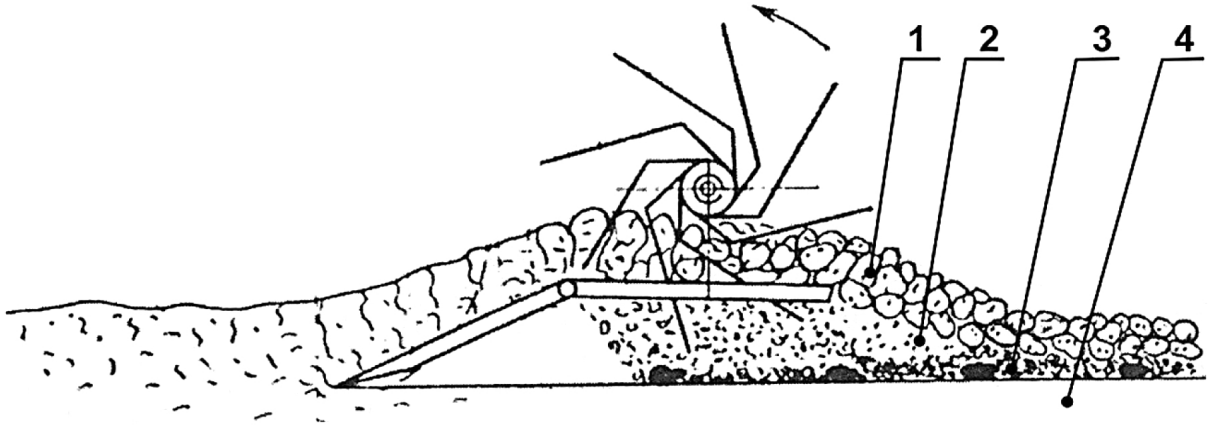


Fig. 2 Structure of treated soil layer
1 – over-seed layer; 2 – seed layer; 3 – under-seed layer; 4 – subsurface layer
Source: Syromyatnikov, 2018

and separation of soil based on the depth of treated layer (Syromyatnikov et al., 2021). In one pass of the unit, together with high-quality soil treatment, the seeds are deepened, and the rhizomes of weeds are released to the surface (Syromyatnikov and Khramov, 2021). This is a mechanical way of weeds removing (Bond and Grundy, 2001). The tillage-separating machine improves the physical and mechanical properties of the treated soil layer (Fig. 2). Thanks to separation of this soil layer, its differentiation by structural composition occurs. The interaction of active-passive working bodies allows the quality improvement of soil layer crumbling while reducing energy costs (Mamatov et al., 2021). Active working bodies crumble the soil layer, move it along the separating grid, redistributing it thus along the structure and thereby providing a finely lumpy structure in the seed sealing zone.

The location of rippers on the rotor shaft affects changes in the drive torque and uniformity of the machine stroke. The rippers are placed on the shaft along a helical line. The beginning of each helical line coincides with the end of the next helical line in opposite part of the shaft. The rippers are evenly spaced along the entire shaft circumference with an angular distance between adjacent rippers (where s – number of rippers). The rippers are placed in a spiral with a constant angular pitch symmetrically relative to the longitudinal machine axis (Fig. 3). This eliminates the torque in the transverse plane, which can disrupt the machine stability in direction of movement and depth (Syromyatnikov, 2021).

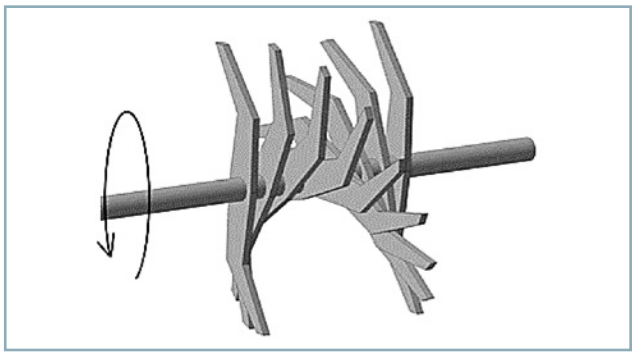


Fig. 3 Rotor of soil-cultivating loosening and separating machine
Source: Pashchenko and Syromyatnikov, 2019

The quality and energy intensities of a tillage machine are characterized by the ability of its loosening device to pass the soil coming from the ploughshare through the separating grid. The throughput transporting capacity of the ripping device is determined by its second soil feed. From the instance the rotor rippers enter the soil until the soil is dropped from the separating grid, their transporting capacity changes. The worst conditions are created in the instance of rippers' entry into the soil when a soil core forms in front of them, complicating the rotor's operation and the descent of soil from ploughshare to separating grid.

The aim of this work was to determine the ways to increase the conveying capacity of the rotor of loosening and separating device in tillage machine.

Material and methods

The interaction of rotor ripper with soil was examined taking into account the soil rheological properties (Aulin et al., 2018; Klyueva and Khaidapova, 2019). The soil was considered a quasi-homogeneous three-phase medium, making it possible to apply the laws of deformation of ideal bodies to it (Chang, Lai and Zhang, 2019). This approach considers the soil to be a combination of perfectly elastic, viscous, and plastic bodies connected in series and in parallel (Markgraf, Horn and Peth, 2016; Swain and Ghosh, 2019). The impact of working bodies of agricultural machines on the soil for no more than 0.5 seconds leads to elastic-viscous-plastic deformations.

Let us examine the ripper interaction with soil in more detail.

The first phase of work is characterized by the ripper deepening into the soil. Tangential stresses do not exceed the internal resistance of the soil to shear. The soil has the properties of a linearly deformable medium. When the stresses reach the limit value, plastic deformations begin in the soil. The increase rate of these deformations exceeds the rate of load increase. A soil core is formed before the ripper.

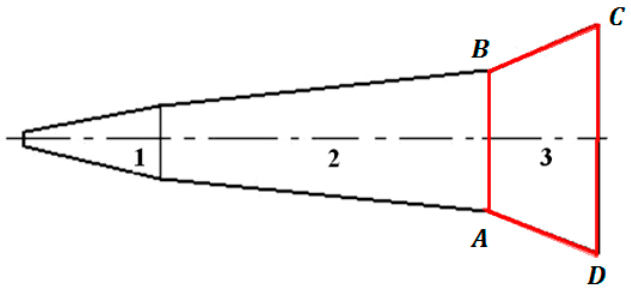


Fig. 4 Furrow shape in soil during the first, second and third phases of rotor ripper passing

In the second phase of work, the soil core grows until the internal stresses in it reach the limit values. This moment is characterized by the beginning of its destruction. The remaining part of soil core moves along with the ripper, which leads to an increase in the soil core. Consequently, a stable-sized soil core is formed in front of the ripper. Periodically, the soil growing on it moves a certain distance in the ripper movement direction. This steady-state process occurs as long as the voltages do not exceed the permissible values.

From this moment, the third phase of the ripper's effect on the soil begins. The soil core is separated from the main part of soil and discharged from the separating grid. After the ripper passage, a furrow with a trapezoid cross-section remains in the soil (Fig. 4), the lower base of which is equal to the ripper width. As the ripper deepens into the soil, the depth and width of the furrow increase. The shape of longitudinal section of furrow is determined by the trajectory of the most distant ripper point from the rotation axis in the soil.

To confirm the furrow shape, a full-scale experiment was conducted. For these purposes, a ripper was installed on the gearbox shaft of the ripping-separating device. Under it, there was a box with a separating grate instead of a bottom. The distance between the bars was 0.01 m. The pre-sifted and moistened soil was filled into the box in layers 0.02 m thick. Chalk layers were laid between the soil layers, the last of which was located below the depth of the ripper stroke. Chalk lines perpendicular to the plane of rotation of the rotor ripper were applied on the soil surface after 0.015 m. The shape and dimensions of formed furrow were determined after the passage of the rotor using photographic equipment and measurements.

Theoretically, formed furrow volume V in soil was calculated as follows (Fig. 5):

$$V_{ABCDFE} = S_{O'MG}\left(QS + \frac{DA + SC}{3}\right) \quad (1)$$

where: $S_{O'MG}$ – cross-sectional area of the figure; $QS = AB = EF = a$ – rotor blade thickness; $DQ = SC$ – furrow height

Cross-sectional area *Q'MG* was determined as follows:

$$S_{Q'MG} = \int_{a_0}^{a_i}\int_{R_1}^{R} RdRd\alpha \pm \int_{a_1}^{a_2}\int_{R_1}^{R_2} RdRd\alpha \quad (2)$$

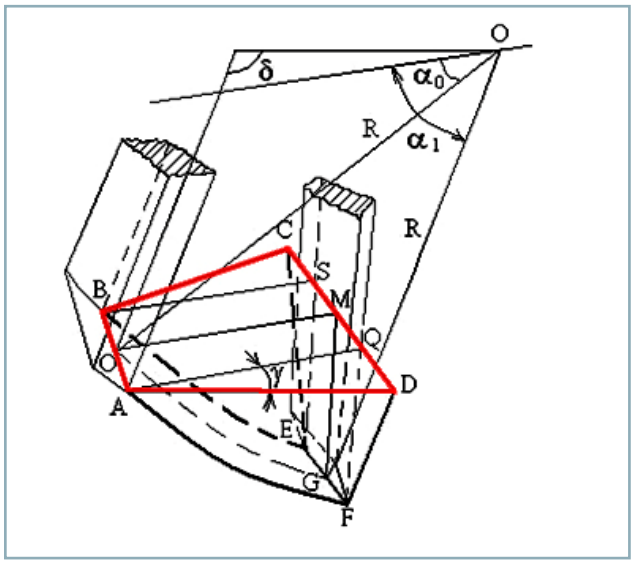


Fig. 5 Scheme for determining the furrow volume in soil

where: R – rotor radius; a_0 – initial angle of blade entry into the soil; a_i – current angle of the rotor blade rotation; the sign ± is selected depending on the blade fracture angle

The integration limits in Eq. 2 are equal to $R_1 = R\frac{\sin\alpha_0}{\sin\alpha_1}$, $R_2 = R\frac{\sin\beta}{\sin(\alpha_i - a_0 + \beta)}$,

$$\alpha_i = arctg\frac{\sin a_0}{\cos a_0 - 2\sin\left(\frac{\alpha_i - a_0}{2}\right)\cos\left(\frac{\alpha_i - a_0}{2} + \beta\right)/\sin(\alpha_i + \beta)},$$

where β angle between the tangent to the cutting edge and the blade radius vector.

The height of the figures *AQFD* and *BSEC* were calculated using the formula:

$$DQ = SC = AQtg\gamma = 2R\frac{\sin\left(\frac{a_i - a_0}{2}\right)\cos\left(\frac{a_i - a_0}{2} + \beta\right)}{\sin(a_i + \beta)}tg\gamma \quad (3)$$

where: γ – angle between the sides *AQ* and *AD* of the triangle

After integrating Eq. 2 with taking into account Eq. 3, the grove volume is obtained:

$$V_{ABCDFE} = \frac{R^2}{2}\left(1 + \frac{4}{3}A_1 Rtg\gamma\right) \quad (4)$$
$$\left[a_i - a_0 + \sin^2 a_0\left(ctga_i - ctga_0 \pm (ctga_i - A_2)\right) \pm \pm \sin^2\beta\left(ctg\beta - ctg(a_i + \beta - artgA_2)\right)\right]$$

where: $A_1 = \frac{\sin\left(\frac{a_i - a_0}{2}\right)\cos\left(\frac{a_i - a_0}{2} + \beta\right)}{\sin(a_i + \beta)}$; $A_2 = \frac{\cos a_0 - 2A_1}{\sin a_0}$

The rotor transporting capacity of the tillage-separating machine directly depends on the furrow volume *V*

in soil. By differentiating Eq. 4 in time, a mathematical model of the second soil feed Y with a rotor blade was obtained:

$$Y = \frac{\omega R^2}{2}\left(a + \frac{4}{3}A_1 R tg\gamma\right)\left\{\begin{array}{l}\sin^2 a_0\left[\pm\left(\frac{2A_3}{\sin a_0} - \frac{1}{\sin^2 a_i}\right) - \frac{1}{\sin^2 a_i}\right]\pm \\ \pm\sin^2\beta\left[\frac{1 - \frac{2A_3}{\sin a_0\left(1+A_2^2\right)}}{sin^2(a_i+\beta-artcA_2)}\right]+1\end{array}\right\}+ \quad (5)$$

$$+\frac{4}{6}\omega A_3 R^3 tg\gamma$$

$$\left[\begin{array}{c}\sin^2 a_0\left[ctga_i - ctga_0 \pm (ctga_i - A_2)\right]\pm \\ \pm\sin^2\beta\left[ctg\beta + ctg(a_i+\beta-artctA_2)\right] + a_i - a_0\end{array}\right]$$

where: $A_3 = \frac{1}{2}A_1\left[ctg\frac{a_i - a_0}{2} - tg\left(\frac{a_i - a_0}{2} + \beta\right) - 2ctg(a_i + \beta)\right]$

ω – the angular speed of rotor rotation

Considering the Eq. 5, it is evident that the transporting capacity Y of the tillage-separating machine depends on the rotor radius R, its angular rotation speed ω, the blade thickness a and the angles a_0, β and the current angle $\alpha_i = \omega t$.

The radius R and angular velocity ω of the rotor determine the work energy performance. Therefore, it is impractical to increase the blade transporting capacity by increasing the number of blades. The blade thickness α is limited by separating grid design features, which determine the machine quality performance.

The angles α_0 and β ultimately determine the blade entry angle into the soil $\Delta = \alpha_0 + \beta$. Therefore, further research was devoted to increasing the rotor conveying capacity by changing the entry angle of rotor blades into the soil.

Results and discussion

The main rotor purpose is to move the soil along the separating grid. The amount of soil passing through the separating grid gaps and dropping from it in one pass of the ripper is the main indicator of tillage machine transporting capacity. During the experiment, the soil that dropped from the separating grid and passed through its gaps was weighed. Factors affecting the amount of displaced soil were identified and provided in Table 1.

Based on the experimental results, the regression equation of the displaced soil mass was obtained in the following form:

$$m = 0.292 + 0.052x_1 + 0.056x_2 + 0.056x_3 + \\ + 0.142x_4 + 0.099x_5 + 0.037x_6 \quad (6)$$

where: m – displaced soil mass; x_i – factors affecting the amount of displaced soil

Verification of the coefficients according to the Student's criterion showed that the selected factors are significant with 95% probability. Regression Eq. 6 indicate that the greatest influence on the rotor ripper transporting capacity is exerted by the layer thickness x_4 of supplied soil to the ripping-separating device, and the fracture angle x_5 of rotor ripper. The width of rotor ripper x_6 has the least influence.

The soil layer thickness x_4 supplied to the loosening and separating device, within the change limits in the depth of seeding (0.01–0.05 m), does not practically change. Further studies were carried out at the thickness of the soil layer

Table 1 Designations and levels of variation of factors affecting the mass of displaced soil

No.	Name of the factor	Designation	Value
1	soil moisture (%)	x_1	19.2–24.4
2	rotor speed (s^{-1})	x_2	2.10–4.30
3	rotor radius (m)	x_3	0.19–0.31
4	soil layer thickness on the grid (m)	x_4	0.05–0.10
5	fracture angle of the ripper (deg)	x_5	90.0–270.0
6	ripper width (m)	x_6	0.025–0.05

Table 2 Experimental matrix and its results

Experience no.	x_1	x_2	x_3	x_4	x_5	x_6	kg
1	+	+	–	–	–	+	0.117
2	+	–	+	–	–	–	0.118
3	+	–	–	+	+	+	0.562
4	–	+	+	+	–	+	0.484
5	–	+	–	–	+	–	0.212
6	–	–	+	–	+	+	0.209
7	+	+	+	+	+	–	0.637
8	–	–	–	+	–	–	0.111

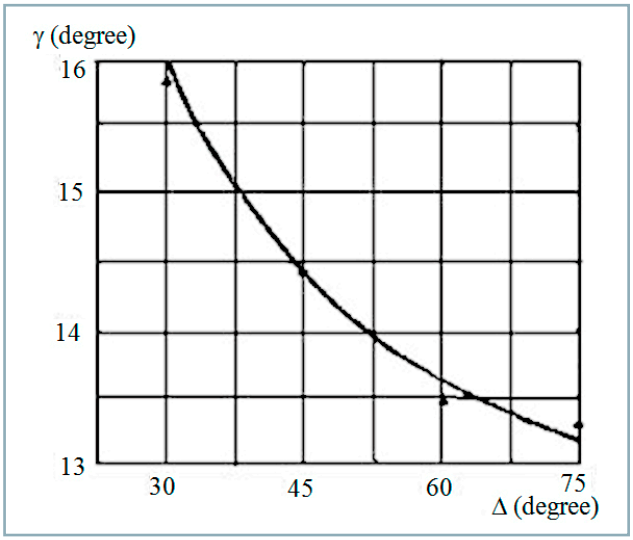


Fig. 6 Relationship between the furrow wall slope and the blade entry angle Δ into the soil

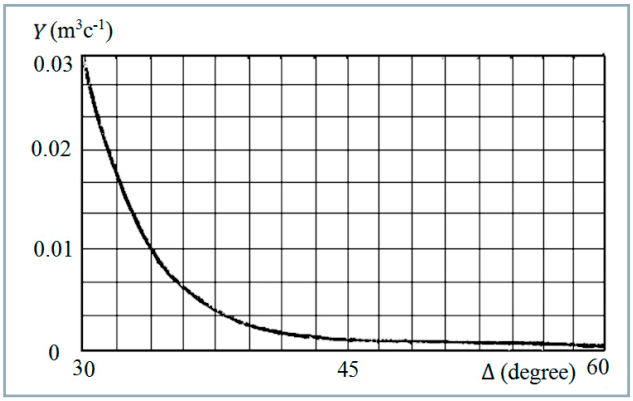


Fig. 7 Dependence of the second soil feed on the blade entry angle of entry into the soil

x_4 = 0.12 m, the rotor speed ω = 2.5 s^{-1} and soil moisture x_1 = 22.6%. The 1/8 matrix of a fractional replica from 2^6 is presented in Table 2.

The experimental data reliability was 99%.

Structurally, the inclination angle of furrow wall varies between 13° and 16°. The effect of this angle γ on the blade entry angle into the soil Δ is shown in Fig. 6.

The dependence of the second soil feed *Y* on the angle Δ at rotor radius *R* = 0.2 m, rotor angular velocity ω = 15.7 s^{-1}, blade thickness α = 0.006 m, γ = 14°, and α_0 = 35° is shown in Fig. 7.

Conclusion

The interaction process of rotor blades in a loosening and separating device with the soil comprises three stages: soil core formation, steady movement, and dumping of soil from the separating grid. The worst conditions for soil transporting in the machine technological process take place at the first stage of work. In the instance of blade penetrating, a soil core is formed in front of it, causing additional resistance to the soil layer movement. This leads to increasing of the process energy intensity and deterioration of the machine quality.

The amount of the soil rolling in front of the rotor can be reduced by reducing the entry angle of working blade edge into the soil Δ, as it showed the greatest effect on the second soil feed *Y* in the range from 30° to 45°. Reducing the blade entry angle Δ from 60° to 45° increases the second soil feed *Y* it the first stage by 2.52 times. Reducing it from 45° to 30° increases the second soil feed *Y* by 42.4 times. A further decreasing of the angle Δ does not practically affect the second soil feed *Y*.

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