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SUBSTANTIATING THE RATIONAL SHAPE OF A DRUM-TYPE WORKING TOOL FOR SURFACE SOIL TREATMENT

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The working bodies of agricultural implements should minimize resistance to movement. The shape of a curved tooth, which is fixed between two cylindrical disks, has been considered in this paper. Several such sections on the shaft form a drum similar to a harrow roller or a needle harrow. When rolling, the tooth sinks into the soil, followed by its loosening. The task was to find such a shape of the tooth, which at the first stage of immersion in the soil would slide over it as much as possible with minimal deformation, and at the second stage would balance it and turn it over.

The object of the study is a drum-type working body. The work of a straight tooth with its transformation into a curved tooth was analyzed. As a result of such an analysis and subsequent search, a rational shape of a drum-type tillage working body was obtained for the purpose of reducing resistance when it is buried in the soil. The involute of a circle turned out to be such a curve. A tooth in the form of an involute of a circle has a peculiarity: at the moment of contact of the tooth with the ground, the absolute velocity vector is directed perpendicular to it. The result is explained by the fact that as the disks roll, the tooth sinks into the soil, and the point of entry remains unchanged, and the tooth itself slides practically along itself, especially in the upper layers of the soil. In known working bodies, their curvilinear form was selected experimentally. The proposed shape of the working body was obtained analytically. To reduce the resistance of the teeth entering the soil, the ratio of the tillage depth to the radius of the drum is important. The immersion of the blade to the full depth should correspond to a 30° rotation of the drum. After diving to the maximum depth, it begins to weigh the soil to the surface or loosen it. The field of application of such a tooth shape can be the improvement of the working bodies of tillage implements

Keywords: energy intensity of penetration into the soil, tooth shape, least resistance, involute of a circle

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1. Introduction

A significant number of tillage tools are used in agricultural machines. Their shape depends on the purpose and principle of action. In harrows, the purpose of working bodies is leveling, mixing, and loosening the soil, destroying weeds. In cultivators – pre-sowing and post-sowing tillage of the soil, its loosening, mixing, and preparation for sowing

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or caring for crops. In rollers – destruction of the soil crust, clods, loosening, leveling and compaction of the soil surface. In milling machines – loosening, mixing, and leveling of the soil. According to the principle of operation, they are passive (harrows, rollers, cultivators) and active (mills). An important characteristic of the tillage unit is traction resistance, which affects the consumption of fuel and lubricants. Tillage units must perform their work qualitatively in compliance with agrotechnical requirements and at the same time have the minimum possible traction resistance. This paper considers the shape of a curvilinear working body, which can be used as a passive drum-type body, provided that it offers the minimum possible resistance when forced into the soil. Existing working bodies are the result of many years of experimental and theoretical research. At the moment, they have perfect forms, but this does not mean the refusal of further improvement. In addition, it is necessary to reduce the traction resistance of the unit.

2. Literature review and problem statement

Monograph [1] focuses on ensuring the efficiency of the working bodies of cultivators. It shows that the structural parameters of the working body affect the effectiveness of its interaction with the soil environment. In particular, the curvilinear shape of the working body is considered. However, the monograph does not cover what shape the working body should be given in order for it to penetrate the soil with minimal resistance.

The design of the surfaces of the working bodies of machines that interact with the soil is considered in paper [2]. The authors have developed a model of the technological process of soil cultivation, according to which it is proposed to consider the soil environment as a Newtonian viscous liquid with the subsequent application of the dynamics of such environments. It is claimed that one of the main requirements for tillage units is to ensure the minimum possible traction resistance. However, the authors do not propose ways to implement such a requirement.

In [3], a methodology for substantiating the construction scheme of the arrow paw is proposed based on the analysis of the body of the biological prototype – the California stingray. An example of a specific calculation of the profile of the cutting perimeter, the basic size of which corresponds to the dimensions of the technical prototype, is given. The disadvantage of the study is the lack of a unified mathematical model. In the paper, a mathematical model of the arrow paw is combined with biological forms, for example, the claws of predatory animals.

Paper [4] reports the results of theoretical studies on the interaction of the disk working body of the tillage tool with the soil environment. The authors carried out mathematical modeling of the movement of elementary soil particles along the spherical surface of the disk working body. Paper [5] theoretically established the influence of the degree of fixation of an abrasive particle in the soil on the mechanism of abrasive wear of the surface of the working bodies of disk tillage machines. In work [6], an analytical description of the interaction of a disk spherical body with the soil environment was carried out. Similar studies concern helical surfaces as working bodies [7, 8]. However, the resulting mathematical models cannot be applied to other forms of working bodies because they are not unified. The models developed by the authors can be applied only to the specific processes considered in these works.

In [9], the interaction of working bodies with the soil is modeled using the Simcenter STAR-CCM+ special software. That made it possible to overcome objective difficulties associated with the impossibility of continuous modeling of the position of the working body during work. However, the software proposed for use by the authors does not allow constructing working bodies of various shapes but only simulating the work of pre-developed bodies to study the effectiveness of such developments.

In paper [10], the well-known dependence of predicting changes in traction resistance of the unit during operation is expanded by introducing a dependence that allows taking into account the resistance to compression and chipping of the soil layer, as well as the resistance of the soil to compression by the thickness of the cutting edge. However, the research is conducted in relation to the wear processes of cultivator paw blades with different types of strengthening.

In work [11], it was established that during the operation of soil tillage machines, in the contact zone of the working body and the soil, three types of friction (sliding friction, rolling friction, and rolling friction with slipping) occur at the same time. To determine the general coefficient of friction between the surface of the working body of soil tillage machines and the soil, taking into account all possible types of friction, a corresponding relationship is drawn up. Study [12] analyzed the types of wear and the effect of abrasive materials on the working bodies of tillage machines. The optimal materials and methods of increasing the wear resistance of the working bodies of tillage machines have been determined. The dependences obtained in these studies do not take into account the variability of working bodies shapes.

The introduction of soil-conserving, energy-saving, and innovative tillage technologies into agricultural production poses the task of developing combined units and improved working bodies for them. Paper [13] considers ways to reduce energy costs for tillage based on mathematical modeling and analysis of connections between unit elements. The authors have developed and substantiated a mathematical model of the soil tillage unit operation process. However, the mathematical model does not take into account the geometric shape of the working body, which can be one of the ways to improve it.

Another area for designing high-performance assemblies is taking into account the physical principles of interaction of working bodies with the soil environment. For this purpose, work [14] introduces the concept of the energy state of the elementary volume of the soil medium and gives its analytical description. But the form of the working body is not taken into account by the authors.

One of the main requirements for the working bodies of tillage units, which must be taken into account during their design, is the reduction of traction resistance when they are used. Therefore, it is necessary to build a generalized mathematical model of the shape of the tillage body (curvilinear tooth or blade) with simultaneous consideration of this requirement.

3. The aim and objectives of the study

The purpose of our study is to develop an analytical description of the shape of a curved tooth or blade, which would slide along themselves as much as possible when immersed in the soil. This will make it possible to reduce the resistance to immersion.

To achieve the goal, the following tasks were set:

– to determine the analytical condition for the transition from the rectilinear form of the tillage working body in the form of a tooth or blade and finding the curvilinear form of the working body, which would have minimal resistance when immersed in the soil;

– to investigate the factors affecting the resistance to immersion of the working body and justify its design parameters to reduce the resistance and wear of the working surface.

4. The study materials and methods

The object of the study is a drum-type tillage working body, which will enable a reduction in resistance when it is buried in the soil. The working bodies of agricultural tools have different shapes: spring teeth, knives, cutters, chisels, paws, disks. All of them interact with the soil environment and can be active or passive. However, both in the first and second cases, the resistance to their movement should be minimal.

It is proposed to use a curvilinear shape of the tooth, which would work like a shovel: at the first stage of immersion in the soil, it would maximally slid over it and minimally deform it, and at the second stage, it would balance it and turn it over. This process of soil deformation should reduce the resistance to its cultivation at the first stage.

Research materials are based on the theory of differential geometry of curves and their properties. In particular, formulas were used for the transition from the equation of a curve in polar coordinates to parametric equations in Cartesian coordinates. The methods of theoretical mechanics and vector algebra were used to find the absolute speed of the points of the working body, which simultaneously performs two movements (rotational and translational). The same methods were used to decompose the absolute velocity vector into components, which can be used to judge the intensity of wear of the working body during its immersion in the soil. Analytical geometry methods were used to find angles between vectors.

The hypothesis of the study assumes that the shape of the working body with the minimum resistance to penetration into the soil can be sought among the well-known curves widely used in technology, which in this case is the involute of a circle. At the same time, it is adopted that the drum with the working body fixed on it rolls over the soil surface without slipping. Simplification assumes that the soil environment is uniform everywhere.

5. Results of investigating the rational shape of a tillage working body and the substantiation of its structural parameters

5. 1. Analytical condition for the transition from a rectilinear shape and finding a curvilinear shape of a working body

The working body in the form of a rectilinear blade, rigidly attached in the radial direction to a drum of radius r, is shown in Fig. 1, *a*. When the drum rolls over the surface of the soil without slipping, its translational speed V_e will be determined by the angular speed ω of rotation of the drum of radius r: $V_e = r\cdot\omega$. The trajectory of the movement of point D will be a cycloid, for the remaining points of the blade – elongated cycloids. The shape of the cycloid depends on the distance ρ from the center of rotation O to the point on the blade and is described by parametric equations:

$$x = r\left(\alpha - \frac{\rho}{r}\sin\varphi\right), \qquad (1)$$

$$y = r\left(1 - \frac{\rho}{r}\cos\varphi\right),$$

where φ is an independent variable – the angle of rotation of a circle point around its center O.

According to equations (1), Fig. 1, *b* shows the trajectories of movement of points D, B, C of the blade. When $\rho = r$, there will be a cycloid, which is the trajectory of point D, for the rest of the points, including B and C, are elongated trajectories.

When the drum rotates, the point C is the first to come into contact with the soil. From this moment, soil compaction begins, which eventually leads to its weighting on the surface. It is obvious that large resistance forces act on the blade. As a task, the deformation of a rectilinear blade into a curved one was set in such a way that at the stage of immersion in the soil it slid along itself as much as possible, and then the soil was lifted to the surface similar to the work of a shovel.

Fig. 1, *b* shows that the difference in the distance between points D and C on the soil surface is $L = r\cdot\varphi$, where φ is the angle by which the drum turned from the moment of entry of point C to the moment of entry of point D on the surface of the soil. The task was to deform the blade in such a way that the distance L was equal to zero, that is, so that all points of the blade entered the soil at the same point. The distance L is equal to the increment of the x coordinate, therefore, at $y = 0$, it is necessary to find the corresponding expression of the angle φ for the curved blade. To this end, the second expression of equations (1) must be set to zero.

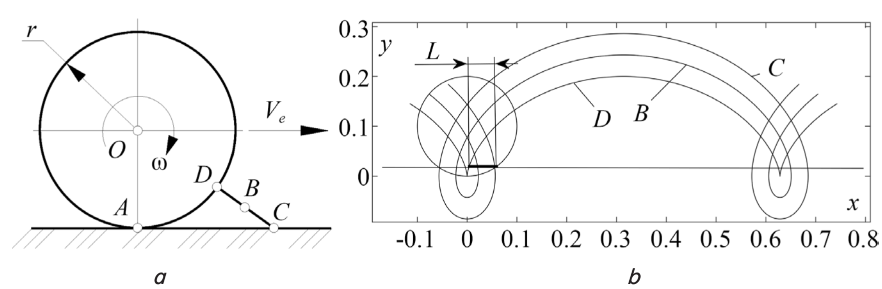


Fig. 1. Graphical illustrations for the construction of the trajectories of the vane points when rolling the drum without slipping: *a* – a drum with a rigidly fixed to it rectilinear vane in the radial direction; *b* – trajectories of movement of individual points of the blade

The result of such an action is the following expressions:

$$\varphi = \arccos\frac{r}{\rho}, \quad (2)$$

$$\sin\varphi = \frac{1}{\rho}\sqrt{\rho^2 - r^2}.$$

Substitution of $x=L=r$ and expressions (2) into the first equation (1) makes it possible to obtain the following equation:

$$\varphi = \arccos\frac{r}{\rho} - \frac{1}{r}\sqrt{\rho^2 - r^2}. \quad (3)$$

Equation (3) is the equation $\varphi=\varphi(\rho)$ in polar coordinates. The transition to parametric equations in Cartesian coordinates is carried out according to the formulas: $x=\rho\cdot\cos\varphi$, $y=\rho\cdot\sin\varphi$. Substitutions and transformations make it possible to obtain parametric equations of the curve, for which the independent variable is ρ – the distance from the origin of the coordinates to the current point of the curve:

$$x = r\cos\frac{\sqrt{\rho^2 - r^2}}{r} + \sqrt{\rho^2 - r^2}\sin\frac{\sqrt{\rho^2 - r^2}}{r}, \quad (4)$$

$$y = r\sin\frac{\sqrt{\rho^2 - r^2}}{r} - \sqrt{\rho^2 - r^2}\cos\frac{\sqrt{\rho^2 - r^2}}{r}.$$

It is appropriate to introduce a new variable α, such that $\sqrt{\rho^2 - r^2}/r = \alpha$. Then the parametric equations (4) take the form:

$$x = r\cos\alpha + r\alpha\sin\alpha, \quad (5)$$

$$y = r\sin\alpha - r\alpha\cos\alpha.$$

Parametric equations (5) are well-known equations of the involute of a circle of radius r. In Fig. 2, a circle of radius r and an involute arc are constructed in the initial position (Fig. 2, *a*). The circle, rolling without sliding on the surface of the field, will take a new position together with the arc of the involute rigidly attached to it (Fig. 2, *b*). It is considered a working body (blade).

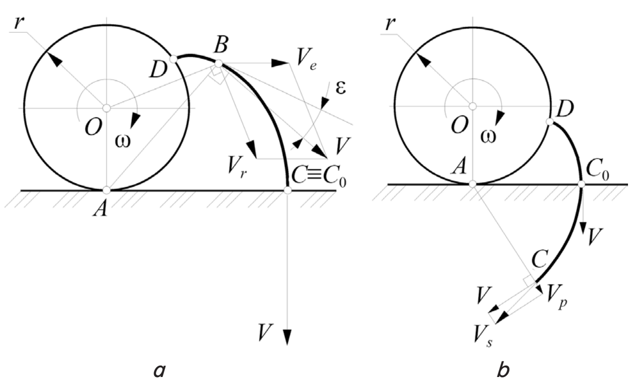


Fig. 2. A circle of radius r (drum) and a vane rigidly attached to it, having the shape of an involute: *a* – the beginning of the vane (point *C*) at the moment of entering the soil massif; *b* – blade after entering the soil massif to a certain depth

A property of the involute is that the length of the segment *AC* is equal to the length of the arc of the circle *AD* (Fig. 2, *a*). As a result of this, when the circle is rolling and the blade is simultaneously immersed in the soil, there will be a moment when the point *D* will match the point C_0 on the surface of the soil, where its beginning was before. This applies not only to point *D* but to all points of the involute, that is, it enters the soil in one and the same place (Fig. 2, *b*), and perpendicular to the field surface. This is due to the fact that point *A* is the instantaneous center of rotation, and the velocity vector *V* is perpendicular to the segment connecting point *A* to the involute point on the field surface. In general, this vector is the sum of two components: translational displacement $V_e=r\cdot\omega$ and rotational displacement $V_r=OB\cdot\omega=\rho\cdot\omega$. The velocity vector *V* makes a certain angle ε with the tangent to the involute (Fig. 2, *b*), which is zero only at point C_0. Given this angle, the velocity *V* can be decomposed into V_s (sliding velocity) and V_p (velocity in the perpendicular direction, the magnitude of which affects the pressure of the soil on the surface).

5. 2. Studying factors affecting the resistance to immersion of the working body and substantiation of its design parameters

The value of the arc of the involute for a given depth of tillage was found. When rolling the circle together with the involute, the distance from the center of rotation *O* to the beginning of the blade *C* does not change. Therefore, the *OC* distance is the sum of $r+h$, where h is the depth of processing. On the other hand, the distance $OC=\rho$ can be determined to any point of the involute (5) by the known formula. Based on this, the dependence is revealed:

$$r + h = \sqrt{1+\alpha^2}. \quad (6)$$

It follows from (6) that the specified depth h of soil cultivation can be ensured with various combinations of the radius r and the final value of the angle $\alpha=\alpha_o$ at point *C*. For example, at $r=0.01$ m and $\alpha_o=0.5\cdot\pi$ the depth of soil cultivation is $h=0.086$ m.

It is advisable to follow individual positions of the curved blade during its gradual immersion in the soil. To this end, parametric equations were built that describe its rotation by the angle α_t and the corresponding linear movement by the distance $r\cdot\alpha_t$:

$$x_t = r\cos(\alpha+\alpha_t) + r\alpha\sin(\alpha+\alpha_t) + r\alpha_t, \quad (7)$$

$$y_t = -r\sin(\alpha+\alpha_t) + r\alpha\cos(\alpha+\alpha_t).$$

At $\alpha_t=0$ and the angle α changes within $\alpha=0...0.5\cdot\pi$, the initial position of the blade can be obtained (in Fig. 3, *a*, its initial position is shown by a thick line). Full immersion of the blade occurs at $\alpha_t=0.5\cdot\pi$. Visualization and analysis of the gradual immersion of the blade into the soil with increasing discrete values of α_t showed that the beginning of the blade (point *C*) reaches a given depth earlier than point *D* reaches point C_o on the field surface. Point *C* of the blade reaches the specified depth h at $\alpha=0.3\cdot\pi$. This means that the blade has not yet completely sunk into the soil but its beginning (point *C*) has already reached the specified depth and after that the soil weighing begins.

Fig. 3, *b* shows the trajectories of movement of individual points of the blade. For their construction, equations (1) were not used since in them the increase in the radius ρ occurs in the radial direction, which is characteristic of a straight blade. For a curved vane, the coordinates of each point should be found according to equations (5) at a certain value of the angle $\alpha=\alpha_c$, and then their trajectories should be built under the condition that they are rigidly attached to the circle. Taking this into account, the parametric equations of the cycloid of a specific involute point corresponding to the value of the angle $\alpha=\alpha_c$ take the following form:

$$x_A = r\cos(\alpha+\alpha_A) + r\alpha_A \sin(\alpha+\alpha_A) + r\alpha, \tag{8}$$

$$y_A = -r\sin(\alpha+\alpha_A) + r\alpha_A \cos(\alpha+\alpha_A).$$

The trajectory of point C corresponds to the angle $\alpha_c=0.5\cdot\pi$; the trajectory of point D, the angle $\alpha_c=0$. The trajectories of all other points can be constructed at values of the angle α_c from the specified interval. Fig. 2, *a* demonstrates that all points of the blade enter the soil in the same place.

The resistance to the immersion of the blade into the soil has two components: the resistance of the penetration of the blade (point C) into the soil and the resistance of the frictional forces acting on the surface of the blade due to the fact that the velocity vector V of the point does not coincide with the one tangent to the blade at this point. There is an angle ε between them (Fig. 2, *a*). This angle is equal to zero only at the point of entry of the blade into the soil. At this point, the pressure on the lateral surface of the blade is minimal since the blade slides along itself. Subsequently, the angle ε increases, so the force of friction also increases. However, it also depends on the speed V, which needs to be decomposed into two components through this angle: V_s and V_p (Fig. 2, *b*).

In Fig. 4, *a*, separate positions of the curved blade when it is immersed in the soil are plotted according to equations (7), as well as the section of the trajectory of its blade (point C) according to equations (8). After the vane is immersed in the soil, when it begins to be weighed, the angle ε begins to increase rapidly.

Knowing the trajectory of movement of any point of the vane according to equations (8), its speed V can be found as a function of the variable α – the angle of rotation of the circle of radius r (drum):

$$V = \frac{ds}{dt} = \frac{ds}{d\alpha}\cdot\frac{d\alpha}{dt} = \omega\cdot\frac{ds}{d\alpha},$$

where s is the length of the trajectory. The angular speed of rotation of the disk was taken as $\omega=1$ since it does not affect the trajectory and the general geometric regularities. The speed V of the displacement of the vane point can be found through the derivatives of its trajectory (8):

$$V_{\omega=1} = \frac{ds}{d\alpha} = \sqrt{x_c'^2 + y_c'^2} =$$

$$= r\sqrt{2+\alpha_c^2 + 2\alpha_A\cos(\alpha+\alpha_A) - 2\sin(\alpha+\alpha_A)}. \tag{9}$$

The angle ε at point C_o where the vane blades enter the soil is zero. It is equal to zero for all points of the blade that enter the soil at this point. However, as it deepens, it grows. It is necessary to find the regularity of its growth for the vane blade (point C). The angle ε is the angle between the tangent to its trajectory (8) at $\alpha_c=0.5\cdot\pi$ and the tangent to the blade (7) at point C at $\alpha_t=0.5\cdot\pi$. The unit vector of the tangent to the trajectory of motion of point C was found by differentiating equations (8) followed by dividing them by the velocity expression (9). The unit vector of the tangent to the blade (7) at point C is stationary relative to it, but moves with it and has coordinates:

$$\left\{\frac{r\alpha-\sin\alpha}{\sqrt{(r\alpha-\sin\alpha)^2+\cos^2\alpha}};-\frac{\cos\alpha}{\sqrt{(r\alpha-\sin\alpha)^2+\cos^2\alpha}}\right\}. \tag{10}$$

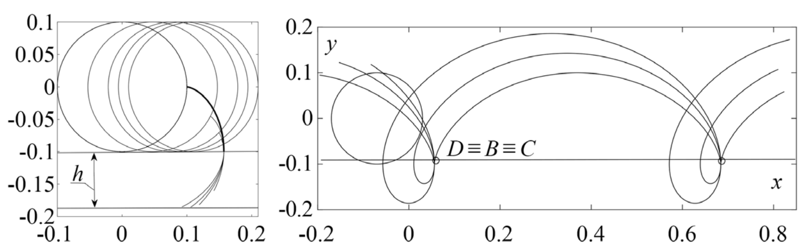


Fig. 3. Graphic illustrations of the movement of a curved blade (involutes of a circle) when the drum is rolling on the field surface without slipping: *a* — sequential movement of the drum and immersion of the blade into the soil; *b* — trajectories of movement of individual points of the blade

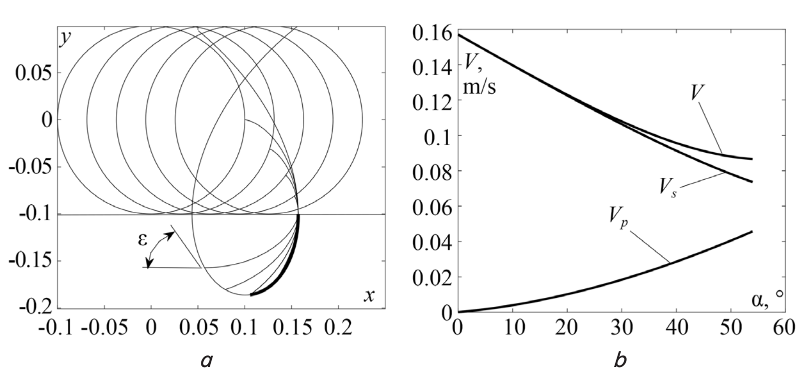
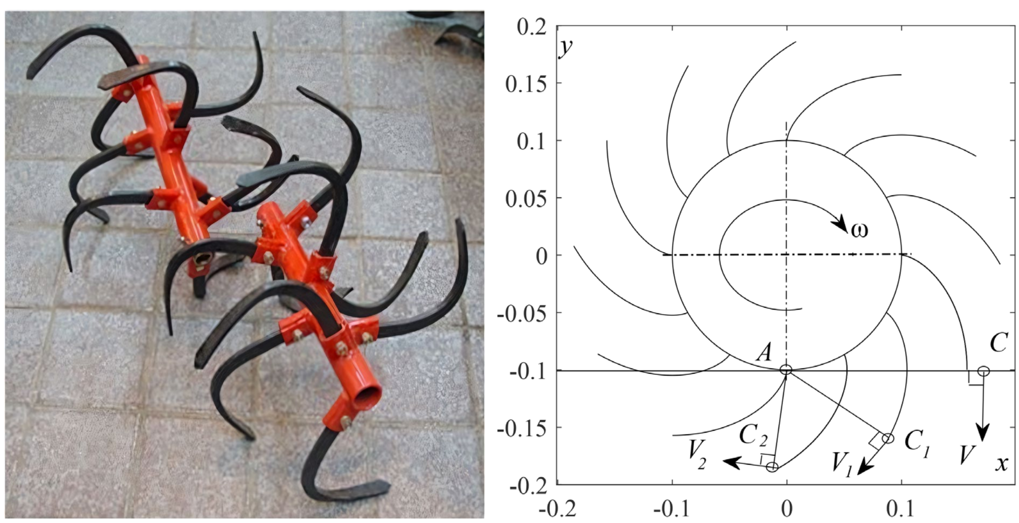


Fig. 4. Graphic illustrations of the kinematic characteristics of the movement of a curved blade when it is immersed to the maximum depth at $\alpha=0.3\cdot\pi=54°$: *a* — individual positions of the blade when it is immersed in the soil and the trajectory of the blade; *b* — plots of speed V and its decomposition into V_s and V_p

After finding the unit vectors tangent to the trajectory of the blade and to the involute at point C (the beginning of the vane, i.e., the blade), the angle ε between them was found (the angle expression is not given due to its bulky appearance). The components V_s and V_p are determined by the angle ε: $V_s = V \cdot \cos\varepsilon$, $V_p = V \cdot \sin\varepsilon$. Fig. 4, *b* shows the plots of speed V and its components depending on the angle α, that is, on the immersion of point C (the blade of the vane) to the depth h. It demonstrates that for most of the way when the blade is immersed in the soil, it slides along itself since the speeds V_s and V coincide. This corresponds to a 30° rotation of the drum. It is in this area that there is minimal abrasion of the side surfaces of the blade, their effective self-cleaning, and a reduction in the energy consumption of the process. Therefore, it is advisable to shorten the length of the vane, then it will not reach the depth where significant pressure begins on the side surface of the blade, which causes the corresponding friction and its wear. But at the same time, the processing depth will decrease. To prevent this from happening, one should increase the radius r of the drum. Therefore, in dependence (6), at a given depth h, the radius r should be taken as large as possible. These two selected parameters (h and r) will correspond to the angle $\alpha = \alpha_o$ found from dependence (6). To construct a vane according to equations (5), the independent variable α must vary within $\alpha = 0 \ldots \alpha_o$.

Among the various tillage working bodies, there are teeth similar in shape to those discussed in this paper. This applies to rotovators [15], which are tillage tools for both walk-behind tractors and powerful tractors (Fig. 5, *a*) [15]. The fundamental difference is that they are not designed to sink into the soil due to the ratio of rotational and translational speeds. They work as active working bodies, the drive of which is carried out by the engine of the walk-behind tractor or the power take-off shaft of the tractor, similar to milling cutters. The instantaneous center of rotation, as point A in Fig. 5, *b*, does not exist for rotators. Fig. 5, *b* also explains the decrease in the speed V of the blade (point C) as it sinks into the soil (Fig. 4, *b*). At a constant angular speed ω of the drum rotation, the value of the instantaneous radius of the AC decreases, therefore, the speed decreases as a product of these values. When $\omega = 1$ and $r = 0.1$ m, the speed of the blade at the moment of meeting the field surface can be found. In this case, $AC = r \cdot \alpha_o = \pi \cdot r/2 = 0.16$ m. Therefore, $V = \omega \cdot AC = 0.16$ m/s.

If the blades of the rotator stir the soil, then the blades of the proposed tool enter it through a certain distance, the value of which depends on the number of blades in the section. Fig. 6 shows separate positions of two blades, the total number of which in the section is six. The blade (the beginning of the vane) and its end move along cycloids (normal and elongated), and intermediate positions of the blade are located between them. Areas of cultivated soil are located within the elongated cycloids. As can be seen from Fig. 6, at a given processing depth h, there are areas with a much smaller depth than the given one since the profile of the untreated soil is formed by depressions and ridges. One can reduce the height of the ridges by increasing the number of blades in the section, for example, up to 12 (Fig. 5, *b*).



a *b*

Fig. 5. Rotovator and diagram of the section of an alternative tillage tool: *a* – rotovator for aggregation with a walk-behind tractor; *b* – a section diagram of a tillage tool with 12 blades

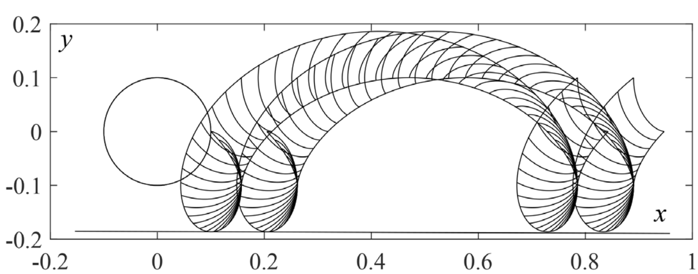


Fig. 6. Intermediate positions of the blades during drum rotation, which are located between the trajectories of their ends

Fig. 7 shows the proposed scheme for attaching blades to a separate section, which is mounted onto a hexagonal pipe and attached to it.

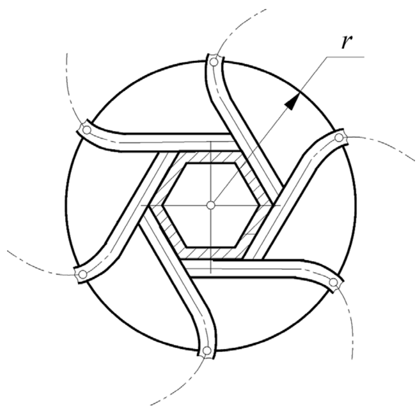


Fig. 7. Possible variant to form a section with six blades fixed on a shaft in the form of a hexagonal tube

The vanes can be clamped between two disks of radius *r*, which serve as support wheels or a drum. From the points on the support wheel, there begins a curved blade in the shape of an involute of a circle, the axis of which is depicted by a dash-dotted line. The necessary number of such sections can be fixed on the hexagonal pipe, which is the shaft.

6. Discussion of the design of the working body for agricultural tools

The reduction of the resistance of the working body into the soil is explained by its shape, which is found analytically. Fig. 1 shows the trajectory of the points of movement of a rectilinear blade, which when entering the soil does not slide along itself but crumples it. The task was to deform a straight blade into a curved blade in such a way that, when immersed in the soil, it would slide along itself as much as possible. Unlike [2], the feature of the proposed approach is the analytical description of the curved shape of the blade. This approach consists in compiling equations (2), as a result of which the equation of the curved blade axis (3) in polar coordinates was built. The transition to parametric equations (4) and their subsequent transformations to form (5) showed that the obtained curve is an involute of a circle. Evidence that the found shape of the blade will actually slide along itself as much as possible when immersed, and not crush the soil, is the construction in Fig. 3, *a* of its intermediate positions when entering the maximum depth. In addition to this visualization, the ratio of the components of the absolute speed of the vane blade was calculated, one of which characterizes sliding, and the second – the pressure of the soil on the blade. This is reflected in the plot in Fig. 4, *b*.

Similar curvilinear working bodies exist, for example, in rotovators (Fig. 5, *a*). However, their shape was not found analytically but as a result of an experiment [4, 12]. In contrast to such a search for shape, our approach is based on the fulfillment of analytical conditions. The advantage of the proposed blade shape is that it has minimal resistance to entering the soil. This became possible owing to the mathematical modeling of the blade shape according to the given task. That also made it possible to formulate certain recommendations regarding the design parameters of the blade and the drum to reduce traction resistance. The resistance to immersion of the blades in the soil will decrease as the diameter of the drum increases. In addition, it is desirable that the blade sinks into the soil completely when the drum is turned no more than 30°.

Blades should sink into the soil under the influence of the weight of the tillage unit. Obviously, this is a limitation on the depth of processing. Artificial additional loading of the unit with ballast will lead to an increase in the energy intensity of the process. The disadvantage is that increasing the tillage depth requires increasing the length of tillage paws. But firstly, this leads to an increase in resistance to the immersion of the paws, and secondly, to reduce this resistance, one should increase the radius of the support wheels or drum. Further development of our research may be aimed at finding another shape of the paw, devoid of the indicated shortcomings.

7. Conclusions

1. The analysis of a rectilinear blade installed on the drum of a tillage tool in the radial direction revealed that the penetration of such a blade into the soil is energy-consuming since soil deformation occurs at this stage. The transformation of a rectilinear blade into a curved blade is carried out on the basis of the condition of its entry into the soil at the same point. The mathematical description of such a blade showed that it should have the profile of the involute of a circle – the section of the drum to which the blade is attached. When sinking into the soil, such a blade slides along itself as much as possible, especially in the upper layers of the soil, and only after sinking to the full depth it begins to lift the soil to the surface. This happens as a result of two movements of the drum with a blade: translational in the direction of movement of the unit and rotational around the axis of the drum.

2. At the moment of entering the soil, the speed vector of the vane blade coincides with the vector tangent to it at the point of the blade. This means that at this moment the main efforts are aimed at overcoming the resistance of the blade penetration into the soil. As the vane sinks, these two vectors form a certain angle, which increases with the depth of immersion. Another component of frictional resistance arises as a result of soil pressure on the side surface of the blade. The dynamics of this resistance can be estimated by decomposing the blade speed vector into components in two mutually perpendicular directions. The component along the tangent to the blade characterizes resistance to its penetration, and the perpendicular component – resistance from frictional forces. The constructed plot shows that as the depth is deepened, the soil pressure on the lateral surface of the blade increases according to a dependence similar to the quadratic one, which causes its wear in the lower layers of the soil. It is possible to reduce wear by reducing the length of the blade, but at the same time, the depth of processing is reduced. It is possible to increase the radius of the drum and to increase the length of the blade appropriately so that the depth of processing does not change. At the same time, the curvature of the blade will

be different and the frictional resistance in the lower layers of the soil will decrease. Thus, for the blade, the curvature of which depends on the drum, its radius should be taken as large as possible. This will contribute to the fact that the blade will slide along itself as much as possible at the stage of deepening.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

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

References

1. Kozachenko, O. V., Shkrehal, O. M., Kadenko, V. M. (2021). Zabezpechennia efektyvnosti robochykh orhaniv kultyvatoriv. Kharkiv: PromArt, 238. Available at: https://repo.btu.kharkov.ua/bitstream/123456789/21300/1/zabezpechennya_efektyvnosti_robochykh_orhaniv_monhraf_2021.pdf
2. Mudarisov, S. G., Gabitov, I. I., Lobachevsky, Y. P., Mazitov, N. K., Rakhimov, R. S., Khamaletdinov, R. R. et al. (2019). Modeling the technological process of tillage. Soil and Tillage Research, 190, 70–77. https://doi.org/10.1016/j.still.2018.12.004
3. Mikhailov, E., Volik, B., Tesluk, G., Konovoy, A. (2019). Method of reasoning of the construction scheme of multiple lapp on the basis of the biological prototypes. Proceedings of the Tavria State Agrotechnological University, 19 (3), 37–45. https://doi.org/10.31388/2078-0877-19-3-37-45
4. Kozachenko, O., Sedykh, K., Volkovskyi, O. (2023). Theoretical analysis of the force interaction of the disk working body with the soil environment. Scientific Bulletin of the Tavria State Agrotechnological University, 13 (1), 1–13. https://doi.org/10.31388/2220-8674-2023-1-6
5. Borak, K. V. (2020). Influence of degree of abrasive particle clinging to wear mechanism of soil-cultivating machines operational mechanisms. Machinery & Energetics, 11 (2), 35–40. https://doi.org/10.31548/machenergy2020.02.035
6. Pylypaka, S., Klendii, M., Klendii, O. (2018). Particle motion on the surface of a concave soil-tilling disk. Acta Polytechnica, 58 (3), 201. https://doi.org/10.14311/ap.2018.58.0201
7. Pylypaka, S., Klendii, M., Kresan, T. (2022). Study of the movement of soil particles on the surface of a screw tillage working body. Machinery & Energetics, 13 (2). https://doi.org/10.31548/machenergy.13(2).2022.62-72
8. Kresan, T. (2021). Movement of soil particles on surface of developable helicoid with horizontal axis of rotation with given angle of attack. Machinery & Energetics, 12 (2). https://doi.org/10.31548/machenergy2021.02.067
9. Kobets, A., Aliiev, E., Tesliuk, H., Aliieva, O. (2023). Simulation of the process of interaction of the working bodies of tillage machines with the soil in Simcenter STAR-CCM+. Machinery & Energetics, 14 (1). https://doi.org/10.31548/machinery/1.2023.09
10. Buslaiev, D. O., Vasylenko, M. O. (2020). Traction resistance of cultivator paws with surface hardening during operation of tillage machines. Machinery & Energetics, 11 (1), 177–182. https://doi.org/10.31548/machenergy2020.01.177
11. Borak, K. V. (2019). Frictional interaction between soil and surface of tilling machine movable operating parts. Machinery & Energetics, 10 (4), 157–162. https://doi.org/10.31548/machenergy2019.04.157
12. Paladiychuk, Yu., Melnik, Ju. (2021). Restoration resource of working bodies of soil treatment machines by applying wear-resistant coatings. Machinery & Energetics, 12 (4). https://doi.org/10.31548/machenergy2021.04.043
13. Sereda, L., Kovalchuk, D. (2021). Mathematical modeling soil tilling unit in the system «soil-aggregate-energy means» for Strip-Till technology soil treatment. Machinery & Energetics, 12 (4). https://doi.org/10.31548/machenergy2021.04.103
14. Sivak, I. M., Chovnyuk, Yu. V., Gumenyuk, Yu. O. (2019). Substantiation of basic principles of creation of high-efficiency soil-processing technology for agricultural appointment. Machinery & Energetics, 10 (1). https://doi.org/10.31548/machenergy2019.01.171
15. Freza-rotovator KIPOR. Available at: http://tehnik.co.ua/p/freza-rotovator-kipor.html