Substantiation of the parameters of the working bodies of undulating disks of soil-cultivating harrows with a bionic approach

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Abstract. The article presents the methods and results of the bionic approach in the system of agricultural mechanics, which made it possible to theoretically substantiate the main parameters of the model of the working organs of wavy discs using two bionic prototypes - the burrowing leg and radial ribs of the bivalve shell of the edible heart-shaped mollusk (Cerastoderma edule) and the burrowing leg of the dung beetle common (Geotrupes stercorarius). The model of the working bodies of undulating disks allows one to preserve the anti-erosion resistance of the soil in the upper cultivated layer in order to preserve its structure and stubble background during non-moldboard tillage in the soil-protective agriculture system for the technologies "Verti-till" and "Strip-till". The results of theoretical studies on the substantiation of the design parameters of the working bodies of wavy discs for surface tillage are presented.

1. Introduction
For vertical (Verti-till) and strip (Strip-till) technologies of soil cultivation for the cultivation of grain crops, in accordance with the agrotechnical requirements, special working bodies of turbo discs - wavy discs of harrows are applicable [1].

However, as the analysis of the existing structures of the working bodies of the wavy discs of the harrows shows, all modern theoretical developments were mainly aimed at studying the qualitative and energy indicators of deformation of loosening of soil layers. In many scientific works, there is practically no systematic approach to solving individual particular problems, such as: substantiation of the parameters of disk working bodies and a diagram of their arrangement. Little consideration is given to the issue of the joint effect of the cutout shapes on the working surfaces of discs with optimal cutting edges on the reduction of the midsection [2]. Particular attention should be paid to the influence of the shape of the side surfaces of the discs on the quality of loosening of the side layers of the soil. All these unsolved problems slow down the process of realizing the potential for the practical implementation of wavy discs of harrows on various agro-soil backgrounds.

As a result, it becomes necessary to theoretically substantiate the effective working bodies of the wavy discs of the harrows with fundamentally new resource-saving methods of influencing the processed environment and meeting the requirements of progressive technologies. This solution is
proposed to be implemented on the basis of the use of a mechanic-bionic approach, which allows analytically describing the geometric shape of the surface of the working bodies of the wavy discs of the harrows.

Research goal. Development of theoretical prerequisites for bionic substantiation of the parameters of working bodies of wavy discs of harrows for surface tillage.

2. Materials and methods
The leading research method in agricultural biomechanics is bionic modeling based on a systems approach. The studied objects were two natural models of biological prototypes of the mollusk (Cerastoderma edule) and the common dung beetle (Geotrupes stercorarius). As a physical model for joint comparative theoretical studies of living systems and machines, working bodies of wavy discs of harrows for surface tillage were used.

3. Results
Chirende B, Li J Q, Wen L G have established a close relationship between the bionic profiles of the disk working body in comparison with the quality of soil cultivation. Having developed disk working bodies on the bionic similarity of a bionic non-smooth surface and carried out experiments, Chirende B, Li J Q, Wen L G confirmed that disk working bodies, in comparison with serial ones, provided less traction resistance [3]. The form of the bionic profile proposed by them satisfies the conditions for concentration of efforts at one point, which favors effective crumbling of the soil and its descent from the surface of the working bodies. However, apart from the empirical dependences obtained, no further development has been obtained for the substantiation of the shapes of the working surfaces of the disk working bodies [4-5].

Analysis of the studies showed that two bionic prototypes deserve special attention: the burrowing leg and radial ribs of the bivalve shell of the mollusk (Cerastoderma edule) [6] shown in Figure 1, and the burrowing foot of the common dung beetle (Geotrupes stercorarius) [7].

![Figure 1. Mollusk (Cerastoderma edule) and its movements in the sea soil.](image)

These two bionic prototypes live in the upper layers of the soil. However, the mollusk (Cerastoderma edule) lives in the shallow waters of the Azov and Black Seas, and the common dung beetle (Geotrupes stercorarius) lives in fields, meadows and pastures. One property unites these two bionic prototypes - the ability to burrow into the ground. The mollusk (Cerastoderma edule) using a burrowing leg 1 and radial ribs 2 of a bivalve shell, partially or completely can be buried in the ground to a depth of 7 cm. The common dung beetle, shown in Figure 2, with its first pairs of jagged legs 1, dig their tunnels 2 to nests 3 to a depth of 15 centimeters to 2 meters.

Such functioning of bionic prototypes for the development of the working surface of corrugated
disks made it possible to take as a basis the following basic geometric parameters presented in Figure 3 (a, b).

These parameters include: the number of teeth, their length, the angle of elevation of the upper face of the teeth of the burrowing legs, as well as the angle of elevation of the radial edges of the bivalve shell of the mollusk corresponding to the angle of attack $\alpha$ when penetrating into the ground, the angle of engagement of the tooth corresponding to the opening angle $2\gamma$ and the angle of the lateral surfaces of the upper face tooth, as well as the opening angle of the intercostal spaces of the bivalve shell of the mollusk corresponding to the angle of inclination of the projected lateral faces of the triangular radial segments $2\Theta$ of the wavy disc of the harrow.

The main design elements in the design of the working surface of corrugated disks are triangular radial segments 1 shown in Figure 4. They have a rigid connection to each other in the form of angular faces 2. The projection of triangular radial segments 1 is constructed taking into account the metal thickness $\delta$ and the rounding radius $r$. To do this, a section of the corner face is drawn through point $B_1$ perpendicular to line $A_1B_1$, and the inner working surface with a rounding of radius $r$ at the apex of the corner $2\Theta$ is built, laying off the thickness $\delta$.

When determining the radius of rounding of the surface of the radial segments, we use the arithmetic mean values of the bionic prototype - the angle of grip of the tooth - the opening angle $2\gamma = 48^\circ$, as well as the angle of rise of the upper edge of the tooth - the angle of attack $\alpha = 18^\circ$. As a result, the expression will look like this:
\[ r = \frac{e}{\sin \alpha} = \frac{e \cdot \tan(2\gamma/2)}{\sin \alpha} \tag{1} \]

where \( e \) is the length of the segment, as shown in Figure 4.

Figure 4. Graphical definition of the main parameters of bionically similar rounded triangular radial segments.

The results of calculations showed that the radius of rounding is 54 mm, which is consistent with the analysis of the approximation of the tooth of the dung beetle burrowing foot and the tops of the radial edges of the bivalve shell of the mollusk on a scale to the radial segments.

Knowing the rounding radius \( r \) from formula (1), we express half of the vertex of the angle \( \Theta \) by the formula:

\[ \frac{e}{\cot \Theta} = \frac{e \cdot \tan(2\gamma/2)}{\sin \alpha} \tag{2} \]

where \( \cot 2\Theta \) is the angle of inclination at the vertex of one corner face 1.

As a result, when determining the total angle of the vertex of the corner faces of the radial segments \( \cot 2\Theta \), the formula will take the following form:

\[ \cot 2\Theta = 2 \left( \frac{e \cdot \sin \alpha}{e \cdot \tan \left( \frac{2\gamma}{2} \right)} \right) = 2 \left( \frac{\sin \alpha}{\tan \gamma} \right) \tag{3} \]

As the analysis of the approximation of the angle of the lateral surfaces of the upper edge of the tooth \( 2\Theta \) shows, its average value is in the range of 128 … 138 degrees. The calculated value obtained on the basis of formula (3) corresponds to 130° degrees, which includes the average value of the rational ranges of the angle of the lateral surfaces of the upper face of the tooth of the dung beetle’s burrowing foot.
Analysis of the crumbling angle $\beta_1$ at the approximated surface of the tooth of the dung beetle's burrowing foot showed that its value is in the range of 19… 26 degrees. Therefore, the average value of this angle during the design was chosen, equal to 22 degrees.

The segment $D_0E_0$ is the length $l$ of the active working face of the tooth surface of the digging foot. From point $E_0$ to point $D_0$, active processes of soil loosening occur. By approximating in scale the projection of this segment onto the projection of the projected radial segments in the form of segments $D_1E_1$, we obtain the length of the corner face, determined by the formula:

$$l = b_1 \frac{\sin \beta_1}{\sin \alpha},$$

where $b_1$ is the projection of the segment $E_1C_1$ of the triangular radial segment for the angle $\beta_1$.

As:

$$b_1 = \frac{B_2F_2}{\sin \beta_1},$$

That equation (4) will take the form:

$$l = \frac{B_2F_2 \cdot \sin \beta_1}{\sin \beta_1 \cdot \sin \alpha} = \frac{B_2F_2}{\sin \alpha}.$$

The segment $B_2F_2 = h_{\text{offset}}$ characterizes the value of the lateral displacement of the formation. It is determined by the formula:

$$h_{\text{offset}} = \cot \theta \cdot l_2,$$

where $l_2$ is the segment $NE$ which is half the width of the projected radial segments.

To determine the number of teeth on the harrow disk, we use the following formula [5, 7]:

$$Z = \frac{L + S - 0,36 \cdot a_{\text{loosen}}}{S},$$

where $L$ is the length of the cutting blade;
$S$ is tooth pitch;
$a_{\text{loosen}}$ is the depth of soil loosening.

Since the cutting blade of the disc has the shape of a circle, and $S=l_2$, then formula (8) will have the following form:

$$Z = \frac{\pi \cdot D + l_2 - 0,36 \cdot a_{\text{loosen}}}{l_2},$$

where $D$ is the diameter of the harrow disk, determined by the formula for the radius of the circumscribed circle of regular polygons [6]:

$$D = 2 \cdot \frac{l_2}{\sin \gamma} = 2 \cdot \frac{l_2}{\sin \frac{\gamma}{2}},$$

where $\gamma$ is half of the angle of grip of the tooth equal to half of the opening angle $\gamma=24^\circ$.

Substituting equation (10) into equation (9), we obtain:

$$Z = \frac{\pi \left(2 \cdot \frac{l_2}{\sin \gamma}\right) + l_2 - 0,36 \cdot a_{\text{loosen}}}{l_2} = \frac{2\pi}{\sin \gamma} + 1 - \frac{0,36 \cdot a_{\text{loosen}}}{l_2}. $$


In this case, the total number of teeth $Z$ of the harrow disc will be 15 pieces.

From formula (11), we determine half the width of coverage of radial segments $l_2$:

$$
\frac{0.36 \cdot a_{loosen}}{l_2} = \frac{2\pi}{\sin \gamma} + 1 - Z,
$$

$$
l_2 = \frac{0.36 \cdot a_{loosen}}{\frac{2\pi}{\sin \gamma} + 1 - Z}.
$$

(12)

Making calculations according to the formula (12) with the value of the maximum working depth for a given disc $a_{loosen} = 16$ cm with a total number of teeth $Z = 15$ pieces, we come to the conclusion that the average $l_2$ value is 9 cm. Substituting this numerical value into formula (9) for the diameter $D$ of the harrow disk, we determined its value, which is 48 cm. Next, you need to determine the height of the teeth $h_{teeth}$ by the formula [5, 8]:

$$
h_{teeth} = \frac{\pi \cdot P_s \cdot \nu}{2},
$$

(13)

where $P_s$ is the traction resistance of the harrow disc, with surface tillage;

$\nu$ is soil deformation index $\nu = 3.4 \times 10^7...4.0 \times 10^7$ m$^2$/N.

After calculating the height of the teeth $h_{teeth}$, we come to the conclusion that when processing the soil to a depth of 6 to 16 cm, its height will be in the range from 5 to 12 mm, as shown in Figure 5.

![Figure 5. Cross-section of the wavy working body of the disc harrow.](image)

When determining the radius of a segment $R_{segment}$ of a circle at points $A_2$ and $B_2$, the height of the teeth $h_{teeth}$ will be taken as $const$. Then the relationship between the degree measure of angles $\gamma$ and $\gamma_1$ is expressed by the formula [9]:

$$
\gamma_1 = 2.6 \cdot \gamma.
$$

(14)

As a result, we get:
\[ R_{\text{segment}} = \frac{l_2}{2 \cdot \sin \left( 2 \arctan \left( \frac{2 \cdot h}{S} \right) \right)} = \frac{l_2}{2 \cdot \sin \left( \frac{2 \cdot 6 \cdot \gamma}{2} \right)}. \]  

The length of the circular arc at points \( A_2 \) and \( B_2 \) is determined by the expression:

\[ L_{A_2B_2} = \frac{\pi \cdot l_2}{2 \cdot \sin \left( \frac{2 \cdot 6 \cdot \gamma}{2} \right)} \cdot \sin \left( 2 \cdot 6 \cdot \gamma \right) \]

\[ = \frac{l_2}{180^\circ} \cdot \sin \left( \frac{2 \cdot 6 \cdot \gamma}{2} \right). \]  

With a value \( l_2 \) equal to 9 cm and a fixed aperture angle \( \gamma = 24 \) degrees according to formula (15), the radius of the circle segment \( R_{\text{segment}} \) will be 10.46 cm, and the value of the circular arc obtained by formula (16) at points \( A_2 \) and \( B_2 \), respectively, 9.3 cm ...

For our case, the resistivity is expressed by the following relationship:

\[ k_{\text{resistivity}} = \frac{P_x}{\alpha_{\text{loosen}} \cdot \alpha_{\text{loosen}} \cdot (h_{\text{bias}} - h_{\text{rounding}})}, \]  

where \( \alpha_{\text{loosen}} \) is the width of the strip processed by the harrow disk and is determined as the difference between \( h_{\text{bias}} \) and \( h_{\text{rounding}} \) - the amount of rounding of the projected radial segments, which is determined by the formula [9]:

\[ h_{\text{rounding}} = 2 \pi \left( r - \frac{\delta}{2} \right) \cdot \frac{90^\circ - \theta}{180^\circ}. \]  

Substituting from equations (6) and (13) into equation (12) the values of \( h_{\text{bias}} \) and \( h_{\text{rounding}} \) we obtain:

\[ k_{\text{resistivity}} = \frac{P_x}{\alpha_{\text{loosen}} \cdot (\cot \theta \cdot l_2 - 2 \pi \left( r - \frac{\delta}{2} \right) \cdot \frac{90^\circ - \theta}{180^\circ})}. \]  

Based on the theoretical assumptions obtained, taking into account the bionic substantiation of the parameters of the working organs of wavy discs based on the prototypes of the common dung beetle (Geotrupes stercorarius) and the mollusk (Cerastoderma edule), the design is presented in Figure 6 [5].

![Figure 6](image-url)
The proposed tillage working body of the harrow contains paired discs 1, assembled into a battery 2 by means of hinges 3, mounted on S-shaped spring-loaded racks 4. Each pair of rotating discs 1 contains a projected wavy disc 5 and a disc 6 with needles 7 movably connected to each other. The needles 7 at an angle of 15°... 25 degrees around the circumference 8 are set toothed blades 9 [10]. The toothed blades 9 are made with three peaks 10 and two depressions 11 in the form of teeth along a curved circle. Disks 1 are connected to racks 4 by means of a screw regulating mechanism 12. The use of the proposed soil-cultivating disk battery with projected wavy disks will reduce traction resistance, simultaneously increase the efficiency of surface loosening of the stubble background of the soil and destroy weeds when disking with mulching on uneven soil reliefs [11].

4. Conclusion

In accordance with the bio system approach, as well as theoretical studies, a new design of the working body of the disc harrow has been developed (patent for a useful model of the Russian Federation No. 173 238). Based on the analysis of the structural features of the bionic prototypes of the burrowing leg and radial edges of the bivalve shell of the mollusk (Cerastoderma edule) and the burrowing leg of the common dung beetle (Geotrupes stercorarius), the following are analytically substantiated: the radius of the radial segment surface rounding, the total apex angle of the angular faces of the radial segments, the diameter of the harrow, the number of teeth, their height, as well as the circumference between them on the harrow disc.

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