Machinery & Energetics
Vol. 15, No. 3. 2024

Journal homepage:
https://technicalscience.com.ua/en

UDC 631.31:519.67
DOI: 10.31548/machinery/3.2024.129

Elchyn Aliiev*
Doctor of Technical Sciences, Senior Researcher
Dnipro State Agrarian and Economic University
49600, 25 Serhii Efremov Str., Dnipro, Ukraine
Institute of Oil Cultures of the National Academy of Agrarian Sciences of Ukraine
69055, 1 Institutska Str., Soniachne, Zaporizhzhia Region, Ukraine
https://orcid.org/0000-0003-4006-8803

Hennadii Tesliuk
PhD in Technical Sciences, Associate Professor
Dnipro State Agrarian and Economic University
49600, 25 Serhii Efremov Str., Dnipro, Ukraine
https://orcid.org/0000-0003-4541-5720

Analytical justifications of constructive parameters of bionic colters for vertical soil treatment

Abstract. Bionic coulters imitate natural forms and functions, which help reduce energy costs for soil tillage. The aim of the research was to justify the design and structural parameters of turbo discs (coulters) for vertical tillage based on the principles of bionic reverse engineering. Using this method, an equation for the shape of the turbo discs (coulters) was derived, which was obtained by approximating the shell of the argonaut (*Argonauta argo*). The equation takes into account the main structural parameters of the turbo discs: diameter D_d, cutout height H_m, wave height H_w, number of cutouts n, and spiral coefficient k. As a result of analytical studies on the interaction process between a solid disc and plant residues, the optimal diameter value was determined to be $D_d = 460$ mm under the condition of submerging stems with a thickness of 10-20 mm to a depth of 80 mm. The analytical studies confirmed that the presence of cutouts on the disc prevents stem deflection and ensures better stem capture. In analysing the obtained dependencies using the Wolfram Cloud software package, the optimal values for the cutouts were determined: cutout height $H_m = 40$ mm, number of cutouts $n = 8$. The presence of waves on the disc surface ensures that the interaction with plant residues is independent of their position on the field surface and creates conditions for vertical soil tillage. It was found that, to minimize specific cutting resistance and maximize the degree of soil fragmentation, the optimal wave parameters for the coulter are a wave height of $H_w = 24.4$ mm. The justified parameters of the coulters provide the best balance between soil fragmentation efficiency and reduction in energy consumption for soil tillage. The obtained results can be used to adapt existing agricultural machinery to the new structural parameters of coulters to improve its efficiency

Keywords: vertical tillage; turbo disc; shape; shell; argonauts; analytical studies

INTRODUCTION

Optimization of agricultural machinery helps preserve soil structure, enhancing aeration and water permeability, which is essential for maintaining soil fertility. Bionic colters, designed based on natural analogues, minimize soil erosion and contribute to sustainable agricultural practices. By tailoring the design to different soil types, these colters can be used more effectively in various agro-climatic conditions. Implementing such advanced technologies in

Article's History: Received: 26.04.2024; Revised: 10.07.2024; Accepted: 15.08.2024.

Suggested Citation:
Aliiev, E., & Tesliuk, H. (2024). Analytical justifications of constructive parameters of bionic colters for vertical soil treatment. *Machinery & Energetics,* 15(3), 129-139. doi: 10.31548/machinery/3.2024.129.

*Corresponding author

farming not only increases productivity but also reduces environmental impact, promoting more sustainable and eco-friendly agricultural practices.

Management of crop residues along with compacted soil under intensive farming systems requires highly efficient and well-adapted soil cultivation tools. According to Yu. Belovol (2014), vertical tillage has been gaining popularity involves vertically oriented turbo discs with wavy turbines, also known as colters, which impact the soil in a vertical direction. Due to their wave-shaped cutting edge, they fragment plant residues, and soil loosening occurs through the formation of cracks. G.V. Teslyuk *et al.* (2016) researched that there were many variations of such discs, but their design could be generalized into two main types: with radial waves and waves directed at an angle to the axis of rotation. To enhance the efficiency of fragmenting plant residues and turning the soil, some manufacturers produce discs with serrations on the edge. This type of disc can be successfully used as part of a turbo disc cultivator. Evaluation of such soil cultivation tools requires proper determination of their technical design, as well as the dynamics of their interaction with soil and plant residues.

Some studies on the interaction of turbo discs (colters) with soil and plant residues are considered. In the study of Z. Zeng *et al.* (2021), an experimental comparison of three vertical soil cultivation discs of different shapes, namely toothed, plain, and serrated, was conducted. The analysis found that the serrated disc was the most efficient among the three discs based on measured performance indicators. The results indicate that changing the working depth would be an effective approach to altering soil dynamics and the cutting performance of residues by discs for vertical tillage.

Field tests of vertical tillage tools in of Z. Zeng (2019) demonstrated that serrated discs leave fewer residues on the surface, incorporate more residues into the soil, create a wider furrow, and cover a larger area than plain discs. The impact of working speed was more dominant than the geometry of the openers on the soil processing efficiency of serrated openers.

In the study of I. Torotwa *et al.* (2022), the soil cultivation effort, structural strength, straw cutting performance, and uniformity of soil cultivation depth of a toothed disc with curved edges were evaluated in comparison to a straight-toothed disc. The design of the curved-toothed disc was inspired by the arc-shaped structure of a digger's claw. It was found that using such a disc reduced soil cultivation effort by 22.8%, ensured uniform soil cultivation depth, and increased straw cutting efficiency by 26.3 %.

J.L. Zhao *et al.* (2021) developed a stubble chopper based on the analysis of bionic prototypes. Inspired by the unique mouthpart structure of a locust, the bionic stubble chopping device acquired a new multi-segment toothed bionic structure and symmetrical rotational motion, significantly increasing stubble chopping speed. Also noteworthy is a patented design of a wavy disc (Piccat, 2006), whose wave profile is asymmetric and offset in the direction of rotation.

The article of I.V. Sobolevsky *et al.* (2021) presented methods and results of the bionic approach in the agro-mechanics system, which theoretically substantiated the main parameters of the model of working elements of wavy discs using two bionic prototypes – the digging leg and radial ribs of the bivalve mollusk *Cerastoderma edule*, and the digging leg of the dung beetle *Geotrupes stercorarius*. The model of the working elements of wavy discs helps to maintain soil erosion resistance in the upper cultivated layer to preserve its structure and stubble background during no-till soil cultivation in soil conservation farming systems using Verti-till and Strip-till technologies.

The aim of the research is to justify the design and constructive parameters of turbo discs (colters) for vertical soil tillage based on bionic reverse engineering.

MATERIALS AND METHODS

Taking into account the bionic reverse engineering approach, the shape equation for turbo discs (colters) had been derived by approximating the form of the Argonaut (*Argonauta argo*) shell. The shells of argonaut octopuses (*Argonauta argo*) served as a fascinating example for mathematical analysis in engineering design as M. Oudot *et al.* (2020) emphasized. The geometric complexity of the shell, particularly its wavy shape, had been explored in previous studies. J. Finn & M. Norman (2010) demonstrated that the wave patterns aid in vertical movement through water, while H. Hoving *et al.* (2022) identified the functional significance of these shapes in burrowing into seabed sand. According to analysis of the mathematical description of various shell shapes (Roccatano, 2018; Larsson *et al.*, 2020; Contreras-Figueroa & Aragón, 2023) particular attention particular attention of this reserch was given to spiral forms, while planar wavy forms have been less explored. Based on the reverse engineering method, the boundary of the shell was represented as shown in Figure 1

In analytical form, the equation of the shell surface can be represented as follows:

$$\begin{cases} x(\varphi_u,\varphi_v) = \left(1 - \frac{H_m}{D_d}|sin(n\varphi_u)|\right) sin\left(\varphi_u + k\frac{\varphi_v}{D_d}\right)\varphi_v, \\ y(\varphi_u,\varphi_v) = \left(1 - \frac{H_m}{D_d}|sin(n\varphi_u)|\right) cos\left(\varphi_u + k\frac{\varphi_v}{D_d}\right)\varphi_v, \\ z(\varphi_u,\varphi_v) = H_w\, cos(n\varphi_u)\left(\frac{\varphi_v}{D_d}\right)^2, \\ 0 \le \varphi_u \le 2\pi, \\ 0 \le \varphi_v \le D_d. \end{cases} \tag{1}$$

where φ_u is the parametric angular variable in radians; φ_v is the parametric linear variable in meters.

The graphical interpretation of the equation (1) in Wolfram Cloud with different parameters D_d, H_m, H_w, n and k is shown in Figure 2.

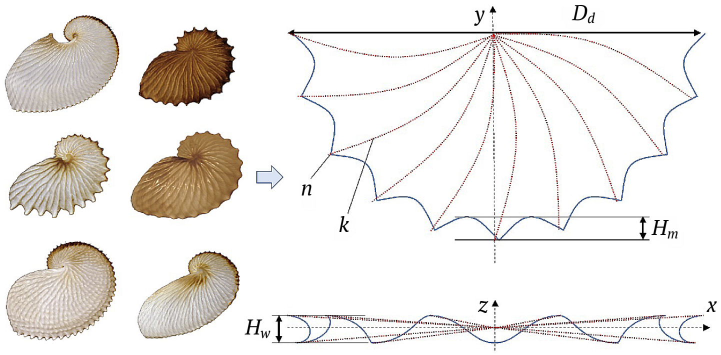

Figure 1. Approximation of the Argonaut Shell (*Argonauta argo*)
Note: D_d – diameter; H_m – notch height; H_w – wave height; n – number of waves; k – spiral coefficient; x, y, z – spatial coordinates in meters
Source: compiled by the authors

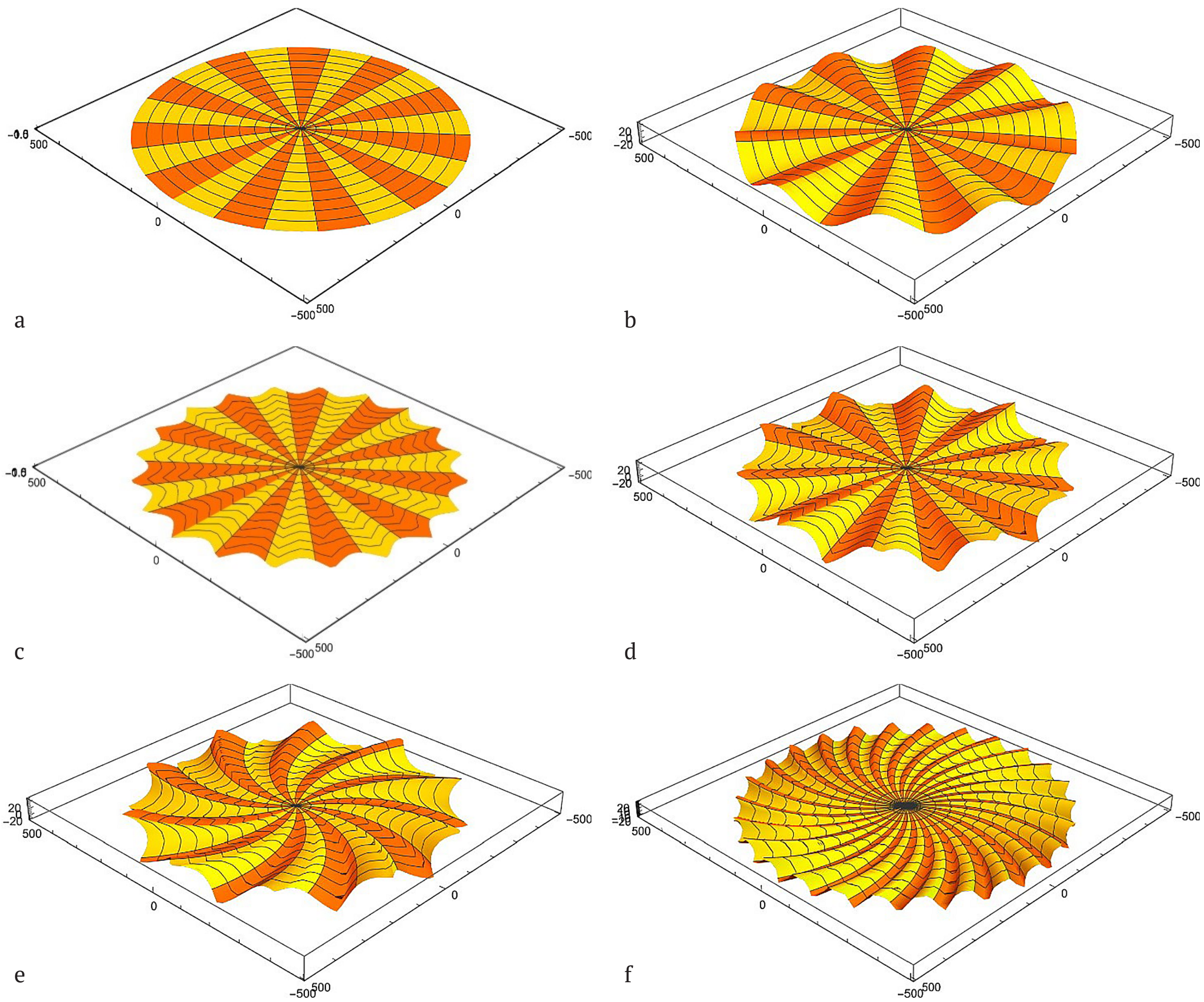

Figure 2. Constructed Variants of Turbo Discs (Colters) Based on the Bionics of Argonaut Shells
Note: a – Flat solid disc (D_d = 460 mm; H_m = 0 mm; H_w = 0 mm; n = 10; k = 0), b – Wavy disc (D_d = 460 mm; H_m = 0 mm; H_w = 30 mm; n = 10; k = 0); c – Flat notched disc (D_d = 460 mm; H_m = 50 mm; H_w = 0 mm; n = 10; k = 0); d – Wavy notched disc (D_d = 460 mm; H_m = 50 mm; H_w = 30 mm; n = 10; k = 0); e – Wavy spiral notched disc (D_d = 460 mm; H_m = 50 mm; H_w = 30 m; n = 10; k = 0.6); f – Wavy spiral notched disc (D_d = 460 mm; H_m = 20 mm; H_w = 30 mm; n = 26; k = 0.6)
Source: compiled by the authors

The next step involved analytical studies of the interaction process between the turbo disc (colter) and the soil environment, as well as plant residues. In determining the forces acting within the model soil environment, the following simplifications and assumptions were made: the soil was conditionally modelled as a medium with internal friction and specific cohesion that did not depend on external pressure. The likelihood of this assumption being valid was confirmed by (Semenyuta, 2014). The soil environment was considered anisotropic in its various properties (Shevchenko, 2001). At pressures of 0.4-0.6 MPa, and for soils with significant compaction up to 0.9 MPa, the relationship between pressure and deformation was considered linear. Thus, to establish the forces acting in the soil environment, elasticity theory was used. The propagation of cleavage lines (cracks) in the soil occurred in a vertical-transverse plane at an angle of $\varphi_2 + \pi/2$ to the cutting edge of the tool, where φ_2 was the internal friction angle of the soil (Kobets *et al.*, 2011). The predominant direction of crack propagation remained unchanged throughout the process (Kobets *et al.*, 2009). The specific cohesion of soil particles was a key indicator that encompassed other mechanical and technological properties. Analytical studies were conducted for different types of colters: flat solid, flat notched, and wavy notched discs. The research was carried out in the software package Wolfram Cloud (Wolfram company, USA).

RESULTS AND DISCUSSION

A mulcher made up of flat solid discs (H_m = 0 mm; H_w = 0 mm; k = 0) can perform cutting of plant residues and surface loosening of the soil environment without mixing and rotating its layers. The scheme for calculating the interaction of the disc with the soil and plant residues is shown in Figure 3.

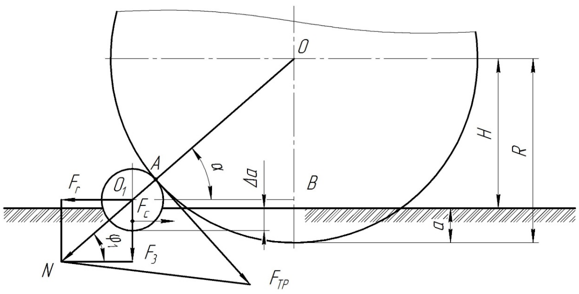

Figure 3. Interaction of a flat solid disc with soil and plant residues

Note: O, A, B, O_1 – points on the drawing; *a, H, R,* Δa – length in meters; α, φ_1 – angles in radians; F_{TP} – the force of friction between the disk and plant remains in Newtons; *N* – the force of normal pressure between the disc and plant remains in Newtons; F_c – soil resistance in Newtons; F_3 – disc reaction force in Newtons; F_r – the force of inertia in Newtons

Source: compiled by the authors

Consider the conditions for cutting plant residues (using a stem as an example) with a disc. The interaction of the disc with the stem can have four possible outcomes:

- forward displacement: this option is unacceptable as it excludes the possibility of cutting;
- side displacement: this occurs with short stems of 5-8 cm in length (which meets agronomic requirements);
- pulling under the disc: although this option does not guarantee cutting of plants, it meets agronomic requirements (Fig. 4), as part of the stem is buried to the depth at which the disc operates;
- stationary stem: this option ensures guaranteed cutting of the plant.

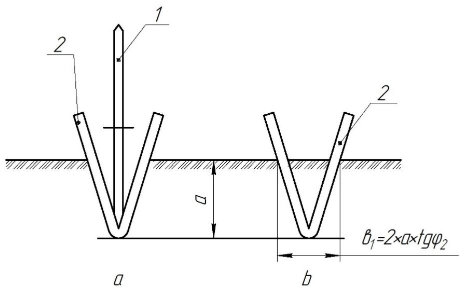

Figure 4. Interaction of the flat solid disc with soil and plant residues

Note: 1 – disk; 2 – stem; a – moment of interaction between the disk and the stem; b – after the disk passes; *a*, b_1 – length in meters; φ_2 – angles in radians

Source: compiled by the authors

The achievement of cutting a stationary stalk can be accomplished in two ways: by cutting without support at increased cutting speeds or by creating conditions for supported cutting. Unambiguously supported cutting can be achieved with a blade speed up to 15 m/s for crops with thin stalks and up to 60 m/s for crops with thick stalks (Kirichenko *et al.*, 2011). The specified speeds are not achieved by passive working elements, so analytical studies need to be considered under the scheme of supported cutting without moving the stalk by the disc (Fig. 3).

As indicated by informational analysis, there is no excessive need for cutting thin-stemmed plant residues (the option shown in Figure 4 is sufficient), but the problem of shredding residues of coarse-stemmed crops is present. Unshredded residues decompose slowly and significantly complicate the operation of seeders. Therefore, it is worth examining the interaction of the disc with crops with thick stalks.

Assumptions made: The stalk to be cut is cylindrical; stalk characteristics are homogeneous and isotropic throughout its length; the strength parameters of the stalks are proportional to the square of their diameters (Kobets *et al.*, 2011); the interaction of the disc with the soil is determined by the wall support law (Kozachenko *et al.,* 2021).

The forces acting on the stalk by the disc are: normal pressure force *N*; resistance force from the soil F_C; friction force F_{TP}. The condition for cutting the stalk is the zero sum of the horizontal components of all forces acting on it (Fig. 3). The most rational option is a small displacement of the stalk backward along the disc's path. The stalk will be pressed into the soil until the pressure force of the blade exceeds the critical cutting force. This depth of immersion is denoted as Δa. The value Δa will determine the coefficient of volumetric soil displacement. According to the calculation scheme (Fig. 5), the volume of the stalk immersed in the soil is calculated by the equation:

$$V = 0.5LS_{BCD} = \\ = 0.5L\left[R^2 \, arccos\frac{R-\Delta a}{R} - (R-\Delta a)\sqrt{R^2-(R-\Delta a)^2}\right], \quad (2)$$

where R is the stem radius; L is the stem length; Δa is the penetration depth.

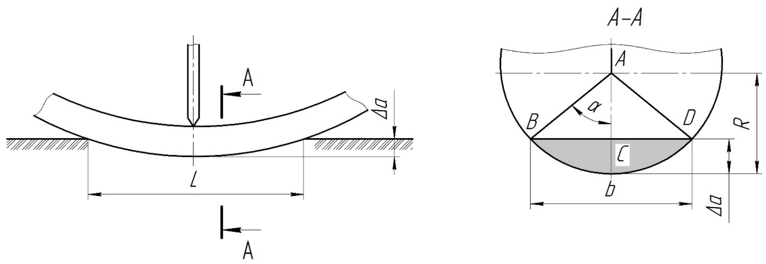

Figure 5. Diagram for calculating stem immersion parameters under the action of the disk
Note: A-A – designation of the section on the drawing; A, B, C, D – points on the drawing; **Δ*a, L, b, R*** – length in meters; ***α*** – angles in radians
Source: compiled by the authors

The relationship for determining the immersion depth is as follows:

$$qV = 0.5qL \\ \left[R^2 \, arccos\frac{R-\Delta a}{R} - (R-\Delta a)\sqrt{R^2-(R-\Delta a)^2}\right] > [P], \quad (3)$$

where $[P]$ – stem shear resistance; q – soil volume change coefficient.

Solving equation (3) in the Wolfram Cloud software yields a graph showing the relationship between the stem immersion depth in the soil and its diameter under the action of a solid disk (Fig. 6). The analysis of this relationship indicates that, for real values of stem radius and the force acting on its cross-section, the immersion depth ranges from 4 to 6 mm. In other words, stems with diameters less than 4 mm will be reliably driven into the soil. It is important to note that the plastic deformation of the stem itself does not affect the immersion depth, as this aspect is already accounted for in the stem resistance. According to Figure 3, the balance of forces acting in the horizontal plane can be expressed as:

$$N \cdot cos\alpha + f_1 \cdot N \cdot sin\alpha = f_2 \cdot F_3, \quad (4)$$

where f_2 – coefficient of friction between the stem and the soil; f_1 – coefficient of friction between the stem and the steel; α – angle of embedding.

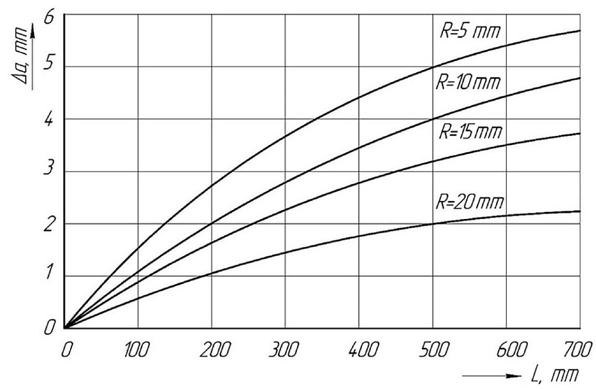

Figure 6. Relationship between stem immersion depth in the soil, its radius and length at q=900 kN/m^3
Note: Δa – the penetration depth; R – the stem radius; L – the stem length
Source: compiled by the authors

The mass of the stem is small enough to be neglected. Then, the force reaction of the disk can be determined from the following relation:

$$F_3 = N \cdot sin\alpha - f_1 \cdot N \cdot cos. \quad (5)$$

By substituting (4) into (5) and performing the mathematical transformations, the following expression is obtained:

$$tg\alpha = \frac{1+tg\varphi_1 \cdot tg\varphi_2}{tg\varphi_2 - tg\varphi_1} = ctg(\varphi_1-\varphi_2) = tg(\frac{\pi}{2}-\varphi_1 - \varphi_2). \quad (6)$$

Taking into account Figure 5, the following is obtained:

$$\alpha = arcsin\frac{OB}{R_d+R} = arcsin\frac{R_d-a-R+\Delta a}{R_d+R}, \tag{7}$$

where R is the stem radius and R_d is the disk radius. By substituting (7) into (6) and performing mathematical transformations, the following is obtained:

$$D_d = 2R_d = 2\frac{R\cdot cos(\varphi_1+\varphi_2)+a+R-\Delta a}{1-cos(\varphi_1+\varphi_2)}. \tag{8}$$

Graphical interpretation of equation (8) is shown in Figure 7. The parameter Δa is obtained from equation (3), Figure 6. Given a soil penetration depth of 80 mm, the optimal diameter of the disc for equation (1) is D_d = 460 mm. It should be noted that plain solid discs are rarely used in their pure form, as their functional capabilities are limited to merely crushing plant residues and clods on the soil surface. In this context, they are considered an intermediate stage for determining the parameters of a turbo-disc (colter).

The solid disc has several drawbacks that limit its capabilities in soil processing, especially in the context of organic farming systems. One of these is the negative entry angle into the working medium. However, for effective stem cutting, it is necessary for the blade's action to be directed vertically during the initial stages. This allows the stem to be partially embedded in the soil and fixes it in place, preventing movement during cutting.

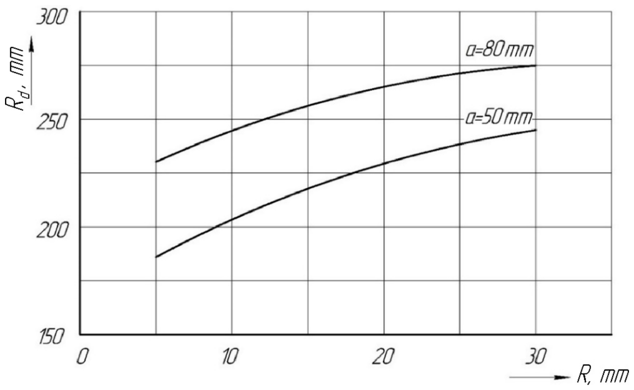

Figure 7. Dependence of the minimum disk radius on the depth of penetration and the coefficient of volumetric soil compression

Note: R_d – the disk radius; a – penetration depth of the disc; L – the stem length

Source: compiled by the authors

The calculation scheme for such a disc is examined, and the working process is broken down into stages according to the number of cuts on the disc (Fig. 8). Each stage corresponds to Fig. 8a-Fig. 8f. The beginning of the stage (Fig. 8a) is determined by the vertical downward movement of the cutting blade. The end of the stage corresponds to the moment when the blade starts moving towards the soil surface (Fig. 8f).

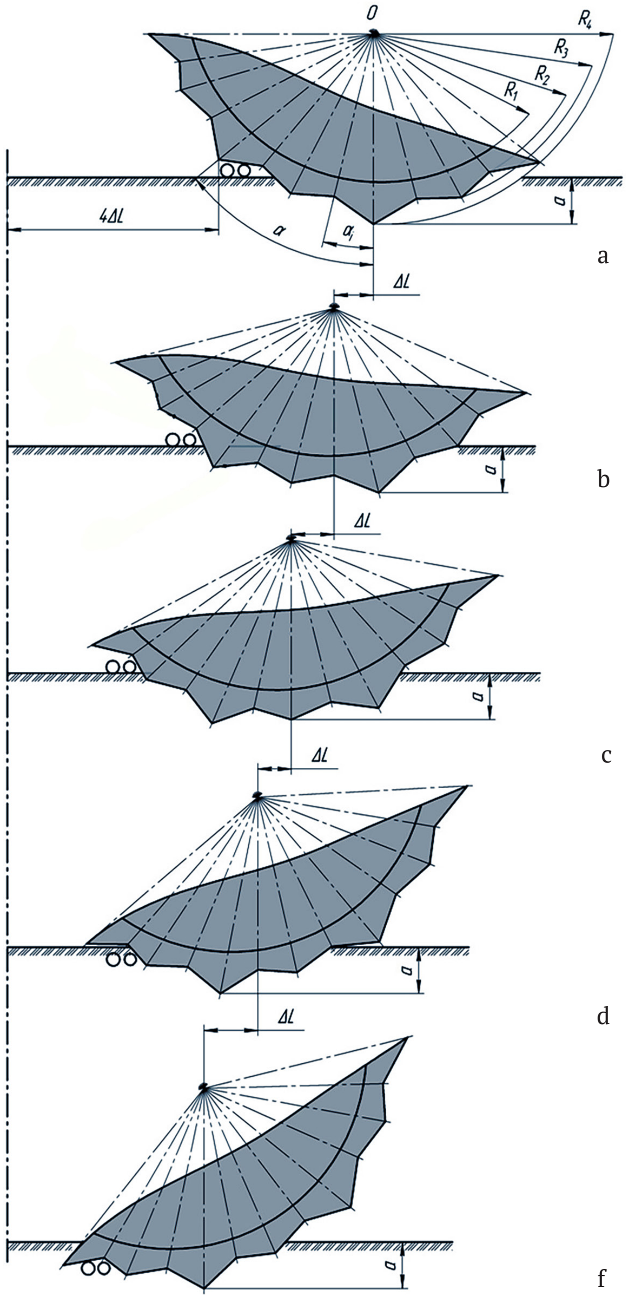

Figure 8. Diagram for calculating the action of a notched disc on soil and stem

Note: a–f – stages of the work process; O – axis of rotation; a, ΔL, R_1, R_2, R_3, R_4 – length in meters; α, α_i – angles in radians

Source: compiled by the authors

From the calculation scheme, the angular step of the cuts can be determined:

$$\alpha < arccos\frac{R_4-a-d}{R_4}, \tag{9}$$

where a – penetration depth of the disc; R_4 – radius of the circumscribed circle; d – diameter of the stem. This allows for the determination of the number of cuts. Calculations are performed using the following data: R_4 = 230 mm, corresponding to a disc diameter of 460 mm; a = 50-80 mm (standard values accepted in most known aggregates); $d = 2$-35 mm – diameter of the stem. Given the requirement for full immersion of the disc cuts in the soil during operation, the radial parameters of the disc are set as follows: $R_1 = 230 - 80 = 150$ mm, $R_2 = 230 - 50 = 180$ mm, $R_3 = (R_1 + R_4)/2 = 190$ mm. Thus, for equation (1), $H_m = R_4 - R_3 = 40$ mm.

By analysing dependence (9) in the Wolfram Cloud software package, the optimal angular step value of $\alpha = 48.3°$ and the number of notches $n = 8$ is obtained. Considering Figure 8, $\alpha_i = \alpha/4 = 12.1°$, $\Delta L = 2\pi R_4 \alpha_i/360 = 48.5$ mm. Such discs are used in Strip-Till and Mini-Till systems for crushing surface clods and plant residues. However, they are not suitable for soil loosening.

In the previous stages, the disc diameter of 460 mm, the number, and the parameters of the notches on it were justified. According to equation (1) and Figure 1, the number of waves of the colter corresponds to the number of notches. The calculation scheme is shown in Figure 9.

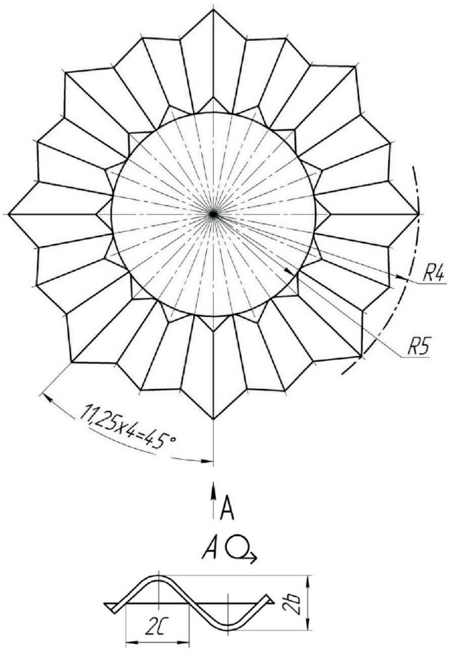

Figure 9. Diagram for calculating the colter

Note: A – reamer on the drawing; C, R_4, R_5 – length in meters

Source: compiled by the authors

Structurally, this modification of the notched disc is an improvement of the previous version, in which the peaks of the cutting segments are made in the form of bends in a staggered order. The presence of waves ensures independence of the interaction process with plant residues from their location on the field surface and creates conditions for vertical soil processing. In the proposed modification, the waves are arranged radially, although there are options where they are positioned at a certain radius to the axis of rotation (Fig. 1). The main purpose of the colter is to perform vertical processing, i.e., loosening through vertical action. The peculiarity of vertical processing is that the wear lines from the cutting element do not propagate in the vertical-transverse plane. This is not only analytically justified but also confirmed during operation.

The separated soil aggregate from the moment of undercutting to placement in the furrow remains in constant contact with the working surfaces of the disc. Thus, to overcome the internal stress in the soil, it will be sufficient to determine the cutting force. For this, it is necessary to know the coefficient of soil particle cohesion and the surface area of the corresponding prism.

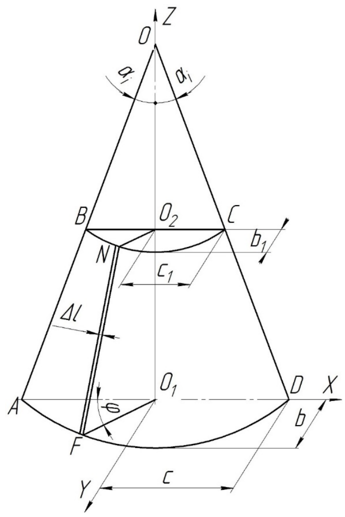

Figure 10. Geometric dimensions of the separated prismatic soil slice

Note: X, Y, Z – spatial coordinates in meters; O, A, B, D, F, N, O_1, O_2 – points on the drawing; Δl, b, c, b_1, c_1 – length in meters; α_i, φ – angles in radians

Source: compiled by the authors

The separated prismatic soil slice is a semi-truncated cone ABCD with corresponding parameters (designated according to Fig. 10): $c = R_4\, tg\alpha_i = 49.3$ mm; the constructively accepted value is $b = 35$ mm; $b_1 = b \cdot (R_4 - H_m)/R_4 = 29$ mm. For the lower ellipse, the radius vector value is:

$$R = \frac{b \cdot c}{\sqrt{b^2 \cdot cos^2\,\varphi + c^2 \cdot sin^2\,\varphi}}. \quad (10)$$

For the lower radius vector:

$$r = \frac{b_1 \cdot c_1}{\sqrt{b_1^2 \cdot cos^2\,\varphi + c_1^2 \cdot sin^2\,\varphi}}. \quad (11)$$

The surface area of the separated soil prism is calculated as the sum of the area of the lower semi-ellipse and the area of the lateral surface DABC. The area of the lateral surface is calculated by numerical integration. The surface is then divided into infinitely thin elementary sections of width Δl. The area of each such elementary section is determined as follows:

$$dS = \sqrt{a^2 + (R - r)^2} \cdot dl = \sqrt{a^2 + (R - r)^2} \cdot R \cdot d\varphi. \quad (12)$$

By integrating expression (12), the total area of the lateral surface is obtained:

$$S_B = \int_{\varphi=0}^{\varphi=\pi} \sqrt{a^2 + (R-r)^2} \cdot R \cdot d\varphi. \quad (13)$$

According to Figure 10, the expression for the total surface area is:

$$S_\Sigma = S_B + S_O + S_{PO} = $$
$$= \int_0^\pi \sqrt{a^2 + (R-r)^2} \cdot R \cdot d\varphi + \pi \cdot b \cdot c + a \cdot (c + c_1). \quad (14)$$

where S_{PO} is the area of the prism cut; S_O is the area of the prism base.

The force required to separate the soil prism can be expressed as follows:

$$F = C_{UD} \cdot S_\Sigma. \quad (15)$$

In turn, the specific cutting resistance can be represented as follows:

$$K_1 = \frac{F}{b \cdot a}. \quad (16)$$

The volume of the separated soil prism is determined for further calculations:

$$V = 0.5 \cdot \frac{\pi \cdot a}{6} \cdot [(2 \cdot c + c_1) \cdot b + (2 \cdot c_1 + c) \cdot b_1]. \quad (17)$$

The degree of soil fragmentation is determined as follows:

$$i = \frac{V}{V_i} = \frac{6V}{\pi d_a^3}. \quad (18)$$

where d_a is the diameter of the formed soil aggregate.

Combining equations (10)-(18) yields the following result:

$$i = \frac{a}{2d_a^3} \cdot [(2 \cdot c + c_1) \cdot b + (2 \cdot c_1 + c) \cdot b_1]. \quad (19)$$

$$K_1 = \frac{C_{UD}}{b \cdot a} \cdot$$
$$\cdot \left(\int_0^\pi \sqrt{a^2 + (R-r)^2} \cdot R \cdot d\varphi + \pi \cdot b \cdot c + a \cdot (c + c_1)\right). \quad (20)$$

Solving the condition for minimizing the specific cutting resistance and maximizing the degree of soil fragmentation in the Wolfram Cloud software package:

$$\frac{a}{2d_a^3} \cdot [(2 \cdot c + c_1) \cdot b + (2 \cdot c_1 + c) \cdot b_1] \to max$$
$$\frac{C_{UD}}{b \cdot a} \cdot \left(\int_0^\pi \sqrt{a^2 + (R-r)^2} \cdot R \cdot d\varphi + \right.$$
$$\left. + \pi \cdot b \cdot c + a \cdot (c + c_1)\right) \to min. \quad (21)$$

The following rational parameters for the colter wave are obtained: $H_w = b = 24.4$ mm; $c = 2b = 48.8$ mm.

The necessity of the spiral shape of the wave cutouts on the disc is difficult to justify analytically, so further research will use numerical modelling methods in the Simcenter STAR-CCM+ software package. The analytical model developed in this study offered further insights into how the geometric features of the disc affected its interaction with soil. By simulating the forces acting on the disc during tillage, the model allowed researchers to predict the performance of different disc shapes under varying field conditions. This proved to be a valuable tool for optimizing the design of the discs and could be used by manufacturers to improve the effectiveness of their products.

Moreover, the wavy disc's unique shape allowed for a more controlled interaction with the soil, reducing the likelihood of soil compaction, which is a significant concern in modern agriculture. Soil compaction can lead to poor root development, reduced water infiltration, and lower crop yields. By reducing the pressure applied to the soil surface, the wavy disc minimized compaction while still performing the necessary tillage functions. Overall, the research demonstrated the potential of using bionic principles to design more efficient agricultural tools. The wavy disc, with its optimized shape, offered a clear advantage over traditional designs, reducing both energy consumption and operational costs while improving soil and residue management. This could have a significant impact on the agricultural industry, particularly in regions where soil health and sustainable farming practices are of paramount importance. By continuing to explore the applications of bionics in agricultural engineering, future research may uncover even more innovative solutions that help farmers meet the growing demands of modern agriculture.

Comparing the proposed designs of the discs (equation (1) and Fig. 2) with the Patent US 2006/0144600 A1 (Piccat, 2006), it could be concluded that the proposed mathematical description of the profile was more universal. With certain parameters, it was possible to achieve known designs. This indicated the generalization of the obtained disc shape.

The application of bionics in justifying the shape of turbo discs, modelled on the basis of the Argonaut shell, improved the capture and cutting of plant residues without repulsion. This approach was further supported by the work of Z. Zeng *et al.* (2021), where bionic prototypes such as the oral apparatus of locusts and the digging legs of mollusks were used. Additionally, this approach was confirmed in the study of I.V. Sobolevsky *et al.* (2021), where bionic prototypes of wavy discs were derived from the radial ribs of the bivalve edible cockle shell (*Cerastoderma edule*) and the digging leg of the common dung beetle (*Geotrupes stercorarius*).

The rational parameters of the wavy disc (wave height of 24.4 mm, number of notches – 8, and diameter – 460 mm) identified in the research aligned with the findings of I. Torotwa *et al.* (2022), where similar designs demonstrated increased efficiency in chopping plant residues and loosening the soil. For example, experiments with fluted discs revealed that they significantly reduced the amount of residue on the field's surface and created a wider furrow, which was similar to the results obtained with wavy discs. Furthermore, the proposed analytical model (3)-(8) could complement the simulation by I. Torotwa *et al.* (2022) and serve as a suitable physical-mathematical tool. The study by I. Torotwa *et al.* (2022) provided a direct comparison of wavy and conventional discs, reinforcing the conclusion that wavy discs are more effective for handling plant residues. In tests, the wavy discs significantly reduced the amount of unprocessed material left on the soil surface, which is critical for ensuring proper seed placement and reducing the likelihood of crop diseases. This was particularly beneficial in no-till or reduced-till systems where crop residues are intentionally left on the surface for moisture retention and erosion control.

The analytical justification for the behaviour of the discs during contact with soil and plant residues demonstrated that the wavy surface of the disc with notches created optimal conditions for vertical soil tillage, as it reduced resistance and promoted uniform chopping of residues. These results were corroborated by the studies of A.M. Semenyuta (2014) and A.I. Shevchenko (2001), which found that fluted discs enhanced soil fragmentation and reduced energy costs for tillage.

The research results presented here supplemented the findings of Z. Zeng (2019), particularly by enabling the development of a methodology for engineering calculations of the structural parameters of turbo discs (colters). In turn, the bionic analogue of the turbo disc, proposed as the basis of the design, confirmed the effectiveness of using the bionic approach in the agro-mechanics system (Kozachenko *et al.*, 2021).

The spiral shape of the wavy disc, proposed in this study, had great potential for reducing the specific cutting resistance and improving the quality of soil treatment. The works of A.S. Kobets *et al.* (2011) and O. Kozachenko *et al.* (2021) also noted that geometric modifications similar to spiral elements could significantly affect the efficiency of soil tillage tools.

By examining the differences between traditional disc profiles and those designed using bionic principles, a more comprehensive understanding of the advantages offered by biologically inspired shapes was gained. The research not only highlighted the utility of imitating natural forms but also validated the effectiveness of applying these forms to agricultural machinery. Traditional flat discs, for example, often struggled to perform optimally when dealing with tough plant residues or compacted soils. The introduction of wavy or spiral designs allowed for better engagement with the soil, leading to improved penetration and more efficient residue cutting.

The use of bionic principles, as seen in this study, aligned with the broader trend in agricultural engineering towards more sustainable and efficient machinery. Bionics, which draws inspiration from nature, offered a novel approach to solving long-standing challenges in the field. In the case of the wavy disc, the inspiration came from natural structures that have evolved to efficiently interact with the environment, such as the shells of molluscs and the limbs of burrowing animals. These natural designs provided a blueprint for creating tools that are both effective and energy-efficient.

CONCLUSIONS

Considering the method of bionic reverse engineering, the equation for the shape of turbo discs (colters) has been determined by approximating the shell of the Argonaut (*Argonauta argo*). As a result of analytical studies of the interaction process of a solid disc with plant residues, the rational diameter value of the disc was determined to be $D_d = 460$ mm, assuming the embedding of stems with a thickness of 10-20 mm to a depth of 80 mm. Analytical studies confirmed that the presence of cutouts on the disc prevents the stems from being pushed aside and ensures better capture. Analysing the obtained analytical dependencies in the Wolfram Cloud software package, rational cutout values were obtained: the cutout height $H_m = 40$ mm, and the number of cutouts $n = 8$.

The presence of waves in the disc plane ensures the independence of the interaction process with plant residues from their location on the field surface and creates conditions for vertical soil cultivation. Thus, according to the results of analytical studies, it was determined that with the condition of minimizing the specific cutting resistance and maximizing the degree of soil fragmentation, the rational parameters of the colter wave are a wave height $H_w = 24.4$ mm.

The substantiated parameters of the colters open new avenues for further research into optimizing agricultural machinery. Future studies could explore the potential for adapting existing equipment to these innovative structural parameters, aiming to achieve a better balance between soil pulverization efficiency and reduced energy consumption. Additionally, further investigation into the integration of bionic principles in machinery design could lead to the development of more efficient and environmentally sustainable soil processing technologies.

ACKNOWLEDGEMENTS

None.

CONFLICT OF INTEREST

None.

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Ельчин Алієв
Доктор технічних наук, старший дослідник
Дніпровський державний аграрно-економічний університет
49600, вул. Сергія Єфремова, 25, м. Дніпро, Україна
Інститут олійних культур Національної академії аграрних наук України
69055, вул. Інститутська, 1, м. Сонячне, Запорізька область, Україна
https://orcid.org/0000-0003-4006-8803
Геннадій Теслюк
Кандидат технічних наук, доцент
Дніпровський державний аграрно-економічний університет
49600, вул. Сергія Єфремова, 25, м. Дніпро, Україна
https://orcid.org/0000-0003-4541-5720

Аналітичні обґрунтування конструктивних параметрів біонічних колтерів для вертикального обробітку ґрунту

Анотація. Біонічні колтери імітують природні форми та функції, які дозволяють знизити енергетичні витрати на обробку ґрунту. Мета досліджень була обґрунтування конструкції і конструктивні параметри турбодисків (колтерів) для вертикального обробітку ґрунту спираючись на принципи біонічного зворотного інжинірингу. Враховуючи цей метод визначено рівняння форми турбодисків (колтерів), яке отримано в результаті апроксимації мушлі аргонавта (*Argonauta argo*). Рівняння враховує основні конструктивні параметри турбодисків: діаметр D_d, висота вирізу H_m, висота хвилі H_w, кількість вирізів n, коефіцієнт спіралеподібності k. В результаті аналітичних досліджень процесу взаємодії суцільного диска з рослинними рештками визначено раціональне значення його діаметра $D_d = 460$ мм при умові занурення стебелів товщиною 10-20 мм, на глибину 80 мм. Аналітичні дослідження підтвердили, що наявність вирізів на диску унеможливлює відштовхування стебла і забезпечує його кращій захват. При цьому аналізуючи отримані залежності у програмному пакеті Wolfram Cloud визначені раціональні значення вирізів: висота вирізу $H_m = 40$ мм, кількість вирізів $n = 8$. Наявність хвиль в площині диску забезпечує незалежність процесу взаємодії з рослинними залишками від їх розташування на поверхні поля та створює умови для вертикальної обробки ґрунту. Встановлено, що при умові мінімізації питомого опору різання і максимізації ступеня подрібнення ґрунту раціональними параметрами хвилі колтера є висота хвилі $H_w = 24{,}4$ мм. Обґрунтовані параметри колтерів забезпечують найкращий баланс між ефективністю подрібнення ґрунту і зниженням енергетичних витрат на обробку ґрунту. Отримані результати можна використати для адаптування існуючої сільськогосподарської техніки під нові конструктивні параметри колтерів для підвищення її ефективності

Ключові слова: вертикальний обробіток ґрунту; турбодиск; форма; мушля; аргонавти; аналітичні дослідження