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Geometric Modeling of Disc Furrow Profile

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Abstract. The provision of sufficient quantities of food products for the population of our planet is currently an urgent global problem. One of the main approaches to successfully solving these critical issues is to improve agriculture and its technical tools, particularly tillage discs. The latter's popularity is due to modern progressive trends in minimal tillage. Compared to plows, discs significantly reduce energy costs, contribute to soil moisture preservation, and improve anti-erosion factors. In this regard, integrated CAD/CAM/CAE/PLM systems are productive tools for practically implementing the described tasks. However, their effective functioning is impossible without developing appropriate mathematical models. This scientific publication is devoted to solving such a problem by creating an analytical geometric apparatus for forming furrow profiles depending on available diameters and installation angles of tillage discs. Simultaneously, the current trends in the construction of agricultural machinery regarding the placement of disc working bodies on individual risers with the regulation of required angles of attack and deviations from vertical were considered. The developed mathematical calculations were illustrated by corresponding graphic images of furrow profiles for specific values of indicated quantities. This research also outlines promising directions for further research on the topic under consideration. Overall, the article aims to solve the problems using the integrated processing of structural and functional parameters and characteristics for agricultural discs.

Keywords: geometric modeling, product innovation, agricultural production, disc tillage tools.

1 Introduction

Properly providing high-quality products is an urgent problem worldwide [1]. The importance of many innovative approaches to improving agricultural production is given in [2].

One of the effective directions is further improving various applied technical tools, including tillage discs. The latter's popularity is due to modern progressive trends regarding minimal tillage. Compared to plows, these discs significantly reduce energy costs, conserve moisture, and improve anti-erosion factors.

With the wide use of information technologies, integrated CAD/CAM/CAE/PLM systems are quite productive means for successfully performing the described tasks. The publication [3] presents the basic properties of the most famous machine-building CAD/CAM/CAE/PLM programs and shows the unifying and coordinating role of geometric modeling for them.

Khan and Rezwana [4] highlight some aspects of the productive integration of CAD and CAM packages thanks to the hierarchical format of intermediate data outlined. The study [5] is devoted to effectively combining theoretical and experimental knowledge to design sheet metal parts for cars. The prospect of spreading this approach to other branches of industry is considered. This may be appropriate to design and manufacture tillage discs.

The article [6] proposes a comprehensive concept of managing the life cycle for complex technical systems. It is based on already-known engineering methodologies. These tasks are relevant to agriculture, too.

Notably, all the publications analyzed above and many others emphasize the fundamental role of geometric models for CAD/CAM/CAE/PLM systems. These tools provide automated shaping of various technical objects and the possibility of comprehensive optimization while designing, manufacturing, and operation.

This publication is devoted to solving some of the presented problems using the example of integrated processing of structural and functional parameters and characteristics of agricultural discs.

2 Literature Review

The scientific problem of creating and using disc tillage tools is covered in detail in scientific studies. This applies to many aspects of the specified objects.

In the article [7], based on field experiments, an analysis of five working bodies in the form of three vertical discs (smooth, toothed, corrugated) and two-disc colters was carried out to compare their efficiency at different tillage depths. Acting forces, the width of soil destruction, and the crushing of plant residues were measured. The results proved that the existing tool geometry significantly affects the obtained agrotechnical indicators. Each of the considered working bodies has certain advantages and disadvantages. Similar questions were also presented by a group of scientists in [8].

Based on the above publications, it is possible to conclude the importance of variant computer modeling based on the appropriate mathematical apparatus. This allows for reducing the number of field experiments of significant cost.

The article [9] is devoted to experiments on using spherical discs on elastic risers, determining rational modes of interaction with the soil, and reducing energy consumption without deterioration of the quality of technological processes. The publication [10] studies the force factors acting on a flat disc that function at different sweep and inclination angles. This confirms the importance of the correct position of tillage implements during their operation.

The specified plowing angles and depths are also studied by Malasli and Çelik [11] and Mankhi and Jebur [12], where the significant influence of the specified parameters on the obtained profile of the furrow, its cross-sectional area, and the nature of crushing plant residues, required traction effort and energy costs.

The research work [13] considers mathematical prediction of the required traction force for high-speed disc tillage operations. At the same time, the speed, installation angles, disc diameters, soil tillage depth, and properties were comprehensively studied [14].

The scientific problem of agrotechnical quality using disc harrows is highlighted by the team of authors in the article [15]. It is emphasized that these tools make it possible to effectively destroy weeds, retain moisture in the soil, and add plant residues and mineral fertilizers to it [16].

Based on a set of such parameters as the speed of movement, the angles of installation of discs, and their working depth, during field experiments, the agrotechnical quality was evaluated in the form of deviations from the required depth of soil cultivation, the resulting unevenness of the field surface, the nature of the furrow profile, and the percentage of plant residues [17]. Through certain generalizations, practical recommendations for effective compliance with agrotechnical requirements have been formed [18].

Damanauskas and Janulevičius [19] claim that soil cultivation is becoming less intensive due to environmental requirements and the need to save energy resources. One of these ways is to minimize the depth of tillage. A cultivator with flexible legs and a disc harrow was investigated. It was established that the achievement of the desired soil structure and the level of application of plant residues is ensured by fuel consumption, which depends on the type of tractor, the speed of movement of the unit, the depth of soil cultivation, and its condition, and the number of plant residues. It is recommended that fuel is saved not by reducing the technological speed of agricultural implements but by reducing the depth of cultivation.

In the publication [20], the authors predict the forces acting on the discs and the nature of soil deformation by them with the help of a fuzzy logic apparatus. The paper [21] is devoted to the modern agriculture system, which involves sowing in uncultivated soil by creating a furrow of the required profile for proper seed penetration. This approach better conserves moisture and prevents soil erosion. Several geometric models of discs at different seeding speeds were analyzed to define the rational modes of the applied technology. The perspective of these studies is a broader consideration of such characteristics as multi-mineral soils and climatic and agrotechnical conditions. The possibility of optimizing the use of tools by choosing the necessary types of discs, their diameters, cutting angles, and movement speed is considered. The report describes the experience of determining the geometric parameters of a double-disc planter for direct sowing after harvesting wheat. Rational disc diameters, their mutual location, and sharpening angles are recommended.

Thus, the information presented above from the cited literary sources indicates that their constructive and operational geometric parameters and characteristics are essential for effectively creating and using such progressive agricultural tools as tillage discs [22]. The complete integration of the described factors is revealed during the interaction of the discs with the soil, that is, the formation of the proper furrow, its depth, width, and profile. That is why, in our opinion, relevant scientific research is quite relevant. This is the reason for the chosen topic of this publication.

The article aims to find analytical solutions for the integrated processing of structural and functional parameters and characteristics of agricultural discs.

3 Research Methodology

There are various disc tillage implements, such as various cultivators, harrows, and plows. Until recently, the fundamental component of disc peelers and harrows, for example, was a battery containing a shaft fixed to the frame in bearing supports, on which the discs were evenly spaced with the possibility of joint variation of their angle of attack. The main disadvantage of the specified layout scheme is that the battery does not copy the existing terrain well due to its relatively long length. Discs with individual spring-loaded risers are now widely used. This realizes smooth overcoming of field irregularities during operation. In disc plows, the working bodies are also placed on separate risers with the provision of step-by-step adjustment of the angles of attack and sometimes also the deviation from the vertical. Accented tools contribute to adapting agricultural tools to the conditions of their practical use.

The specified progressive constructive aspects determine the need to develop appropriate new mathematical models, which form the basis for further effective computer reproduction of the studied agricultural processes. The scheme of the technological formation of the disc furrow is shown in Figure 1.

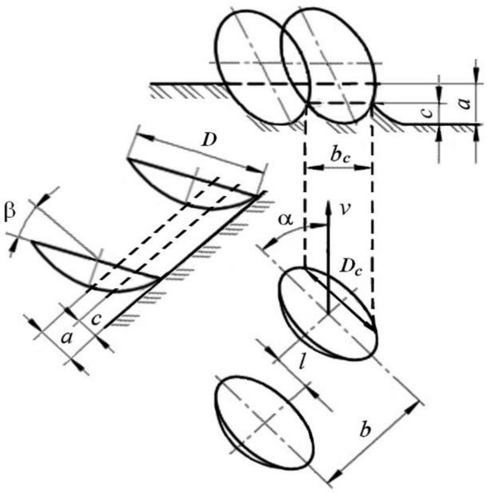


Figure 1 – Formation of a ridged disc furrow

During operation, a furrow with ridges of height *c* is formed in the soil, which depends on the diameter *D* of the discs and the angles of their installation (α – attack, β – deviation from the vertical). The following notations are used in Figure 1: *v* – tool speed vector; *a* – processing depth; D_c – the disc chord corresponding to *c*; b_c – width of capture; *b* and *l* – parameters that determine the distance between discs.

According to agrotechnical requirements [23], the height of the ridges should not exceed half the depth of cultivation, i.e.,

$$c < 0.5\,a. \tag{1}$$

As can be seen from the image above, the width of the disc grip is equal to the distance between the ridges and is calculated by the formula

$$b_c = D_c \cdot \sin(\alpha). \tag{2}$$

Notably, an increase in the parameter *l* decreases the height of the ridges and increases the distance *b*.

To maintain the height *c*, the constant is provided:

$$b_c = b \cdot \cos(\alpha) - l \cdot \sin(\alpha), \tag{3}$$

that is the negative value of $l \cdot sin(\alpha)$ is compensated by the appropriate increase in the value of *b*.

The distance between the axes of rotation of the discs

$$L = \sqrt{b^2 + l^2}. \tag{4}$$

Ratios (3) and (4) are widely used during the layout of agricultural implement data.

It can be seen from formulas (1)–(4) that the value c of the height of the ridges is quite important for the quality of soil tillage processes with discs. For its definition, depending on the diameter *D* of the used disc and its installation angles α and β, the appropriate mathematical model of the furrow profile will be determined.

4 Results

4.1 Developed mathematical apparatus

A rectangular Cartesian coordinate system *Oxyz* is used (Figure 2), the abscissa *x* of which is opposite to the speed *v* of the tool, the *Oxy* plane is horizontal, and the appliqué *z* is vertical.

The equation of the lower part of the circle located in the *Oxz* plane with a parameter in the form of an angle *u*, which is counted from the *x*-axis counterclockwise, has the form:

$$x = \frac{D}{2}\cos(u),\ y = 0,\ z = -\frac{D}{2}\sin(u),$$
$$u \in [0^0, 180^0]. \tag{5}$$

Based on Figure 1, after turning the arc (5) and the *Oxyz* coordinate system to the angle of attack α around the *z*-axis, it will receive an image (Figure 3), where the dashed line shows the new position of this arc. Its analytical definition in the new coordinate system has not changed.

Next, let's rotate this arc by an angle β around the *x*-axis in the current coordinate system (Figure 4) using transformation matrices defined in homogeneous coordinates.

Then, the following can be considered:

$$[x\ \ y\ \ z\ \ 1] \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\beta & \sin\beta & 0 \\ 0 & -\sin\beta & \cos\beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} =$$
$$= [x\ \ y\cos\beta - z\sin\beta\ \ y\sin\beta + z\cos\beta\ \ 1]. \tag{6}$$

Based on expressions (5) and (6) of the equation of the arc of the circle under consideration in the current coordinate system

$$x = \frac{D}{2}\cos(u),\ y = \frac{D}{2}\sin(u)\sin\beta,$$
$$z = -\frac{D}{2}\sin(u)\cos\beta,\ u \in [0^0, 180^0]. \tag{7}$$

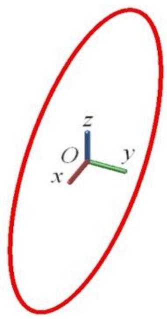
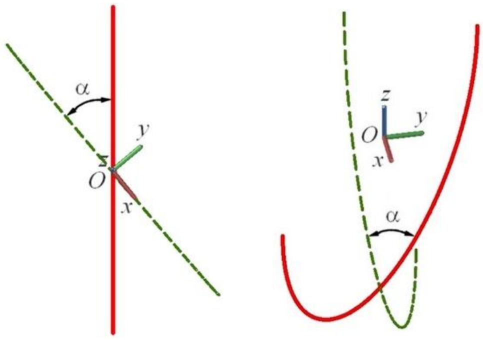


Figure 2 – The outer circle of a disc with diameter *D* centered at the origin of the *Oxyz* coordinate system



a b

Figure 3 – Rotation of the lower arc of the disc and the *Oxyz* coordinate system by the angle α: a – top view; b – axonometric view

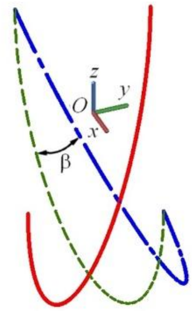


Figure 4 – Rotation of disc arc by an angle β

Formulas for the transformation of the *Oxyz* coordinate system when rotated by an angle α around the *z*-axis into the system *Ox'y'z'* are:

$$x' = x\cos\alpha + y\sin\alpha,\ y' = -x\sin\alpha + y\cos\alpha,\ z' = z. \quad (8)$$

Based on the existing ratios (7) and (8) with the use of the value $-\alpha$, it can be obtained the equation of the circle arc being worked on in the initial coordinate system *Oxyz* (Figure 2)

$$x = \frac{D}{2}(\cos(u)\cos\alpha - \sin(u)\sin\beta\sin\alpha),$$
$$y = \frac{D}{2}(\cos(u)\sin\alpha + \sin(u)\sin\beta\cos\alpha),$$
$$z = -\frac{D}{2}\sin(u)\cos\beta,\quad u \in [0^0, 180^0]. \quad (9)$$

To ensure compliance with Figure 1, the Oxy plane will be placed at the level of the bottom of the furrow. Then, the coordinates (9) will be written as follows:

$$x = \frac{D}{2}(\cos(u)\cos\alpha - \sin(u)\sin\beta\sin\alpha),$$
$$y = \frac{D}{2}(\cos(u)\sin\alpha + \sin(u)\sin\beta\cos\alpha),$$
$$z = -\frac{D}{2}\sin(u)\cos\beta + \frac{D}{2}\cos\beta =$$
$$= \frac{D}{2}\cos\beta(1 - \sin(u)),\ u \in [0^0, 180^0]. \quad (10)$$

The disc retains its performance when immersed in the soil no more than 2/3 of the radius *R* (Figure 5), i.e., the maximum depth of the furrow is equal to

$$a = \frac{2}{3}\cdot\frac{D}{2}\cdot\cos\beta. = \frac{D}{3}\cdot\cos\beta. \quad (11)$$

From the given image, the following can be written:

$$R\cdot\sin u_{\min} = \frac{R}{3}. \quad (12)$$

$$u_{\min} = \arcsin(\frac{1}{3})\cdot 180/\pi^0 \approx 19{,}5^0. \quad (13)$$

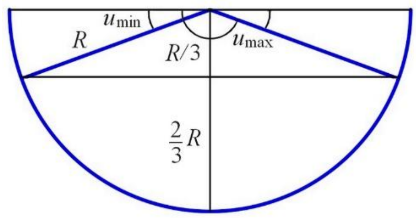


Figure 5 – Restrictions on changing the parameter *u*

Based on the dependencies (11)–(13), it can be specified the coordinates (10) of the furrow profile:

$$y = \frac{D}{2}(\cos(u)\sin\alpha + \sin(u)\sin\beta\cos\alpha),$$
$$z = \frac{D}{2}\cos\beta(1 - \sin(u)),$$
$$u \in [u_{\min}, 180^0 - u_{\min}], u_{\min} = 19{,}5^0. \quad (14)$$

Thus, formulas (14) determine the profile of the disc furrow in the plane perpendicular to the direction of movement of this agricultural tool, depending on the diameter *D* of the disc, its angles of attack α and deviation β from the vertical, as well as the maximum possible depth of cultivation.

Some specific examples of the practical application of the propozed mathematical apparatus are analyzed below.

4.2 Examples of practical use

Figures 6–7 show several profiles constructed according to expressions (14) for a disc with a diameter of *D* = 700 mm.

The first case concerns different angles of attack α for vertical deflection $\beta = 0°$.

In the second case, the angles of attack α = (30°, 40°, 50°) and deflection β = (0°, 15°, 30°) vary.

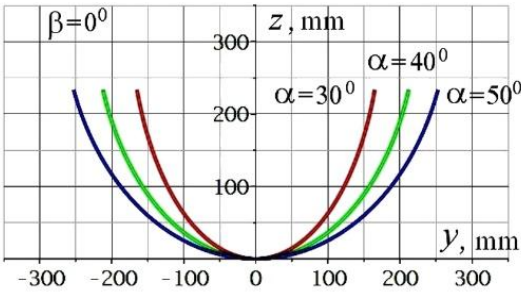
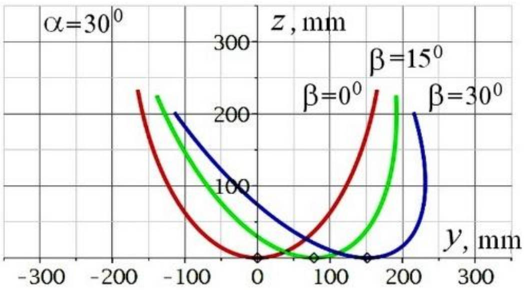
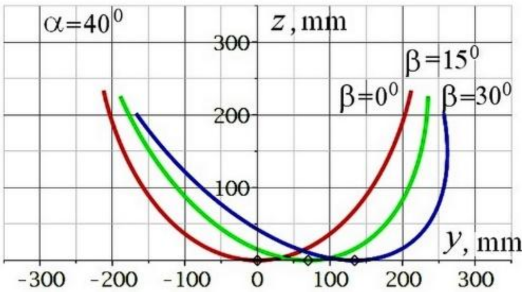


Figure 6 – Furrow profiles at α=(30°, 40°, 50°), β=(0°)



a



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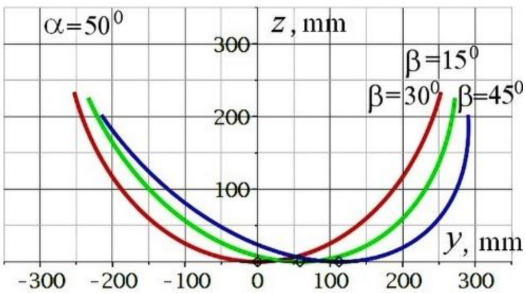

c

Figure 7 – Furrow profiles: a – $\alpha = 30^0, \beta = (0^0, 15^0, 30^0)$; b – $\alpha = 40^0, \beta = (0^0, 15^0, 30^0)$; c – $\alpha = 50^0, \beta = (0^0, 15^0, 30^0)$

Based on the second formula (14), for a certain calculated height c of the ridges, the u_{min} parameter is determined by the expression:

$$u_{min} = \arcsin(1 - \frac{2c}{D\cos\beta}) \cdot 180/\pi^0. \quad (15)$$

Based on the relation (15) for the data in Figure 6 and c = 50 mm, it can be obtained:

$$u_{min} = \arcsin(1 - \frac{2 \cdot 50 \text{ mm}}{700 \text{ mm} \cdot \cos 0^0}) \cdot 180/\pi^0 \approx 59^0. \quad (16)$$

After using formulas (14) and (16), appropriate furrow profiles can be built (Figure 8).

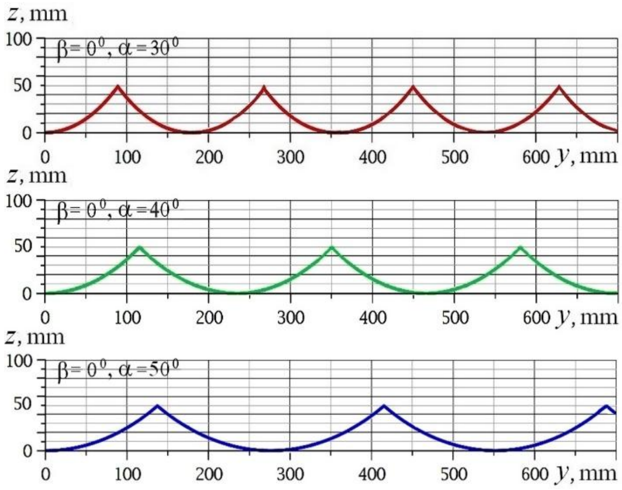

Figure 8 – Profiles of the furrow of the disc with a diameter of D = 700 mm at a processing depth of c = 50 mm

The distance between the tops of the ridges is equal to

$$b_c = y_{max} - y_{min}, \quad (17)$$

where

$$y_{max}(u_{min}) = \frac{D}{2}(\cos(u_{min})\sin\alpha + \sin(u_{min})\sin\beta\cos\alpha),$$

$$y_{max}(u_{min}) = \frac{D}{2}(\cos(u_{min})\sin\alpha + \sin(u_{min})\sin\beta\cos\alpha),$$

$$u_{max} = 180^0 - u_{min}, \; u_{min} = 59^0.$$

The quantity (17) can also be calculated in another way. Particularly, from Figure 9, for a disc with a diameter D and a height c of the ridges, it can be obtained:

$$(D_c/2)^2 = R^2 - (R-c)^2, \; R = D/2,$$

whence the value of the chord that corresponds to c,

$$D_c = 2\sqrt{c(D-c)}. \quad (18)$$

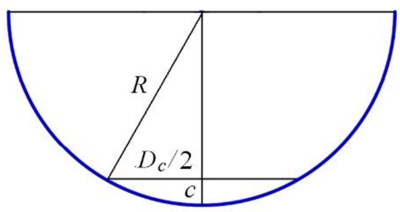

Figure 9 – To the definition of the chord D_c

In the case under analysis,

$$D_c = 2\sqrt{c(D-c)} \cdot = \; 360.56 \text{ (mm)}. \quad (19)$$

Based on expressions (2) and (18),

$$b_c = D_c \cdot \sin\alpha = 2\sqrt{c(D-c)} \cdot \sin\alpha. \quad (20)$$

According to the data in Figure 8, using formulas (17), (19), and (20), it can be obtained for:

1) $\alpha = 30^0$: $b_c = 180.3$ mm;
2) $\alpha = 40^0$: $b_c = 231.8$ mm;
3) $\alpha = 50^0$: $b_c = 276.2$ mm.

The above control calculations confirm the correctness of the proposed mathematical model (14).

Figure 10 shows the furrow profiles built according to the method discussed above using the values $D = 700$ mm, $c = 50$ mm, $\beta = (15°, 30°)$, and $\alpha = (30°, 40°, 50°)$.

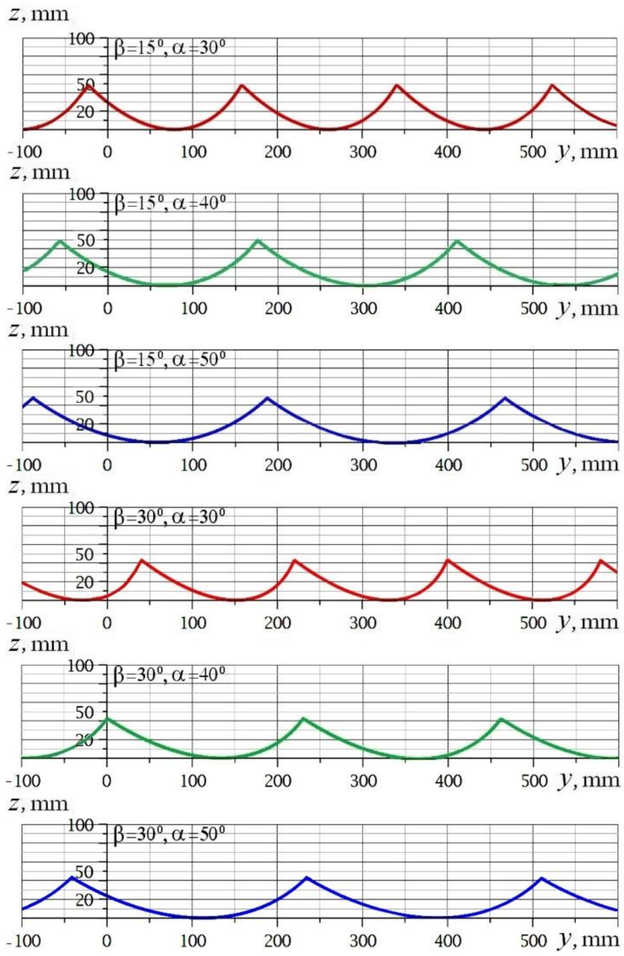

Figure 10 – Profiles of disc furrow in diameter $D = 700$ mm

Using the dependence of the height c_β of the crest, which corresponds to the angle β and a slightly smaller height c at zero value of the latter,

$$c_\beta = z(u_{\min}) = \frac{D}{2}\cos\beta(1-\sin(u_{\min})) =$$

$$= z(u_{\max}) = \frac{D}{2}\cos\beta(1-\sin(u_{\max})) = c\cdot\cos\beta \quad (21)$$

and formulas (17) it can be obtained:

1) $\beta = 15^0$: $c_\beta = 48.3$ mm:
   a) $\alpha = 30^0$: $b_c = 180.3$ mm;
   b) $\alpha = 40^0$: $b_c = 231.8$ mm;
   c) $\alpha = 50^0$: $b_c = 276.2$ mm;
2) $\beta=30^0$: $c_\beta = 43.3$ mm:
   a) $\alpha = 30^0$: $b_c = 180.3$ mm;
   b) $\alpha = 40^0$: $b_c = 231.8$ mm;
   c) $\alpha = 50^0$: $b_c = 276.2$ mm.

The specified information, together with the appropriate values of b_c, calculated above for the angle $\beta = 0°$ through $\sin(\alpha)$, also testify to the correctness of the proposed expressions (14), (15), (17), and (21) for determining the profile of the groove of the disc working bodies.

In the considered model, the values D_c and u_{min} are invariants concerning the application of the angles α, β.

The analysis of the images in Figures 8, 10 show that at zero β, the furrow profile has a vertical axis of symmetry. Otherwise, the latter becomes gentler in the direction of the disc tilt and somewhat steeper in the opposite direction.

The positions of the points with zero height, that is, the bases of the inclined axes, are illustrated by the appropriate designations in Figure 7. Increasing the angle of attack α increases the width of the disc. The maximum height of the ridges decreases with increasing β.

For discs of other diameters, values of angles of attack, and deviations from the vertical, modeling of furrow profiles is carried out according to the general method of forming described above.

5 Discussion

Agriculture is an important activity for the whole world and the state of Ukraine in these difficult war times, which guarantees the food security of humankind [24]. Therefore, its improvement is a significant actual problem. One of the ways to successfully solve this issue is to improve further technical tools, particularly tillage discs [25]. The latter is quite effective in progressive current trends concerning minimal land cultivation. Compared to plows, discs significantly reduce fuel consumption, help preserve moisture in the soil, and reduce soil erosion.

Modern computer information technologies in integrated CAD/CAM/CAE/PLM systems implement high-quality virtual reproduction of many processes of the entire life cycle of various industrial products: their design, manufacture, and operation [26]. However, in addition to technical and software, they require appropriate mathematical, methodical, and other types of support. This article is devoted to the last two mentioned regarding developing structural and functional parameters and characteristics of agricultural discs [27].

The analysis of literary sources on the selected topic showed the expediency of these scientific investigations [28]. The obtained results in the form of the proposed mathematical apparatus and the methodology of its use, together with the given illustrative examples, confirmed the achievement of the set goal [29]. According to the authors, this will improve computer software for the automated development of agricultural machinery [30].

The publication [31], made with the participation of the authors of this article, is devoted to computer modeling of plows. The above-described approach to the analytical definition of disc furrow profiles can be extended to a refined cross-section of the soil ridge depending on the shape, size, and position.

One of the fundamental principles of creating and functioning modern computer-aided design systems (CAD/CAM/CAE/PLM) is the principle of openness and development. Therefore, relevant systems (e.g., Autodesk Inventor, SolidWorks, and Catia) have appropriate application programming interface (API) tools, i.e., application programming interface. Also, Visual Basic for Applications (VBA) is a specific case for the above systems. Thus, having the appropriate mathematical apparatus, in our case for the profile of a disc furrow, it is possible to build a 3D model of such a tool, the appropriate soil using any of the specified CAD tools, and then use VBA to reproduce the dynamic process of soil cultivation using Boolean operations.

6 Conclusions

The publication provides a proposed mathematical apparatus for analytically determining the profile of the disc furrow, considering the modern features of the construction of the specified agricultural tools. This refers to the arrangement of discs on individual risers with the possibility of adjusting their angles of attack and deviations from the vertical. This facilitates adaptation to the existing field agrotechnical operating conditions, improving the relevant indicators. Prospects for further scientific research on the outlined subject may be clarification of the obtained results by adjusting them depending on the existing specific use circumstances. This applies to the soil type, physical and chemical conditions, and cultivation speed. It is appropriate to conduct the necessary field experiments, their systematization, evaluation of deviations from theoretical profiles, and development of the necessary recommendations for direct practical application.

The above aspects are elements of currently popular computer models that dynamically reflect various processes. This contributes to the proper study of the latter. These facts are relevant to agricultural production. Thus, the approach presented in this article regarding the geometric modeling of disc furrow profiles is relevant in the current conditions in theoretical and practical terms and has good prospects for further development.

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