Influence of Design and Technological Parameters of Disk Working Bodies on the Height of the Crest of the Bottom of the Furrow

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Abstract. Disks are one of the most common tillage working bodies used both on independent machines and tools, and as part of combined aggregates. Compliance with agrotechnical requirements is a necessary condition for improving the technological efficiency of the disk working bodies. The height of the furrow bottom ridge depends on a number of design and technological parameters of adjacent disks, as well as the distance between them. In the article, analytical expressions are obtained that allow us to describe the relationship between the height of furrow bottom ridge formed between the projections of cutting edges of adjacent disks, structural and technological parameters, and a given orientation scheme.

1 Relevance of research

In the process of crop production, a large number of various technological operations are performed, which are aimed at obtaining the maximum yield with minimal material costs, labor and energy costs. Of all the technological processes that make up any cultivation technology, it is possible to distinguish the process of tillage as one of the most complex and unstable [1-5]. The complexity and instability of tillage is characterized by a large number of structural, technological and agrotechnical features, the ratio of which varies depending on the specific technological operation and working conditions [6-10]. For example, the main tillage with and without soil formation turnover is carried out by machines of various designs. On the other hand, fallow and pre-sowing cultivation is carried out by machines of the same group – cultivators, but for each type of cultivation, designs of cultivators have their own technological and design features. And, finally, if the soil clearing is carried out after harvesting winter crops, it has a completely different agrotechnical purpose and requirements than compared to the clearing, which is carried out after harvesting long-stemmed row crops. In recent years, soil scientists, agronomists and economists have begun to jointly look for a solution to the problem of determining the limits of profitability of crop production, taking into account the soil degradation, the

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formation of optimal growing conditions for a plant and costs of their implementation [11-15].

2 Problem statement

Of all the types of working bodies for tillage, disk ones are among the most common and popular, which are used both as independent machines and in the technological schemes of most combined units [16, 17]. Often, when working with disk units, it is necessary to make multiple passes to give the soil the specified agrotechnical parameters, which not only significantly increases the cost of production, but also contributes to the development of soil erosion processes. Therefore, reducing the required number of passes of the disk unit across the field is one of the most relevant issues.

After soil processing with disk working bodies, a number of agrotechnical requirements are imposed on it. The ridges of the furrow bottom, as one of the indicators of the number of agrotechnical requirements, on the one hand depends on the design and technological parameters of the disk working bodies, and on the other hand, on the scheme of their placement on the frame [18-22]. And if, for example, it is currently impossible to predict the soil crumbling with high accuracy, then the height of the ridge can be determined quite accurately, and its value has recently become an adjustment parameter. Thus, the analytical determination of the relationship between the height of the furrow bottom ridge and the design and technological parameters of the disk working bodies will allow us to set separate ranges of adjustment parameters at the design stage of the disk harrows.

3 Presentation of main research material

Disk harrows are most often performed with a row-by-row individual arrangement of working bodies. In this case, the mutual arrangement of adjacent disks is performed in three variants (Fig. 1): the orientation of the disks in one direction, the orientation in the "dump" and "collapse", which are characterized by the size of the radii of the disks, the angles of attack and the inclination of the disks to the vertical. Based on the design parameters, technological reliability and efficiency of disk units, the interaction of neighboring working bodies will be especially strongly reflected in the height of the ridge of the furrow bottom [17].

Fig. 1. Diagram of the relative position of the projections of adjacent disks

To study the influence of the design and technological parameters of disk working bodies on the ridges of the furrow bottom during their operation, it is necessary to obtain their relationship theoretically. To do this, we will use the coordinate system shown in
Figure 2, in which the plane formed by the blade of the disk and representing a circle of radius $R$ centered at its intersection with the ray $AC$ lies in the I$^\text{st}$ octant. Then the radius $AF_1$ of this circle will touch the $XOZ$ plane and form an angle $\alpha$ with it, equal to the angle of attack of the disk. At the same time, the radius $AF_4$ will form an angle $\beta$ with the same plane, which is equal to the angle of inclination of the disk to the vertical.

**Fig. 2.** Scheme for determining the ridges of the furrow bottom

In the specified coordinate system, the coordinates of the arbitrary point $F$ of the cutting edge will be described by the system of expressions:

$$
\begin{align*}
    x &= V_n t + R \sin \alpha \sin \beta \sin \omega t + R \cos \alpha \cos \omega t; \\
    y &= R \sin \alpha + R \cos \alpha \sin \beta \sin \omega t - R \sin \alpha \cos \omega t; \\
    z &= R \cos \beta - R \cos \beta \sin \omega t;
\end{align*}
$$

where $x$, $y$, $z$ – coordinates of the arbitrary point of the cutting edge of the disk working body;

$V_n$ – forward speed of the disk working body;

$\alpha$ – angle of attack of the disk working body;

$\beta$ – angle of inclination of the axis of rotation of the disk working body to the horizon;

$\omega$ – angular speed of rotation of the disk working body;

$\omega t$ – angle of rotation of the disk working body.

Despite the fact that at any orientation of the single disk with specified operating and design parameters, the projection value of its cutting edge will not change, then when considering adjacent working bodies, it is their interaction that will directly affect the height of the furrow bottom ridge and the performance indicators of the entire unit as a whole. In the selected coordinate system (Fig. 2), the projection of the cutting edges of adjacent disks on the $YOZ$ plane will be described by the expression systems:

$$
\begin{align*}
    y_1 &= R_1 \sin \alpha_1 + R_1 \cos \alpha_1 \sin \beta_1 \sin \omega_1 t - R_1 \sin \alpha_1 \cos \omega_1 t, \\
    z_1 &= R_1 \cos \beta_1 (1 - \sin \omega_1 t), \\
    y_2 &= R_2 \sin \alpha_2 + R_2 \cos \alpha_2 \sin \beta_2 \sin \omega_2 t - R_2 \sin \alpha_2 \cos \omega_2 t + b, \\
    z_2 &= R_2 \cos \beta_2 (1 - \sin \omega_2 t),
\end{align*}
$$
where \( b \) – distance between adjacent disk working bodies along the axis \( OY \), m;
\( R_1 \) and \( R_2 \) – radii of disk working bodies, m;
\( \alpha_1 \) and \( \alpha_2 \) – angles of attack of disk working bodies, degree;
\( \beta_1 \) and \( \beta_2 \) – angles of setting of disk working bodies to the vertical, degree;
\( \omega_1 \) and \( \omega_2 \) – angular speeds of cutting ridges of disk working bodies, \( \text{s}^{-1} \);
\( y_1, z_1, y_2 \) and \( z_2 \) – coordinates of projections of cutting ridges of two disk working units located on the distance \( b \).

The obtained systems of expressions (2) and (3) describe the relative position of the projections of cutting edges of two arbitrary disk working bodies, in particular in the case of \( R_1 \neq R_2, \alpha_1 \neq \alpha_2, \beta_1 \neq \beta_2, \omega_1 \neq \omega_2 \).

We find from the second expressions of systems (2) and (3) the rotation angles \( \omega_1 t \) and \( \omega_2 t \):

\[
\omega_1 t = \arcsin(1 - \frac{z_1}{R_1 \cos \beta_1}),
\]

\[
\omega_2 t = \arcsin(1 - \frac{z_2}{R_2 \cos \beta_2}),
\]

After substituting and converting the obtained expressions (4) and (5) into corresponding expressions of the systems (2) and (3), we obtain:

\[
y_1 = R_1 \sin \alpha_1 + R_1 \cos \alpha_1 \sin \beta_1 - z_1 \tan \beta_1 \cos \alpha \pm R_1 \sin \alpha_1 \cos(\arcsin(1 - \frac{z_1}{R_1 \cos \beta_1})),
\]

\[
y_2 = R_2 \sin \alpha_2 + R_2 \cos \alpha_2 \sin \beta_2 - z_2 \tan \beta_2 \cos \alpha \pm R_2 \sin \alpha_2 \cos(\arcsin(1 - \frac{z_2}{R_2 \cos \beta_2})) + b,
\]

The resulting expressions (6) and (7) will describe the projections of the cutting edges of the adjacent disks on the \( YOZ \) plane, which are ellipses located at a distance \( b \) from each other. Since the rotation angles \( \omega_1 t \) and \( \omega_2 t \) were replaced by the corresponding projections during the transformations, the last terms of equations (6) and (7) are taken with the sign "-" when considering the right parts of the corresponding ellipses and with the sign "+" when considering their left parts.

The interaction of the projections of the cutting edges of adjacent disks can be carried out in four ways: the absence of their intersections, touching at one point, crossing at two points, and their intersection at a set of points, up to their coincidence. From the point of the operation of disk units’ view, not crossing the projections of the cutting edges of adjacent disks or touching them at one point leads to the formation of errors in the work, which will not meet the agrotechnical requirements. On the other hand, the presence of many points of their intersection, or their coincidence, indicates an excessive overlap of adjacent passages, which, provided that the course stability is maintained, leads to a significant increase in energy intensity of the process. Therefore, for applied problems, the case when the projections of the cutting edges of neighboring disks will have two points of intersection will be of primary interest.

To determine the intersection points of the ellipses described by expressions (6) and (7), it is necessary to equate them and solve them with respect to the common coordinate \( z \), i.e., the common point located from the bottom of the furrow at a distance \( z \). When determining the common point \( z \), it is necessary to use the left part for the \( y_1 \) coordinate of the first ellipse, and the right part for the coordinate \( y_2 \) of the second ellipse, i.e. the last term of the expression (6) is taken with the "+" sign, and for the expression (7) with the "-" sign. As a result, we will have:
\[ R \sin \alpha_1 \sqrt{\frac{2 z R \cos \beta - z^2}{R_1^2 \cos^2 \beta}} + R_2 \sin \alpha_2 \sqrt{\frac{2 z R \cos \beta - z^2}{R_2^2 \cos^2 \beta}} + z C_2 + A_2 - B_2 = h, \]  

(8)

where \( A_2 = R (\sin \alpha_1 + \cos \alpha_1 \sin \beta_1) \), \( B_2 = R (\sin \alpha_2 + \cos \alpha_2 \sin \beta_2) \),  
\( C_2 = \tan \beta_2 \cos \alpha_2 - \tan \beta_1 \cos \alpha_1 \).

Expression (8) allows us to determine the height of the intersection points of adjacent disks above the bottom of the furrow at their different parameters and the distance between them. In other words, by setting the initial parameters according to expression (8), it is possible to analytically determine the height of ridges of the furrow bottom, or by setting the agrotechnical tolerance for it, to calculate the necessary distance between adjacent disks with different schemes of their placement to comply with it [1].

Since the serial designs of disk units most often use working bodies with the same parameters, i.e. \( R_1 = R_2 = R \), \( \alpha_1 = \alpha_2 = \alpha \), \( |\beta_1| = |\beta_2| = |\beta| \), then we will perform further calculations for such a case. However, this does not limit the possibility of using expression (8) to determine the height of the ridge of the furrow bottom with other combinations of structural and technological parameters of adjacent disk working bodies.

In the case of placing adjacent disk working bodies on the unit’s frame in the same direction, it is necessary to substitute \( R_1 = R_2 \), \( \alpha_1 = \alpha_2 \), \( |\beta_1| = |\beta_2| = |\beta| \) in the resulting equation (8). Then, the height of the ridge of the furrow bottom will be determined by the expression:

\[ z_{1,2}^o = (R \pm \sqrt{R^2 - \frac{b^2}{4 \sin^2 \alpha}}) \cos \beta, \]  

(9)

where \( z_{1,2}^o \) – coordinates of intersection points of adjacent ellipses along the axis of OZ, if they are of the same orientation.

When the adjacent disks are oriented on the unit according to the "collapse" option (Fig. 1), the following parameters must be used in the resulting equation (8): \( R_1 = R_2 \), \( \alpha_1 = \alpha_2 \), \( |\beta_1| = |\beta_2| = |\beta| \). Then, the height of the ridge of the furrow bottom will be determined by the expression:

\[ z_{1,2}^p = \frac{A_3 + \cos \alpha \cos \beta \sin \beta (2 R \cos \alpha \sin \beta + b) \pm B_3}{C_3}, \]  

(10)

where \( z_{1,2}^p \) – coordinates of intersection points of adjacent ellipses along the OZ axis when they are oriented in the "collapse".

\( A_3 = 2 R \sin^2 \alpha \cos \beta \)  
\( B_3 = \sin \alpha \cos \beta \sqrt{4 R^2 \cos^2 \alpha (\cos^2 \beta + 2 \sin^2 \beta) + 4 R^2 (1 - 2 \cos^2 \alpha) - b^2} \)  
\( C_3 = 2 \cos^2 \alpha \sin^2 \beta + 2 \sin^2 \alpha \)

To determine the height of the ridge of the furrow bottom when the adjacent disks are oriented on the unit’s frame according to the scheme "dump" (Fig. 1), the following parameters must be used in equation (8): \( R_1 = R_2 \), \( \alpha_1 = \alpha_2 \), \( \beta_1 = |\beta_2| \). After transformations, we obtain:

\[ z_{1,2}^c = \frac{A_3 + \cos \alpha \cos \beta \sin \beta (2 R \cos \alpha \sin \beta - b) \pm B_3}{C_3}, \]  

(11)

where \( z_{1,2}^c \) – coordinates of intersection points of adjacent ellipses along the OZ axis when they are oriented in the "dump".
Since the height of the ridge of the furrow bottom formed between the projections of two adjacent disk working bodies will be determined only by the lower point of intersection, then in the expressions (9, 10 and 11) it is necessary to use terms with the sign “−”. The correctness of obtained positions is confirmed by the fact that equation (9) is similar to the previously obtained expression of Professor Kanarev F. M. for a disk plow. Graphs of the dependence of the height of the furrow bottom ridge on the design and technological parameters and the orientation scheme of adjacent disk working bodies are shown in Figures 3, 4 and 5.

**Fig. 3.** Graphs of the dependence of the ridges of the furrow bottom on parameters of adjacent disk working bodies with their identical orientation and $R = 0.28 \text{ m}$, $b = 0.1 \text{ m}$, $\alpha = 20^\circ$, $|\beta| = 10^\circ$

**Fig. 4.** Graphs of the dependence of the furrow bottom ridges on parameters of adjacent disk elements when they are oriented "in collapse" and $R = 0.28 \text{ m}$, $b = 0.1 \text{ m}$, $\alpha = 20^\circ$, $|\beta| = 10^\circ
After analyzing the resulting graphical dependencies of expressions (8, 9, and 10), we can formulate the following conclusions. The influence of the design and technological parameters of the adjacent disk working elements on the amount of ridges between them is curved. The minimum is affected by the variation in the angle of inclination of the disks to the vertical, and the maximum is the distance between them. An increase in the distance between adjacent disk working units leads to a significant increase in the height of the ridge of the furrow bottom in any orientation, and only for the case of orientation according to the scheme "in dump" to the value $b = 90$ mm, its decrease occurs, and then there is also a sharp increase. An increase in the distance between adjacent disk working bodies leads to a significant increase in the height of the ridge of the furrow bottom in any orientation, and only for the case of orientation according to the scheme "in dump" to the value $b = 90$ mm, its decrease occurs, and then there is also a sharp increase. At the same time, the distance between the adjacent disk working bodies, at which the height of the ridge of the furrow bottom will correspond to agricultural requirements, will be different for different orientation schemes. Exceeding the height of the ridge of the furrow bottom by a value equal to 60 mm for the orientation of adjacent disks in one direction occurs at a distance between them of 90 mm, for the orientation according to "in collapse" scheme already at 50 mm, and for the orientation according to the "in collapse" scheme only at 180 mm.

An increase in the radii of adjacent disks when they are oriented in the same direction leads to a decrease in the height of the ridge of the furrow bottom, and for the cases "in collapse" and "in dump" first decreases, and then increases slightly.

The decrease in the height of the ridge of the furrow bottom in any orientation is caused by an increase in the angle of attack. Increasing the angle of inclination of adjacent disks to the vertical, for orientation in one direction, leads to its decrease. For the case of "in collapse", the height of the ridge of the furrow bottom first increases, and then begins to decrease, and the opposite phenomenon occurs when the orientation according to the scheme "in dump".

4 Conclusion

The resulting expression 8 allows us to determine the height of the ridge of the furrow bottom formed between adjacent disk working elements that have different design and
technological parameters and a given distance between them. When designing technological arrangement schemes for the most common case of the arrangement of working units on the unit’s frame, when $R_1 = R_2$, $a_1 = a_2$, $\beta_1 = \beta_2$, using expressions 9, 10 and 11, it is possible to determine the distance between adjacent disks, at which the agrotechnical tolerance for it will be observed.

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