Analytical study of the design parameters of the grinding unit of disk harrows

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Abstract. The article describes the need for multiple passes with disc harrows to increase the degree of grinding of crop residues when preparing the soil for sowing winter cereal crops after row crops. The effectiveness of using additional grinding units for disk harrows is indicated in order to increase the technological efficiency and reliability of the soil preparation process. The analytical dependences are proposed for determining the radius of the grinding unit and the number of bars depending on the structural and technological parameters of the process, biometric parameters of the cut stems and soil hardness, subject to the established cutting value. As an example, a calculation based on the initial data from the reference literature is presented. Based on the obtained dependencies, graphs were constructed, and their analysis was carried out in order to determine ways to increase the efficiency of using the grinding unit. To increase the efficiency of the grinding unit, additional ballast weights and the manufacture of bar fasteners at different distances from the axis of rotation are proposed as technological adjustments.

1. Introduction
Crop production in the Russian Federation is distinguished by the diversity of both cultivated crops and the technologies used for this. Such diversity is explained, first of all, by a huge territory with various zones of agriculture and the corresponding soil and climatic conditions. Despite this, the vast number of cultivation technologies include operations to prepare the soil for sowing. Among all crops, the most common is winter cereals. The main predecessors of winter cereals are the row crops. According to the recommendations of leading agricultural scientists, after harvesting row-crop predecessors to prepare the soil for sowing, two-track disking is carried out. The main reason for this operation is explained by the need for high-quality grinding of crop residues [1].

2. Formulation of the problem
In order to increase the technological efficiency and reliability of the soil preparation process with disk implements, the leading manufacturers of agricultural machinery produce various grinding units, bars and harrows. [2, 3] Such grinding units include the Väderstad grinding unit (Figure 1), which is intended for intensive grinding of crop residues, tillage to a depth of 3 cm, as well as provoking seed germination.
For the most efficient operation of grinding units, it is necessary at the design stage to determine the main structural and technological parameters and their adjustments, which will be the basis for creating the entire machine [4-6]. These parameters include the radius of the grinding unit, the number of bars and the speed of their movement [7].

3. Presentation of the main research material

The main difficulty in grinding the stems of row crops, for example, corn, is that they are directly on the soil. In the process of cutting the stem with the bar of the grinding unit, it undergoes bending, as a result of which the supporting reactions of the stem and soil arise.

The main condition for cutting the stem is the amount of cutting force $F_y$, which should be the sum of all resistance forces $P$. Otherwise, instead of cutting the stem, it will be crumpled. Since when cutting the stem with a chopping unit, it does not have a rigid anti-cutting part, then acting with this force will be characterized by a dynamic effect, as a result of which inertia forces will arise. In this case, the condition of cutting the stem will be determined by the expression [8]:

$$F_y < P_{\text{bend}} + P_{\text{inertia}} + P_{\text{the soil}}$$

where $F_y$ – stem cutting force, N;
$P_{\text{bend}}$ – bending resistance of the stem, N;
$P_{\text{inertia}}$ – stem inertia force, N;
$P_{\text{the soil}}$ – soil resistance force, N.

At the initial moment of cutting, when the cutting edge of the bar is inserted into the stem, it will first bend and only then will it be destroyed. In this case, the stem should be considered from the point of view of the elastic rod (Figure 2).

According to the theory of deflection of elastic rods, bending resistance will be determined by the expression [9]:

$$P_{\text{bend}} = \frac{3 \ell E J}{b^2 a^2}$$

where $f$ – deflection value, m;
$l$ - the length of the stem being cut, m;
$E$ – elastic modulus of the stem, Pa;
J – moment of inertia of the stem, m$^4$;
a and b – lengths of sections for which the stem is being cut, m.

The speed of the bar of the grinding unit and the time of its interaction with the stem will be functionally dependent on the magnitude of the deflection of the stem. This dependence has the form:

$$ f = V_y \Delta t, $$

where $V_y$ – linear speed of the bar of the grinding unit, m / s;
$\Delta t$ – time of interaction between the bar and the stalk, s.

Since the stems of most row crops predecessors (corn, sunflower) in the cross section perpendicular to the centerline are circles, the interaction time of the bar will be:

$$ \Delta t = \frac{d_{stem}}{V_y}, $$

where $d_{stem}$ – stem diameter, m.

In the process of operation, the bar together with the grinding unit will make a movement around its axis of rotation, then the magnitude of the deflection of the stem can be written in the form:

$$ f = \frac{\pi \alpha R_y}{180^\circ} = \alpha R_y, $$

where $\alpha$ – the angle passed by the bar when cutting, rad; $R_y$ – grinding unit radius, m.

Then, the bending resistance of the stem can be represented as:

$$ P_{bend} = \frac{3\alpha R_y J E J}{b^3 a^2}, $$

The inertia force arising in the process of deflection of the stem by the bar tends to restore the position of the stem to its original position. In this case, the inertia of the stem is determined by the expression:

$$ P_{inertia} = m_{stem} a_y, $$

where $m_{stem}$ – stem mass, reduced to the point of interaction, kg; $a_y$ – stem acceleration, m/s$^2$.

Since the initial speed of the stem is zero, expression 7 can be written as:

$$ P_{inertia} = m_{stem} V_y \Delta t, $$

From where:

$$ P_{inertia} = m_{stem} \frac{\omega_y^2 R_y}{\alpha}, $$

where $\omega_y$ – angular speed of the bar, rad/s.

The resistance of the soil to pushing the stem into it with the bar of the grinding unit depends on the hardness of the soil and the area of their contact and will be determined by the expression:

$$ P_{soil} = T_{soil} S_{stem}, $$

where $T_{soil}$ – soil hardness, Pa;
$S_{stem}$ – contact area of the stem with the soil during cutting, m$^2$.

The morphological structure of the stem of sunflower or corn is a cone (Figure 3). The area of contact between the stem and the soil varies widely and depends on the hardness of the soil and the stem. In order to obtain a workable design with wide functional capabilities, it is necessary to use the maximum
possible resistance when designing. The maximum contact area of the stem with the soil will be limited by its line of symmetry. In this case, the contact area of the stem with the soil will be:

\[ S_{\text{stem}} = \frac{1}{2} \pi (r_1 + r_2) \sqrt{l^2 + (r_1 + r_2)^2}, \]  

(11)

where \( r_1 \) and \( r_2 \) – accordingly, the radius of the base and top of the stem being cut, m

\( l \)– length of the stem being cut, m.

Figure 3. To determine the area of contact of the stem with the soil.

To determine the soil resistance, let us substitute expressions 10 into expression 9, then after the transformations we get:

\[ P_{\text{soil}} = \frac{1}{2} \pi T_{\text{soil}} (r_1 + r_2) \sqrt{l^2 + (r_1 + r_2)^2}, \]  

(12)

Finally, the condition for cutting the stem will be:

\[ F_y < \frac{3\alpha R_y E J}{b^2 a^2} + \frac{m_{\text{soil}} \omega^2 R_y}{\alpha} + \frac{1}{2} \pi T_{\text{soil}} (r_1 + r_2) \sqrt{l^2 + (r_1 + r_2)^2}, \]  

(13)

The left side of expression 13 will be determined by the mass of the grinding unit, and its acceleration, which can be written as:

\[ F_y = m_y \omega^2 R_y, \]  

(14)

where \( m_y \) – mass of grinding unit, kg.

After substituting the expression 14 into 13 and carrying out the transformations, we obtain the function of the size of the radius of the grinding unit from the structural and technological parameters of the process, biometric parameters of the stems and soil hardness, subject to the conditions for the required cutting value, which will have the form:

\[ R_y = \frac{1}{2} \frac{T_{\text{soil}}}{m_y \omega^2 ab^2} - 3\alpha^2 E J - \frac{m_{\text{soil}} \omega^2 b^2 a^2}{\alpha}. \]  

(15)

The resulting dependence is transcendental, since the angle \( \alpha \) depends on the radius of the grinding unit. However, if you set the initial parameters, then the required radius of the grinding unit can be determined. Diagram of the dependence of the radius of the grinding unit from the structural and technological parameters is presented in Figure 4.

For example, let us set the initial data:
- length of the stem being cut \( l = 0.3 \) m;
- lengths of sections for which the stem is being cut a = 0.15 m, b = 0.15 m;
- radius of the base and top of the stem being cut r₁ = 0.012 m, r₂ = 0.009 m;
- elastic modulus of the corn stem E = 2117 MPa;
- moment of inertia of the stem, J = 0.3926D³δ = 0.1628 \cdot 10^{-7} \text{ m}^4, where δ – stem wall thickness, m;
- soil hardness T_{soil} = 981000 \text{ Pa};
- chopping unit angular speed, \( \omega_y = 8\pi \text{ rad/s}. \)
- stem mass reduced to the interaction point m₁ = 0.1 kg;
- the angle passed by the knife of the grinding unit when cutting the stem, \( \alpha = \pi/36 \text{ rad}; \)

Substituting the initial data in the resulting expression to determine the radius, we obtain \( R_y = 0.219 \text{ m}. \) However, using the obtained radius value to determine the angular velocity of the bar at a given speed of movement of the unit by the expression \( V_a = V_y = \omega_y R_y, \) the resulting value will not match the one taken for the calculation. This is due to the fact that the grinding unit at work in the soil will be stalled.

Figure 4. Dependence of the size of the radius of the grinding unit on structural and technological parameters.

The resulting chart of the dependence of the radius of the grinding unit on the structural and technological parameters will have a hyperbolic dependence. After analyzing the presented charts, we can conclude that the greatest influence on the radius of the grinding unit has its mass. From the charts 1, 3 and 4, it can be seen that at the same angular speed, increasing the mass from 50 to 110 kg will reduce the radius of the cutting unit by 4 times. Figure 2 data shows that at the same angular speed, an increase in diameter by 20% will let to increase the diameter of the stem by 6 mm.
In addition, the presented charts show that to increase the centrifugal force of the grinding unit, it is necessary to increase its mass. The next adjustment parameter should be used to increase the radius of the grinding unit, for which additional holes can be made in the places where the bars are attached to the unit, which will allow for adjustment in accordance with the specified soil, climatic and technological conditions, subject to the conditions for cutting the stems.

During the operation of the grinding unit, the number of bars should ensure the cutting length within the agricultural requirements. A necessary condition for the steady progress of the process of cutting the stems with a bar and eliminating their slipping is to create a pinch angle in the cutting pair of the bar - stem - soil. Usually, the bars on the grinding units are arranged in a multiple-thread screw or parallel to its axis of rotation.

To determine the number of bars, we consider the simplest case when the stems are perpendicular to the axis of rotation of the node and the bars are parallel to it (Figure 5).

![Figure 5. Scheme for determining the number of bars of the grinding unit.](image)

In this case, the number of bars will depend on the size of the segment AB, which in turn will be influenced by the depth of the grinding unit h. Then the number of bars on the grinding unit, subject to agronomic requirements for grinding, will be determined by the expression:

\[ n = \frac{2\pi}{\arcsin \frac{AB}{R_y}} \]  \hspace{1cm} (16)

where n – number of bars, pcs;
AB – the size of the grinding of crop residues, according to agricultural requirements AB = 5-10 cm.
A graphical representation of this dependence is presented in Figure 6.
Figure 6. Chart of the number of bars on the length of grinding and the radius of the grinding unit

After analyzing the chart in Figure 6, it can be concluded that the dependence is straightforward, and when designing the grinding unit, it is necessary to take the number of knives between these lines.

4. Conclusions

Summarizing the data obtained, it can be concluded that when designing the grinding unit, it is necessary to use the range of agrotechnically acceptable speeds of the unit, the biometric parameters of the cut stems and soil hardness.

At the same time, adjusting the grinding unit under operating conditions is possible due to the installation of additional ballast weights on it, as well as the manufacture of slats with the possibility of their fastening at different distances from the axis of rotation. The presented theoretical dependencies will allow us to determine the design and adjustable parameters of the grinding unit.

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