Theoretical study of the plant residue movement along the needle of a rotating working organ

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Abstract. The article is devoted to the identification of dependences to determine the main rational constructive and technological parameters of the proposed rotating working organ.

1. Introduction
Sowing is paid special attention to in the technological system of cultivation of grain crops, in addition to such operations as preparation of seeds [1] and soil, harvesting. The future development of the crop depends mainly on the quality of this operation, which ultimately affects the quantitative and qualitative yield indexes. The technological requirements for the process of tillage and sowing on stubble backgrounds are based on several conditions:

1) high-quality seeding to a depth of 0.06–0.08 m;
2) stable operation of coulters (without soil bulldozing in the inter-coulter space) [2, 3, 4, 6];
3) reduction of tractive resistance [5].

The application perspectiveness of designing a rotating working organ for sowing machines on stubble backgrounds predetermined the need for research to substantiate the parameters of its working organs.

The analysis of works on the existing selection seeders, patent and literature sources shows that they can not perform sowing on stubble backgrounds that dominate crop rotations in the Omsk region. During the seeding process, the soil is loaded with plant residues and the inter-coulter space is clogged.

At the same time, it is possible to eliminate the clogging of the inter-coulter space with plant residues and improve the quality of work of the selection seeder on the stubble background, by installing active needle-shaped rotating hoe wheels between the coulters on the common shaft, which allow shifting plant residues back along the course of the unit's movement. This hypothesis was used as the foundation for designing a modernized selection seeder for sowing on a stubble background on the basis of the SCS-6-10 mock-up model.
In order to ensure high-quality seeding, it is necessary to use machines that meet the cutting-edge requirements. For this reason, the design and development of technologically advanced and promising sowing machines and their working organs is one of the main tasks of modern mechanical engineering.

To meet the above-mentioned requirements, it is necessary to theoretically justify the main design and technological parameters of the proposed working organ.

2. Model
The scheme of the proposed model of the coulter group of the selection seeder is shown in figure 1.

![Figure 1](image1.png)

**Figure 1.** The scheme of the coulter group of the selection seeder with active needle-shaped rotating hoe wheels.

The direction of the circumferential speed of rotation of the needle rotating working organs is opposite to the direction of movement of the coulter, in view of this, the needles of the working organs capture plant residues and shift them in the direction opposite to the movement of the unit. Due to the rotation of the rotating working organs, the plant mass completely moves from the front to the back of the coulter. Intensive cleaning of the coulter tip and the distance between coulters makes it possible to move steadily in the soil and ensure high-quality seeding down to a given depth.

To implement the above-mentioned requirements, it is necessary to justify the most significant design and technological parameters of the proposed working organ. See figure 2:

![Figure 2](image2.png)

**Figure 2.** Variable parameters of the working organ.
Technological:

- $V_{\text{unit\ speed}}$ – unit speed, m/s;
- $h_{\text{rot}}$ – processing depth;
- $\lambda \pm$ – the kinematic parameter.

Constructive:

- $R$ – the radius of the rotating working organ;
- $r$ – the radius of the transition points of a straight needle to a curved needle;
- $R_c$ – the needle radius;
- $\omega$ – rotation frequency of the working organ, rad/s.

The movement of plant residues in the zone of the rotating working organ can be divided into 3 stages:
- movement of plant residues when interacting with the disk needles;
- movement of plant residues on the working part of the needle;
- movement of soil after leaving the surface of the needle.

Let’s consider the above-given stages in more detail, provided that the final parameter, which depends on the above-mentioned factors, is the specific volume ($sp.\, vol$) moved by the needle working organ.

During the operation of active needle-shaped rotating working organs, partial movement of plant residues occurs, and a common front of soil bulldozing is formed. The unit's speed with plant residues is equal to the speed of the working organ’s movement, i.e. $V_{\text{unit\ speed}} = V_0$. The purpose of the proposed coulter is to shift the residues from the front to the back of the working organ’s leg. The following conditions must be met:
- working organs must not be involved in tillage;
- plant residues should not significantly change their location relative to the soil. See figure 3. That means that they should not be randomly scattered.

![Figure 3. The interaction of plant residues with the needle: a) the moment when the needle touches the plant residues; b) the moment when the plant residues descend from the needle.](image)

To meet the above-given conditions, the following equality must be observed:

$$V_{\text{unit\ speed}} = V_0 \cos \alpha; \quad m_1 = m_2,$$

where $m_1, m_2$ – accordingly, the mass of unloaded plant residues and the mass of plant residues moved by the disk needles;
- $\alpha$ – the angle formed by the contact surface of the needle and the normal to the soil surface, degrees;
- $V_0$ – circumferential speed of the upper point of the needle (point A).
When working, the rotating disk crushes plant residues with its needle in the soil with its curved part (the part curved forward, or the occipital part). This results in a resistance force \( P \) proportional to the volume being crushed [5]. The compression resistance is much higher than the resistance to other types of deformation: shear, stretching, etc. Therefore, the basis of the reaction that pushes the needle out of the volume of plant residues, which prevents rotation, is precisely the compression force.

The previously conducted works devoted to the assessment of needle working organs considering the degree of their impact on the soil showed that the quality of tillage depends on the configuration of needles at fixed values of the radius of the working space of the working organ \( R \) and the radius of curvature of the needle \( R_c \).

Moving along the needle of the working organ figure 4, the mass of plant residues acquires resultant velocity \( V_{\text{res}} \), which is the result of the geometric addition of the maximum peripheral speed \( V_p \) and the maximum speed of movement along the needle of the working organ (further – along the needle) \( V_r \).

The peripheral speed \( V_p \) is defined as:

\[
V_p = \frac{\pi R}{30} n, \quad (1)
\]

where \( R \) – the distance from the center of rotation to the tip of the needle of the working organ, m;

\( n \) – rotation frequency of the rotating working organ, min\(^{-1}\).

The value of the movement speed of plant residues along the needle of the working organ is determined by the dependence:

\[
V_r = m \cdot \omega^2 \cdot p, \quad (2)
\]

where, \( m \) – the value the mass of the plant residues moving along the needle, kg;

\( \omega \) – the value of the angular velocity of the rotating working organ, rad/s;

\( p \) – the value of the radius-vector of the center of gravity, particles of plant residues located along the needle of the rotating working organ, m.

The friction force \( F_f \) consists of the following values:

\[
\vec{F} = \vec{F_c} + \vec{F_p} = \sqrt{F_c^2 + F_p^2}, \quad [2],
\]

where, \( F_c \) – the value of the centrifugal force acting along the needle of the working organ, \( \text{H} \);

\( F_p \) – the value of the force acting perpendicular to the surface of the needle of the working organ \( \text{H} \).

\( F_c \) – this value is aimed at moving plant residues in the direction along the needle of the disk and is calculated using the following expression:

\[
F_c = m \cdot \omega^2 \cdot p \cdot \sin \alpha, \quad (3)
\]

where, \( \alpha \) – the value of the inclination angle of the needle of the working organ, degrees.
The force that affects the friction force, \( H \):

\[
F_p = m \cdot \omega^2 \cdot p \cdot \cos \alpha .
\]  

(4)

The value of the Coriolis force for plant residues moving along the needle of the rotating working body is determined by the expression:

\[
F_C = m \cdot \omega \frac{dr_1}{dt} .
\]  

(5)

The Coriolis force acts perpendicular to the surface of the needle of the working organ and affects the friction force \( F_{fr} \).

3. Findings and Discussion

Using the formulas considered above we can identify the friction force as:

\[
F_{fr} = f \cdot (F_C - F_p) = f (2m \cdot \omega \frac{dr_1}{dt} - m \cdot \omega^2 \cdot p \cdot \cos \alpha) ,
\]  

(6)

where \( f \) – the friction coefficient of plant residues on the material from which the needle of the working organ is made.

The equation of the plant residue movement along the surface of the needle will have the following form:

\[
F_c - F_{fr} = m \frac{d^2 r_1}{dt^2} .
\]  

(7)

Substituting the expressions of the force \( F_c \) и \( F_{fr} \) values in the equation 7, we reduce the mass value \( m \) considering that \( p \cdot \sin \alpha = r_1, p \cdot \cos \alpha = r_1 \cdot \tan \alpha \). After these mathematical transformations, we obtain a differential equation for the plant residue movement along the surface of the needle of the rotating working organ:

\[
\frac{m}{r_1} \frac{d^2 r_1}{dt^2} + 2f \cdot \omega \frac{dr_1}{dt} - \omega^2 \cdot r_1 - f \cdot \omega^2 \cdot r_1 \cdot \tan \alpha = 0 .
\]  

(8)

Based on the analysis of expression 4, we determine the required value of the rational angle of the needle of the working organ. Since the needle of the working organ rotates, the value of the rational angle will be in the range of values from \( \alpha_{min}=0^\circ \) to \( \alpha_{max}=25^\circ \), on the basis of which the needle of the rotating working organ will take the form of a curved profile.

The work of the rotating working organ is based on the conditions that the rotation of the disk will occur, provided that the magnitude of the external applied forces \( (M_p) \) must exceed the value of the sum of the moments of forces that originate from plant residues, namely the moment of the friction forces of the \( M_{fr} \) and the moment of resistance to peripheral rotation \( M_{per} \).

\[
M_p > M_{fr} + M_{per} .
\]  

(9)

The value of friction force moment is identified as:

\[
M_{fr} = f \cdot F_{fa} = f \cdot \frac{J \omega^2}{r_1} ,
\]  

(10)

where, \( \frac{J \omega^2}{r_1} \) – the component of the centrifugal force;

\( F_{fa} \) – force acting on plant residues;

\( J \) – the value of the inertia moment of plant residues moving on the surface of the needle.
Figure 5. The analysis of the plant residue movement along the needle of the rotating working organ during their descent.

The moment of circumferential effort is identified as:

\[ M_{\text{per}} = F_{\text{per}} \cdot R = \frac{N}{n \cdot z}, \]  

(11)

where, \( R \) – the distance from the rotation center the needle tip of the working organ, m;
\( F_{\text{per}} \) – the value of circumferential effort, H;
\( N \) – the value of the power transmitted to the rotating working organ, H;
n – the rotation frequency of the working organ, min\(^{-1}\);
z – the number of blades, items

Based on the analysis of expression 10 and inequality 9, we get:

\[ M_p \geq f \cdot \frac{1}{r_1} \cdot \frac{\omega^2}{n \cdot z} + \frac{N}{n \cdot z}. \]  

(12)

The minimum value of the inertia moment required for the plant residue movement can be determined using the expression:

\[ J = \frac{(M_p - \frac{N}{n \cdot z})}{f \cdot \omega^2}. \]  

(13)

The total value of the projection of all forces on the surface of the needle is defined as:

\[ \sum P = mR \cdot \omega^2 \cdot \sin \tau - m \cdot \tan \phi \cdot R \cdot \omega^2 \cdot \cos \tau \cdot \cos \left(\cos \phi \cdot (\cos (\tau - \phi)) \right), \]  

(14)

where, \( \tau \) – the value of the angle between the \( V_r \) and \( V_{\text{per}} \) velocity vectors;
\( \phi \) – the value of the angle of static friction of plant residues on the material from which the needle is made.

By determining the total force \( P \), it is possible to identify the variable \( t \) from the equation 5. The value of the absolute velocity is determined based on the condition – \( p \cdot \sin \alpha = r_1 \), \( p \cdot \cos \alpha = r_1 \cdot \tan \alpha \):

\[ V_p = \sqrt{V_{\text{per}}^2 - V_{r}^2 - 2V_{\text{per}} \cdot V_r \cdot \cos (\tau - \phi)}. \]  

(15)
Expressing the absolute velocity in terms of the trajectory length (needle length), we obtain an equation of the form:

\[ V_p = \sqrt{\omega^2 - R^2 + l \cdot R \cdot \omega^2 \cdot \sin(\tau - \varphi) \cdot \cos \varphi + 2 \omega \cdot R \sqrt{l \cdot R \cdot \omega^2 \cdot \sin(\tau - \varphi) \cdot \cos \varphi} \cdot \cos \tau}, \]  

(16)

where, \( l \) – the distance covered by the plant residues along the needle of the rotating working organ, m.

The rotating working organ performs two types of movement: forward movement, when moving the unit, and rotational movement, performed by the needles of the working organ. The trajectory of needles with a horizontal axis of rotation is geometrically a cycloid, the change in shape of which is affected by the ratio of the peripheral and translational velocity.

The value of the cycloid step is determined by the following equation:

\[ \lambda = \frac{V}{V_a} = \frac{\omega \cdot R}{V_a}, \]  

(17)

where, \( \omega \) – the value of the angular velocity of the rotating working organ, rad./s.;
\( R \) – the distance from the rotation center to the needle tip of the working organ, m;
\( V_a \) – the value of the translational velocity of the unit, m/s.

As a rule, in rotary tillage machines \( \lambda > 1 \) [4], so the absolute trajectory of the working organs is an elongated cycloid. The absolute velocity of the working organ's movement or cutting speed is determined by the expression:

\[ V_0 = V_a \sqrt{\lambda^2 + 1} \pm 2 \lambda \sin \beta + 1, \]  

(18)

where, \( \beta = \omega \cdot t \) – the value of the rotation angle of the rotating working organ at a time, \( t \).

The "minus" sign in formula (18) refers to the forward rotation, and the "plus" sign refers to the reverse rotation. In the cutting zone, the maximum velocity corresponds to: \( V_0 = V_a \sqrt{\lambda^2 + 1} \) in forward rotation, at \( V_0 = V_a \cdot (\lambda^2 + 1) \) rotation.

Based on the theoretical calculations and design data, it is possible to determine the performance and operating parameters of the unit.

\[ a = d \cdot \xi \]  

(19)

\[ b = \left( \frac{1}{\cos \varphi} \right) \left[ R \cdot \arccos \left( \frac{r^2 + R^2}{2Rr} \right) - \arccos \left( \frac{R - r}{R} \right) \right] + \frac{R \sqrt{4R^2 - 2r^2 - (r^2 + R^2)^2} \cdot h_{dep} \left( 2R - h_{dep} \right)}{2R} \cdot \theta \cdot \lambda \]  

(20)

where: \( \varphi \) – the angle of friction, degrees;
\( a \) – the width of the needle grab, m;
\( b \) – the length of the needle grab zone, m;
\( d \) – the working width of the needle grab, m;
\( R \) – the external radius of the working organ, m;
\( r \) – the radius of the transition points from the straight surface to the curved surface, m;
\( R_c \) – the radius of the needle curvature, m;
\( h_{dep} \) – the depth of processing, m;
\( \xi, \theta \) – the coefficient of the soil bulldozing;
\( \lambda \) – the kinematic parameter.

The volume of plant residues moved with a single needle is identified as:
The volume of plant residues moved by the working organ per one rotation is found based on experimental data:

\[ Q_0 = \frac{1}{3} \pi \cdot a \cdot b \cdot h_{dep} \]  \hspace{1cm} (21)

where \( \mu \) – the influence coefficient of the number of needles on the volume of plant residues moved per 1 rotation (determined experimentally):

\[ \mu = n_d (30n_d^2 - n_d + 9) \cdot 10^{-4} \]  \hspace{1cm} (22)

where \( n_d \) – the number of needles on a disc, item.

We obtain:

\[ Q_0 = \frac{1}{3} \pi \cdot a \cdot b \cdot h_{dep} \cdot n_d (30n_d^2 - n_d + 9) \cdot 10^{-4} \]  \hspace{1cm} (23)

\[ \frac{Q_{sp.vol}}{L_{unit}} = \frac{Q_0 \cdot \lambda}{\mu} = \frac{\pi \cdot a \cdot b \cdot h_{dep} \cdot \omega \cdot R \cdot n_d (30n_d^2 - n + 9)}{3 \cdot 10^4 \cdot V_{dep} \cdot L_{unit}} \]  \hspace{1cm} (24)

where: \( \omega \) – rotation frequency of the working organ, rad./s.

\( L_{unit} \) – the distance covered by the unit is calculated as follows \( L_{unit} = 1 \) m.

Based on the equation (25), let us construct the graphs of the dependence of plant residues movement on the structural and technological parameters. See figures 6–9.

**Figure 6.** Theoretical dependences of the movement of plant residues \( Q_{sp.vol} \) (m³/m) depending on the kinematic coefficient \( \lambda \) and the depth of processing \( h_{dep}(m) \), \( Q_{sp.vol} = f(\lambda, h_{dep}) \).
Figure 7. Theoretical dependences of the movement of plant residues $Q_{sp\text{-vol.}}$ (m$^3$/m) depending on the number of needles $n_d$ and the unit's speed $V_{unit\text{ speed}}$ (m/s), $Q_{sp\text{-vol.}} = f(n_d, V_{unit})$.

Figure 8. Theoretical dependences of the movement of plant residues $Q_{sp\text{-vol.}}$ (m$^3$/m) depending on the radius of needle curvature $R_c$ and the radius of the transition points of the straight needle surface to the curved needle surface $r$ (m), $Q_{sp\text{-vol.}} = f(R_c, r)$. 
4. Conclusion
The obtained dependences make it possible to select the optimal performance parameters of the rotating working organ. The movement of plant residues is mainly influenced by the depth of processing, the number of needles in the working organ, and the kinematic coefficient. The optimal performance parameters include the following ranges: the disk radius of 0.2–0.3 m, the number of needles on the disc equals 2–6 items, the kinematic coefficient is from 1.5 to 3.5. Due to design considerations, we take the radius of the transition points of the straight needle surface into the curved needle surface of 0.1 m, the curvature radius of the needles equals 0.8 m; the needle diameter is 0.015 m.; the overhang distance of rotation axis of the disks forward the axis of the coulters is 40 mm; the relative angular displacement of the needles of adjacent disks in the planes of rotation – half the step of the needles’ installation.

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