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RESEARCH INTO THE MAIN DESIGN CHARACTERISTICS OF THE ROTARY WORKING BODY OF A MACHINE FOR HARVESTING ROOT AND TUBER CROPS

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The improvement of technical equipment for harvesting root and tuber crops remains a key task in modern agricultural engineering. This is driven by the need to intensify production, increase energy efficiency, and reduce mechanical damage to the harvested crop. A decisive role in this process belongs to the rotary working element, which directly interacts with the soil and ensures crop extraction.

The aim of this study is to substantiate and determine the optimal design and technological parameters of a rotary working element affecting the completeness of extraction, soil separation efficiency, tuber damage, and energy consumption. The research combines theoretical analysis, CAD/CAE-based modeling of the stress-strain state, DEM simulation of soil and tuber movement, and laboratory testing in a soil bin under different soil and moisture conditions. A comparative analysis of domestic and foreign harvesting machines was also carried out.

The main parameters studied were the number, geometry, and arrangement of rotor blades, the profile of the gripping surface, the inclination angle of the working element, and the ratio between forward speed and rotor rotational speed.

The results showed that the most effective design is a rotary element with four spiral blades. Experimental and theoretical investigations confirmed that placing the blades at an angle of 25° to the horizontal provides a soft entry into the soil, reduces frontal resistance, and improves load distribution. This configuration reduced mechanical damage to tubers by 18% compared with passive and disc-type working elements. The optimal rotor speed was found to be 120 rpm, ensuring a balance between productivity, soil separation quality, and energy efficiency.

The practical value of the work lies in engineering recommendations for improving root and tuber harvesters, reducing crop losses, and increasing machine reliability.

Keywords: *rotary working body, design parameters, root crop harvester, root crops, tuber crops, digging, harvesting, potato, beet.*

Eq. 5. Fig. 7. Ref. 29.

1. Problem formulation

In today’s world, increasing attention is being paid to the development of machines for harvesting root and tuber crops, as the future of the agricultural sector depends on mechanization and production intensification. Scientific research over the past 3–5 years has focused on the design of rotary components, which play a key role in reducing crop damage and increasing productivity. For example, Bulgakov et al. (2021) demonstrated that increasing the rotor diameter to 1.0 m and using a travel speed of 0.8–1.5 m/s significantly improves soil

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distribution efficiency and reduces tuber damage to 1.5% (Bulgakov et al., [6]). Similarly, Brusenkov and Konovalov [5], (Du, X. et al., [13]) developed a new rotary chopper for root crops with low energy consumption and optimal arrangement of cutting elements around the drum (Brusenkov & Konovalov, [5]). In the studies by Deepan Kumar et al. [10], a mounted plow-machine was developed for collecting leftover root crops, which improves efficiency and reduces in-field losses (Deepan Kumar et al., [10]). The research by Ulyanov et al. [27] proposed a harvester design for tuber crops with a belt conveyor and a drum-type cutting element, which increases productivity and reduces crop damage (Ulyanov et al. [27]). Laboratory testing of a device designed to assess the suitability of potatoes for mechanized harvesting includes parameters such as vibration and sorting (Dorokhov et al., [12]). In addition, field trials of a universal harvester have demonstrated that an optimal blade length of approximately 30 cm and an entry angle of around 25° ensure 98% harvesting efficiency with low energy consumption (Al Sammarraie et al., [1]). A 2025 review highlights the use of rotary elements in designs, which improve soil separation by varying rotation frequency, disc diameter, and spacing between discs (Al Sammarraie et al., [1]).

Thus, a review of current literature confirms that rotary elements significantly reduce tuber damage and enhance the quality of soil separation; there is a clear trend toward optimizing parameters such as rotor diameter, rotational speed, blade shape, and entry angle; however, there are technological limitations in manufacturing complex forms of rotating working parts.

The relevance of this study is substantiated by the need for further optimization of rotary working unit designs that simultaneously ensure high harvesting efficiency and minimal crop damage.

The aim of the research is to investigate the main design characteristics of the rotary working unit of a machine for harvesting root and tuber crops.

The objectives of the study are: to review the designs of recent rotary component modifications; to determine the influence of rotor diameter, rotational speed, and installation angle on performance and crop damage; and to develop an optimal configuration of the working unit, taking into account technological constraints.

The scientific novelty lies in a comprehensive analysis of the interaction between rotary unit parameters (diameter, speed, spacing) and field results, as well as design configurations, which have previously been studied only partially or in isolation.

2. Analysis of recent research and publications

In theoretical studies by Olt and co-authors [24], a mathematical model was developed to simulate the movement of soil particles in contact with conical and cylindrical blades of a vertical rotor in a potato harvester. The researchers established relationships between mechanical contact parameters (rotation frequency, travel speed) and the velocity of soil ejection as well as the contact duration with the working surface (Olt et al., [24]).

Beznosyuk and colleagues [4] investigated the effect of vibration-based separation. They found that a vibration frequency of 130 rpm and a finger rake inclination angle of approximately 34° provided optimal soil separation beneath the conveyor belt, significantly improving tuber cleaning without causing damage (Beznosyuk et al., [4]).

Wei and co-authors [29] focused on optimizing separation parameters in a multistage harvesting process. They analyzed vibrating surfaces, belt-based vibrating elements, and conveyor movement speed. The findings indicated that combined parameter adjustment enhanced harvesting performance and reduced mechanical losses (Wei et al., [29]).

Hrushetskyi and co-authors [17, 19, 20] analyzed the design and technological configurations of rotary working bodies, investigating the structure of digging elements and separation mechanisms. Their work notably emphasized lift-type separators and the structural analysis of transport-separation mechanisms (Hrushetskiy et al., [17]; Hrushetskyi et al., [19]; Hrushetskyi et al., [20]).

A fundamental review published in *Frontiers in Plant Science* [14] summarized key operational parameters for harvesting machines: travel speed (up to 7.9 km/h), digging element angle (10–24°), and transportation speed, all of which significantly influence tuber losses and machine performance (Frontiers Review, [14]).

The international technical documentation from SAE [10] presented a modernization concept for root crop harvesting machines. A new plow-harvester design was proposed, aimed at simultaneously loosening the soil and extracting crop residues from the field, which significantly reduced post-harvest losses (Deepan Kumar et al., [10]).

The studies by Babii et al. [2] present an engineering methodology for investigating the kinematic parameters of the blade drive mechanism. This method enables the description of the interaction patterns between the mechanism's links and characterizes the linear and angular velocities and accelerations of any points or links within the mechanism under investigation.

Based on experimental studies, a mathematical model was developed to describe the influence of the distributor's design parameters on tuber contamination with soil impurities. The rational range of distributor parameters, previously determined theoretically, was confirmed experimentally (Bulgakov et al., [9]; Bulgakov et al., [7]).

The experimental results obtained by Bulgakov et al. [8] confirmed the outcomes derived through numerical solutions of the mathematical model. The rational angular velocity (ω) of spiral rotation was determined to be between 20.0 and 30.0 rad/s, with the spiral radius (R) ranging from 0.12 to 0.15 m.

The article *"Potato of the Future: Opportunities and Challenges in Sustainable Agrifood Systems"* (Devaux et al., [11]) describes research and innovation strategies, as well as policy directions, that could support the needs of both rural and industrial potato-based agrifood systems.

Experimental results (Li et al., [22]) showed that, with a shaker element installation height of 43 mm, a machine speed of 1.4 m/s, and a secondary separation unit linear speed of 1.5 m/s, the clean potato yield reached 97.6%, while the yield of damaged potatoes was 1.5%. These results meet national standards for potato harvesters and fieldwork requirements, providing a benchmark for optimized harvester design.

A study by Tikuneh et al. [26] presented the design, fabrication, and testing of a tractor-mounted two-wheeled potato digger. The experimental evaluation used a split-plot diagram, with conveyor inclination angles (10°, 15°, and 20°) as the main factor, and tilt angles (15°, 20°, and 25°) as the sub-factor, tested in three replicates.

The dynamic identification and cleaning method for potatoes based on RGB-D sensors (Fu et al., [15]) showed that, when the speed was set to 0.4 m/s, the cleaning precision reached 96.35%. This research provides a method and theoretical reference for further development of intelligent potato cleaning systems.

A wheel-chassis potato harvester was developed with integrated systems for bag packaging and ton-bag lifting, capable of simultaneously performing tuber digging, soil separation, film separation, automatic bagging, and ton-bag lifting (Wang et al., [28]). Field trials showed a tuber loss rate of 2.1%, a tuber damage rate of 1.7%, skin damage rate of 2.5%, impurity content of 1.9%, and capacity ranging from 0.15 to 0.23 ha/h. These results comply with national and industry standards.

Particle modeling can reduce the need for large-scale field trials in optimizing potato harvesting processes (Poppa et al., [25]). The Discrete Element Method (DEM) provides deeper insight into potato harvesting processes. Building DEM models requires information on material behavior, particle shape, and interactions between particles and machine components.

Potato production in North-Western Europe (Germany, France, the Netherlands, UK, and Belgium) is characterized, and key challenges and opportunities are analyzed in a SWOT framework (Goffart et al., [16]). This aims to identify potential solutions to overcome environmental, technical, economic, political, and social challenges for sustainable potato production in the coming years and decades.

Global average yield increases range from 9 to 20% considering adaptation measures. According to Jennings et al. [21], adaptation to climate change leads to an average global yield increase of 10–17% under different climate models. Potato cultivation is associated with lower greenhouse gas emissions compared to other staple crops, making it a climate-smart option in light of projected yield increases with adaptation.

A critical analysis of a large-scale renewable energy system integrating solar PV panels and wind turbines was conducted, assessing its partial contribution to the total energy budget of a potato farm producing 8,000 tons of yield annually, 4.500 tons of which are stored in cold storage for up to 8 months (Muneer et al., [23]). The findings and recommendations of this case study will support renewable energy specialists in planning and evaluating similar systems.

This review shows that in recent years, researchers have actively analyzed individual aspects of rotary working body design**,** such as soil particle movement**,** vibratory separation**,** conveyor configurations, and digging element design. This forms the basis for a comprehensive study in our work, which aims to analyze all design parameters in an integrated and interrelated manner.

3. The purpose of the article

The purpose of this research was to determine the main design characteristics of the rotary working unit that affect the quality of harvesting, the degree of crop damage, and the energy consumption of the process.

4. Results and discussion

Analytical studies of the separating devices used in root crop harvesting machines (Hrushetskiy et al., [18]), as well as the intensifiers working in conjunction with them (Hrushetskiy et al., [18]), have demonstrated functional advantages of rotary-type separators over other designs. They exhibit high separating capacity, reliability, low weight, low energy consumption, and minimal injury to the harvested root crops.

Based on the results of previously conducted rotary separator studies (Hrushetskiy et al., [18]), a new design of a rotary root crop harvesting machine was proposed. The goal of eliminating the identified drawbacks is achieved by introducing a partially cylindrical moldboard attached to the digger instead of a flat one. The front part of the cylindrical moldboard consists of a concave body during the first stage of the technological process, which digs toward the potato heap. This change in the moldboard's shape reduces the flow of the potato heap to the separating device by 25-30% in ridge planting and by 50-60% in flat planting.

In the second stage, the middle part of the shelf surface body is flat, with rods in the transverse-vertical plane, and a rotor is placed above it to separate the tubers from the soil and direct them toward the rotary separator and the separating rods in the longitudinal-vertical plane. In the third stage, the final part of the shelf surface is convex, with rods in the transverse-vertical plane, causing the soil layer to break up and partially separate along the longitudinal-vertical plane, as well as uniformly distribute it on the separating surface to facilitate separation.

On both sides of the cylindrical moldboard, vertically positioned toothed discs are placed. The non-working edges of the teeth are equipped with soil cleats in the shape of an isosceles right triangle, where the lateral sides of the triangle have a cutting edge bent at 90° alternately in both directions relative to the plane of the disc. A series of holes are made in the toothed disc, with their centers positioned concentrically to the axis of rotation of the toothed disc. The distance from the outer edge of the disc's teeth to the axis of the holes equals the depth of potato heap digging, and it is permissible to range from 140 to 250 mm. The diameter of the holes in the toothed disc can vary between 30 and 37 mm.

The proposed rotary root crop harvesting machine is depicted in Figure 1 – side view during potato harvesting: V_m – machine speed; ω – rotational speed; Q_o – total flow rate of the heap, which includes $r(t_i)$ – the number of fine soil particles at time t, $k(t_i)$ – the number of tubers at time t, $m(t_i)$ – the number of plant residues at time t, $q(t_i)$ – the number of large soil clumps at time t; α_l – angle of the cylindrical moldboard relative to the horizon; Figure 2 – top view of the rotary root crop harvesting machine: γ – angle of the sliding slope of the moldboard with the dug-up potato bush across the edge.

The technological diagram of the digging process consists of the potato heap 1, with two vertical toothed discs 2 with soil claws 3 placed on both sides. The disc is equipped with a series of holes 4, the centers of which are concentrically arranged along the axis of rotation of the toothed disc. The distance between the outer edge of the disc tooth and the hole axis is permissible within 140 to 250 mm. The diameter of the hole in the toothed disc can range from 30 to 37 mm. The cylindrical share 5 of the root-tuber harvesting machine moves along the dug potato heap 1, which undergoes some changes in shape and deformation on the separating rods 6 in the longitudinal-vertical plane. The fingers 7 of the rotor separate the tubers from the soil and deliver them to the rotary soil separator with rubber-fingered rotors 8 to minimize tuber damage due to the torque transmitted via the chain drive. The tubers are then further transferred to the rod separator 9, where the technological process of separation occurs.

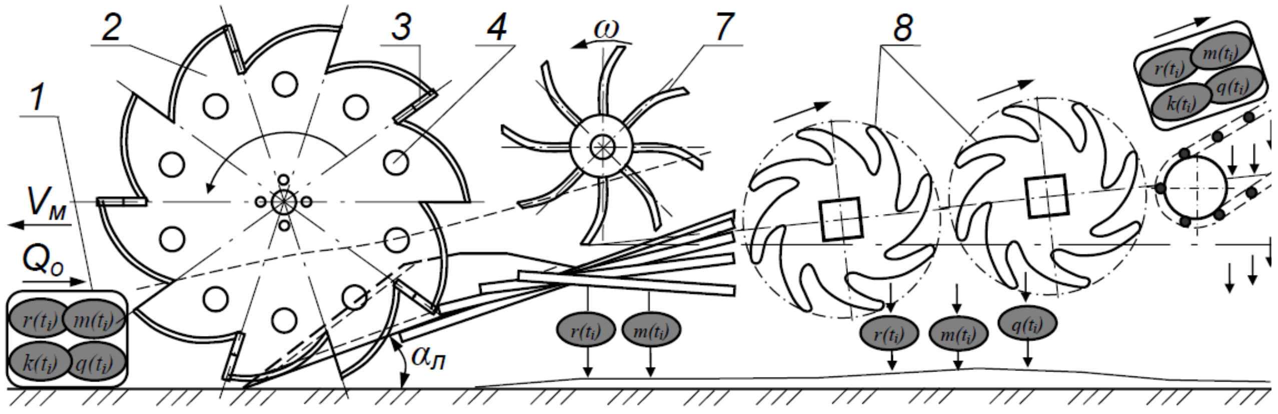

Fig. 1. Technological diagram of a rotary root-tuber harvesting machine (side view during potato harvesting)

Source: developed by the author based on research by S.M. Hrushetskiy [18].

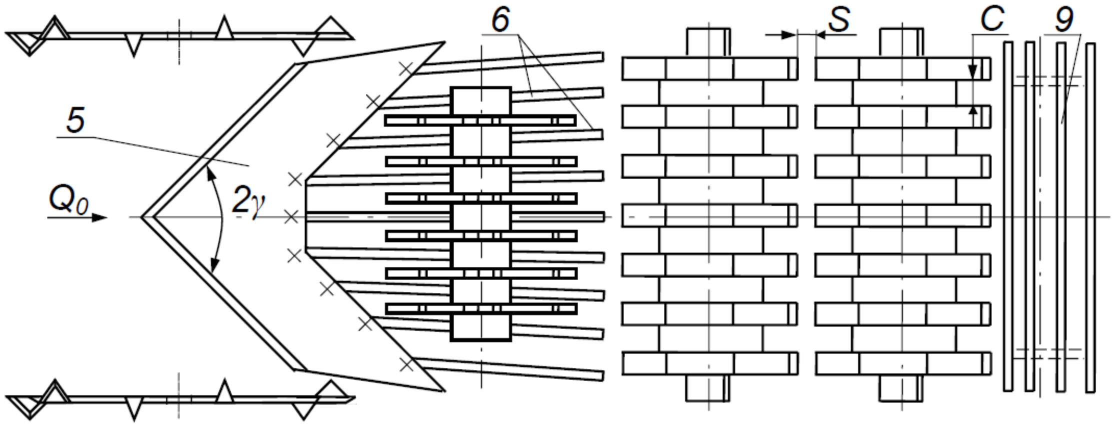

Fig. 2. Technological diagram of a rotary root-tuber harvesting machine (top view)

Source: developed by the author based on research by S.M. Hrushetskiy [18].

The rotary potato harvester operates as follows. As the machine moves along the rows of the potato field, driven by the tractor's traction, the working organ penetrates the potato heap, and the layer is cut from below by the cylindrical share 5. Due to the gradual movement of the potato digger and the engagement of the toothed discs 2 with the soil, which are ensured by frictional forces on the lateral surfaces, the soil claws 3 rotate the discs on their axes. This results in the cutting of plant residues both by the working edge of the toothed disc 2 and by the cutting edges of the soil claws 3, as well as the cutting of the potato layer on the sides. Due to the compression between the discs 2 and the cylindrical share 5 of the potato harvester, a reduced layer of the heap 1 is conveyed along the concave front part, then along the flat rod 6 in the longitudinal-vertical plane. The fingers 7 of the rotor, with rubber tips used to reduce tuber damage under the action of the torque transmitted through the chain drive, separate the tubers from the soil. Once separated, they move along the convex rod-separating surface in the transverse-vertical plane, reaching the rotary soil separator with rubber-fingered rotors 8 to minimize tuber damage due to the torque. The tubers are then transferred to the rod separator 9, where partial crushing, separation, and even distribution for further separation occur.

In the design of the rotary separator, based on earlier research, it was proposed to use 2 to 3 working sections arranged parallel and rotating in the same direction. Each section consists of a shaft with rotating working organs fixed to it. Between the rotors, it was proposed to install replaceable spacer bushings. These bushings will allow the shifting of the rotors along the shafts to create separating gaps, including those equal to the minimum permissible tuber size. Thus, the gap size can be set by selecting the width of the bushings within 30 to 50 mm.

When the gaps (*C*) are set between 35 mm and 50 mm, it will increase the soil separation productivity. Reducing the gap to 30 mm will decrease the loss of potatoes for those with a minimal commercial size. The working organs of adjacent sections should be installed one after another without overlapping the projections of neighboring rows. According to research, this configuration will allow for the shifting of the rotors, preventing interference between the projections of adjacent sections and changes in the size of the separating gaps (Figure 2). At the same time, the technological gap (*S*) between adjacent sections will enhance the separating capacity of the rotary separator, depending on specific soil-climatic conditions and the minimum commercial size of the harvested tubers.

Earlier studies allowed for the determination of the structural parameters of the share, the outer diameters of the rotor fingers D_n=300 mm, and the separator rotors D_p=300 mm, as well as the total number of sections N_c = 3. In the following stages of theoretical research, a more detailed definition of the design parameters of the working surface, as well as the operational modes of the fingers and rotors, was carried out.

To determine the optimal parameters for the fingers and the rotary separator, we conditionally divide the potato digger into three operational zones. The first (digging-separation zone) includes the share along with the rotor fingers, the second (intensive soil separation zone) includes the first three sections of the separator, and the third (final potato heap cleaning zone) includes three sections. The working processes in these areas will significantly differ. To obtain more accurate results, the theoretical justification of their structural parameters and operating modes will be carried out in accordance with the technological sequence.

After determining the quality of potato heap separation by the digging working organs of the potato harvester (Hrushetskiy et al., [18]) and the outer diameter of the rotary working organ, studies were conducted to justify its main structural parameters. The newly proposed rotary working organ, considering the agrotechnical recommendations, should have a rounded surface made of high-strength rubber, with conical protrusions placed at an angle to the inscribed circle (Figure 3). For the research, the following main parameters of the rotor will be taken: its outer diameter D_p, the angle of the protrusions $\beta_в$, their height $H_в$, length $L_в$, rounding radius $R_в$, the height of the peaks $b_в$, and the total number of protrusions $N_в$ on the outer diameter D_p, as well as the rotor thickness B the hole mounting parameter.

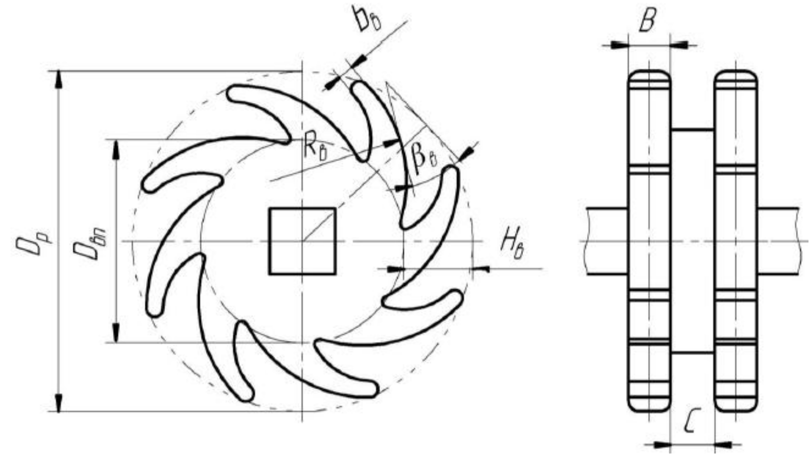

Fig. 3. Rotary Working Organ

Source: developed by the author based on research by S.M. Hrushetsky [18].

The center of each working component is structurally equipped with a square-section mounting hole for installation on rotating shafts. Due to the square shape of the mounting seat, the likelihood of the working components rotating around the axis of the shaft is eliminated. The separating gap ***C*** between adjacent rotors is established using spacer bushings. Each shaft with mounted rotational working components and spacer bushings forms an individual working section.

The installation of adjacent sections relative to each other without overlapping projections ensures the possibility of shifting the rotors along the shafts to change the separating gap C with the help of spacer bushings. This will allow for an increase in separating gaps and the efficiency of the separation process, as well as facilitate the harvesting of potatoes with different intended purposes.

The arrangement of rows without overlapping projections will also eliminate mutual jamming of the rotors of adjacent sections and prevent contact wear on their surfaces. However, in this case, a depression is formed between the rows of rotors of adjacent sections. This may reduce the average speed of movement of the bulk components and increase the impact on the potato tubers. Research conducted by scientists shows that the operation of rotational separating devices primarily depends on the separator's tilt angle, the shape of the projections, and the peripheral speed of the rotors. Therefore, according to scientists' recommendations, for stable transportation of the potato bulk and reducing the dynamic impact on the tubers, we will adopt a minimal tilt angle (10°) for the rotary separator, and the outer diameter of the working components D_p, based on the results of graphical-analytical studies, is 300 mm. The small tilt angle will reduce the kinetic energy required for the tuber to exit the depression, which, in turn, will lead to a decrease in the number of collisions with the rotor surfaces.

The increased outer diameter of the rotational working components D_p is intended to provide them with a higher peripheral speed, increase the intensity of separation, and improve the stability of transporting clay soil with increased moisture content. According to recommendations, to reduce the likelihood of tuber jamming, a rounded shape of the projections and an angle $\beta_в$ of their inclination against the direction of rotation were adopted.

The justification for more detailed projection design parameters was carried out in two stages. In the first stage, an analysis of the positional-force scheme was performed, and based on the equilibrium equations, the most effective parameters were determined: the tilt angle $\beta_в$, the height $H_в$, the length $L_в$, and the rounding radius $R_в$ of the projections. In the second stage, the height of the projection tips $b_в$ and their total number $N_в$ at the adopted diameter were calculated.

To conduct the first stage of research, a force diagram was built, which illustrates the interaction between a section of the potato bulk and the surface of the projection of the rotor of the second section (Fig. 4).

In this section of the separator, there is a large amount of unsieved soil, which increases the likelihood of unloading the transported potato bulk. Therefore, the projections of the rotors in the second and third sections should capture and reliably move its components at an ascent angle α_1 = 36…42° and a catch angle of the rotational working components of the subsequent section $\alpha_2(0)$=40…44°. By adopting the external diameter of the working components D_p=300 mm, we can determine the tilt angle of their projections $\beta_{\text{в}}$ (Fig. 4).

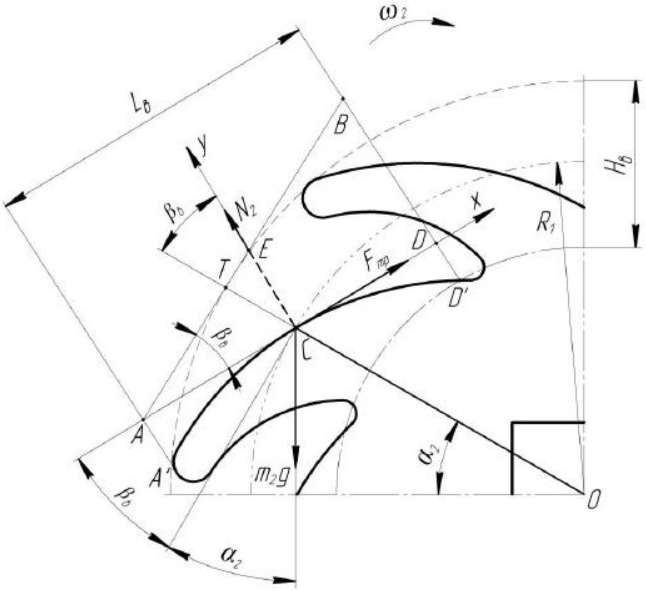

Fig. 4. Forces acting on a section of the potato bulk, rotor, located on the projection

Source: developed by the author based on research by S.M. Hrushetskiy (2020).

The system of equilibrium equations for this case is as follows (1):

$$\begin{cases} F_{mp} - m_2 g\cos(\alpha_2 + \beta_{\text{в}}) = 0 \\ N_2 - m_2 g\sin(\alpha_2 + \beta_{\text{в}}) = 0\,, \end{cases} \tag{1}$$

where N_2 – is the normal reaction force of the rotor projection of the second section, H.

Based on the equilibrium condition, the equations of the system (1) will have the following form (2):

$$\begin{cases} F_{mp} = m_2 g\,(\cos\alpha_2\cos\beta_{\text{в}} - \sin\alpha_2\sin\beta_{\text{в}}) \\ N_2 = m_2 g\,(\sin\alpha_2\cos\beta_{\text{в}} + \cos\alpha_2\sin\beta_{\text{в}}). \end{cases} \tag{2}$$

By replacing the frictional force F_{mp} with $f_p N_2$, we obtain the equality:

$$\sin\beta_{\text{в}}\,(f_p\cos\alpha_2 + \sin\alpha_2) = \cos\beta_{\text{в}}\,(\cos\alpha_2 - f_p\sin\alpha_2)\,, \tag{3}$$

where f_p – is the coefficient of friction of the tubers sliding on rubber, f_p = 0,7.

Then, we will express $tg\,\beta_{\text{в}}$ from equation (3):

$$tg\,\beta_{\text{в}} = \frac{\cos\alpha_2 - f_p\sin\alpha_2}{f_p\cos\alpha_2 + \sin\alpha_2}. \tag{4}$$

From equation (4), we find that the most suitable value for the tilt angle of the projections $\beta_{\text{в}}$ of the rotational working components is 28.5°.

The height of the projections $H_{\text{в}}$ of the rotational working components was calculated using the known methodology. Based on the specific relationship between the height of the projections $H_{\text{в}}$, their tilt angle $\beta_{\text{в}}$, and the outer diameter of the rotors D_p, it was computed that for $\beta_{\text{в}}$=28,5° and D_p=300 mm, the calculated height of the projections $H_{\text{в}}$ = 62 mm. From this, the diameter of the base of the projection depressions $D_{\text{вп}}$ = 176 mm was determined.

Knowing the height $H_{\text{в}}$ and the tilt angle $\beta_{\text{в}}$ of the projections, we can find their length $L_{\text{в}}$. To do this, we will determine the length of the median line *CE* of triangle *ABD* (Fig. 4).

$$CT = \frac{H_{\text{в}}}{2\cos\beta_{\text{в}}}. \tag{5}$$

Based on this, the length of the base *DB* is (6):

$$DB = \frac{H_{\text{в}}}{\cos\beta_{\text{в}}}. \tag{6}$$

Then, the hypotenuse *AB* will be equal to (7):

$$AB = \frac{H_{\text{в}}}{\cos\beta_{\text{в}} \sin\beta_{\text{в}}}. \tag{7}$$

The length of the projections $L_{в}$. of the rotational working component will be (8):

$$L_{\text{в}} = \frac{H_{\text{в}}}{\sin\beta_{\text{в}}}. \tag{8}$$

Substituting equation (8), $H_{в} = 62$ mm and $\beta_{в} = 28{,}5°$, we obtain that the rational value for the length of the projections $L_{в}$ of the rotational working component is 130 mm.

Based on the obtained design parameters of the rotor, we will determine the radius of curvature of the projections $R_{в}$ using geometric constructions. To do this, from points *A* and *D* of triangle *ABD*, we will drop perpendiculars *AA'* and *DD'* to the intersections with the external diameter of the rotor D_p and the diameter of the depressions $D_{вп}$ (Fig. 4). Through points *A'CD'*, we can draw a circle with a radius of 120 mm. Therefore, the most rational value for the radius of curvature of the projections is $R_{в} = 120$ mm**.**

To determine the height of the projection tips $b_{в}$, we will compile a differential equation for the curved axis of the beam (9):

$$E_p I_{\text{в}} S''_{\text{в}} = M_y, \tag{9}$$

where E_p – is the Young's modulus of the rotor material, MPa; $I_{в}$ – is the moment of inertia of the projection section of the rotor, m⁴; $S_{в}$ – is the deflection of the rotor projection, m; M_y – is the bending moment, Nm.

The moment of inertia of the projection section is equal to (10):

$$I_{\text{в}} = \frac{b_{\text{в}} B^3}{12}, \tag{10}$$

where *B* – is the width of the rotor projection, m.

The bending moment in the projection section is:

$$M_y = -F_y x_{\text{в}}. \tag{11}$$

Substitute equation (11) into equation (9):

$$E_p I_{\text{в}} S''_{\text{в}} = -F_y x_{\text{в}}. \tag{12}$$

Let's integrate the obtained expression.

$$E_p I_{\text{в}} \gamma'_{\text{в}} = -\frac{F_y x_{\text{в}}^2}{2} + C_1. \tag{13}$$

Let's integrate the expression a second time.

$$E_p I_{\text{в}} S_{\text{в}} = -\frac{F_y x_{\text{в}}^3}{6} + C_1 x_{\text{в}} + C_2. \tag{14}$$

The coefficients C_1 and C_2 can be determined from the following conditions:

a) when $x_{в} = L_{в}$, $S_{в} = 0$;

b) when $x_{в} = L_{в}$, $\gamma_{в} = S'_{в} = 0$.

From the first and second conditions, we obtain (15), (16):

$$C_1 = \frac{F_y x_{\text{в}}^2}{2}. \tag{15}$$

$$C_2 = -\frac{F_y L_{\text{в}}^3}{3}. \tag{16}$$

It is evident that $S_{вmax}$ and $\gamma_{вmax}$ will only occur when $x_{в} = 0$. Based on this (17):

$$S'_{\text{в}} = \gamma_{\text{в}} = \frac{F_y L_{\text{в}}^2}{2E_p I_{\text{в}}}. \tag{17}$$

$$S_{\text{в}} = -\frac{F_y L_{\text{в}}^3}{3E_p I_{\text{в}}}. \tag{18}$$

By applying Newton's third law to equation (18), we found N_{cp} (19):

$$N_{\text{ср}} = \frac{3E_p I_{\text{в}} S_{\text{в}}}{L_{\text{в}}^3}. \tag{19}$$

According to the previously conducted studies, the rational thickness of the rotors *B* lies within the range of 20 mm to 30 mm, and the maximum deformation of the projection $S_{в}$ under loads N_{cp} up to 1300 N/m² should exceed 2…3 mm. For the calculations, average values of the rotor thickness $B = 25$ mm and projection deformation $S_{в} = 2.5$ mm were adopted. Based on this, using formulas (10) and (19), it was determined that the rational height of the projection tips $b_{в}$ should be 15 mm. Based on the obtained design parameters of the rotor projections, it was found that several projections $N_в$ can be placed on the outer diameter of the rotor D_p = 300 mm. Using geometric constructions, their rational number $N_в$ = 8 pieces was determined (Fig. 3).

To determine the rational thickness of the rotors B and ensure high soil separation efficiency, it is necessary to investigate the elastic stability of the rotor projections during their interaction with the potato bulk.

The completeness of impurity separation by the rotational potato harvester S_c was modeled using regression equations for each pair of interacting factors, assuming the value of the third factor at the zero level.

$$\text{I. } V_m,\ n_b;\quad S_c = 149.4\, V_m + 2.8 n_b - 57.7\, V_m^2 - 0.005\, n_b^2 - 451.7 \tag{20}$$

$$\text{II. } V_m,\ n_p;\quad S_c = 149.4\, V_m + 1.45 n_p - 57.7\, V_m^2 - 0.003\, n_p^2 - 218.5 \tag{21}$$

$$\text{III. } n_b,\ n_p;\quad S_c = 2.8\, n_b + 1.45 n_p - 0.005\, n_b^2 - 0.003\, n_p^2 - 530.43 \tag{22}$$

Based on equations (20), (21), and (22), graphs were constructed that describe the distribution of the area of optimal values of impurity separation completeness S_c by the rotational potato harvester on response surfaces (Fig. 5, 6, 7).

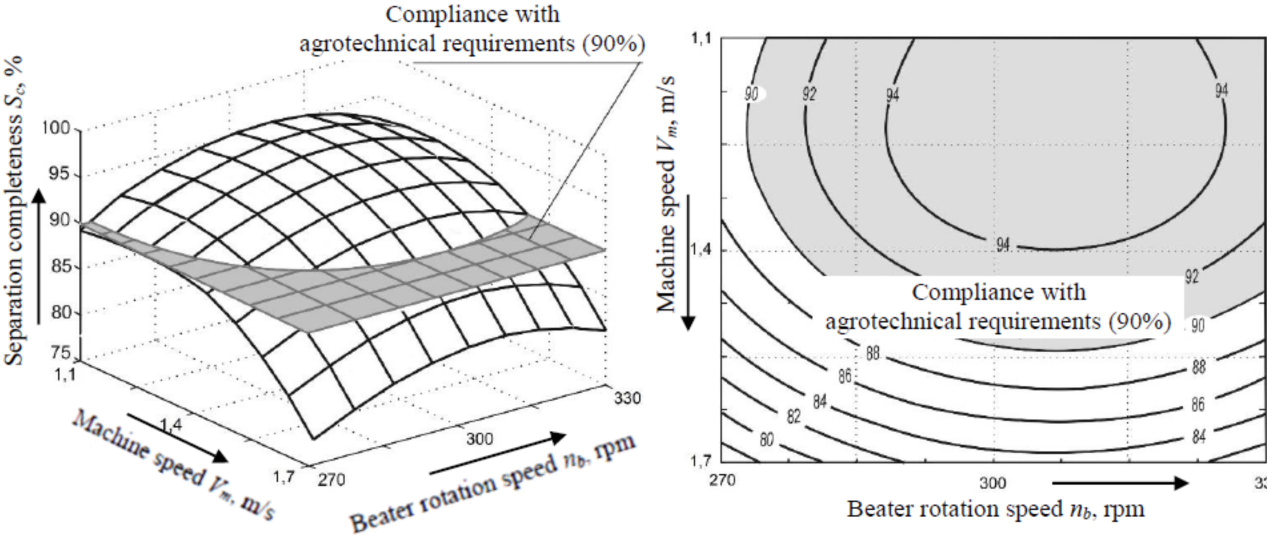

Fig. 5. Response surface and its contour plot characterizing the separation completeness depending on changes in V_m and n_b, with a constant value of the factor n_p.

Source: developed by the author of this study

Based on the analysis of the obtained equations (20), (21), (22) and the coordinates of the stationary point, it was established that the optimal value of the rotational potato harvester speed V_m is below the zero level and equals 1.3 m/s. As V_m increased to 1.7 m/s, the throughput of the potato mass onto the working surface increased, resulting in a decrease in the soil separation completeness S_c. The experiments were conducted under complex soil-climatic conditions (the moisture of the loamy soil ranged from 9.3% to 12.8%), during which a large number of unbroken clods were present in the soil layer. When working on gray forest and light loamy soils with moisture from 12% to 23%, the operational speed of the rotational potato harvester can reach 1.6–1.7 m/s, ensuring high separation efficiency.

At the same time, the experiments showed that the range of rational values for the rotational frequency of the working rotors n_p is above the zero level. During the experiments, the maximum separation completeness S_c was achieved at n_p = 242 rpm. At this value, the movement of the potato mass was stable, i.e., without clogging or overturning through the working sections. This is explained by the presence of a large number of unbroken clods in the soil layer, as significant effort is required to lift them. From the above, it can be concluded that the rational values for the rotational frequency of working rotors for different soil types range from 230 to 250 rpm.

The analysis of the experimental results showed that the range of rational values for the frequency of rotation of the agitator n_b is between 300 and 330 rpm. These values nearly fully correspond to the values obtained during theoretical research.

During the experiments, the amount of plant impurities wound onto the rotational working components and spacer bushings was also monitored.

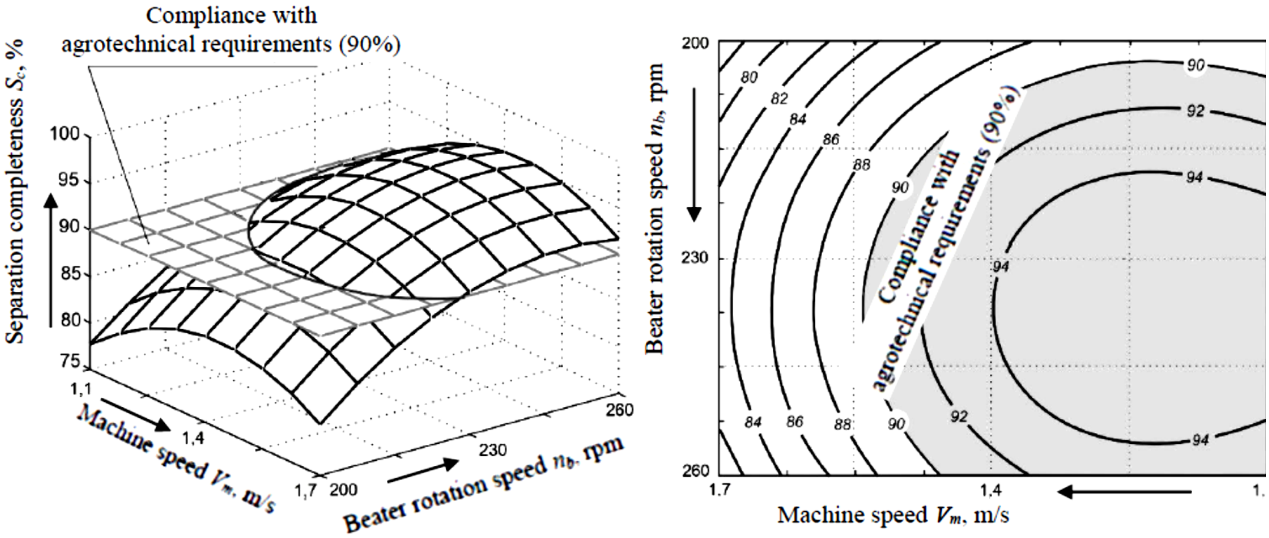

Fig. 6. Response surface and its contourgraph, characterizing the completeness of separation S_c with changes in V_m, n_p, and with a constant value of the factor n_b.

Source: developed by the author of this research

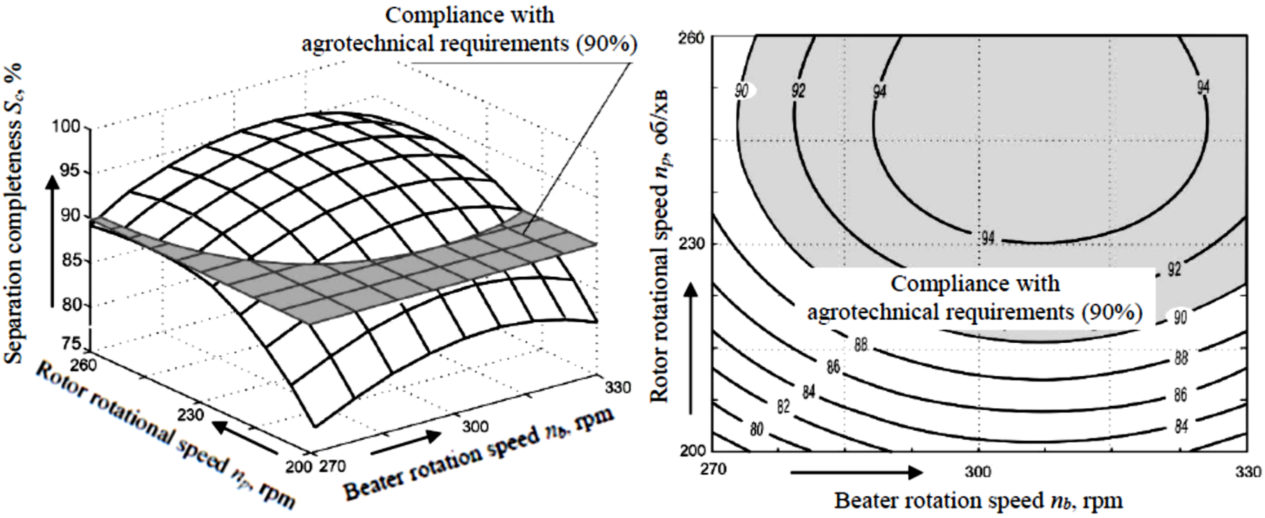

Fig. 7. Response surface and its contour graph, characterizing the completeness of separation S_c with changes in n_b, n_p, and with a constant value of the factor V_m

Source: developed by the author of this research

The large external diameter and high peripheral speed of the rotational working organs prevented the winding of plant residues. However, partial winding occurred on the spacer bushings of the third and fourth sections, located at the center of the separating surface. The maximum height of the plant residue layer on the spacer bushings was 1...1.5 cm. After this, the increased external diameter and the raised peripheral speed prevented new layers from winding onto them. Based on the above, it can be concluded that the proposed design of the rotational working surface ensures the removal of plant residues without the need for additional devices.

As a result of these studies, the theoretical assumptions regarding the promising combination of a blade agitator and a rotational separator in the design of the new rotational potato harvester were confirmed. The rational operating modes were also determined, at which the impurity separation completeness S_c by the rotational potato harvester is 94%. The regression equations, response surfaces, and contour plots obtained, which characterize the dependence of the completeness of separation of rotational impurities of the potato harvesting machine S_c on all combinations of the main factors, showed that its maximum value (94%) is achieved at the following conditions: V_m = 1.1…1.4 m/s (rotational speed of the harvester), n_b = 300...330 rpm (frequency of the blade agitator), n_p = 230...250 rpm (rotational frequency of the rotors).

5. Conclusion

The study of the main design characteristics of the rotary working organ of the root crop harvester has yielded important results that contribute to the improvement of root crop harvesting technology. The analysis revealed that optimizing the geometric parameters of the working organ, particularly the diameter and angle of inclination of the blades, as well as adjusting the rotational speed and torque, significantly affects the efficiency of harvesting and reduces mechanical damage to the root crops.

In particular, it was found that increasing the diameter of the working organ and reducing the angle of inclination of the blades contribute to smoother movement of the working organ in the soil, reducing the number of damaged root crops. The optimal rotational speed of the working organ allows maintaining product integrity while increasing machine productivity. As a result of experimental studies, the most effective design parameters for different soil types and crops were determined, ensuring maximum operational efficiency.

The experimental studies revealed that at operating speeds of the rotary root crop harvester V_m = 1.1; 1.3; 1.7 m/s, stable movement of the soil mass with the blade agitator and high separation efficiency of the rotary separator is ensured at biting speed n_b = 300 rpm and rotor speed n_p = 230 rpm.

As a result of the full-factorial experiment, interpolation formulas were developed, regression equations were derived, and response surfaces and contour graphs were constructed to characterize the impurity separation completeness (S_c) of the rotary potato harvester as a function of all combinations of key factors.

Based on the regression equations, response surfaces, and contour graphs, rational operating ranges for the rotary root crop harvester were determined V_m = 1.1...1.4 m/s, n_b = 300...330 rpm, and n_p = 230...250 rpm, which ensure maximum impurity separation (S_c = 94.0%).

It was also established that reducing energy consumption during the operation of the rotary working organ is achieved by correctly adjusting the torque, which reduces the load on the machine and lowers fuel consumption. This has important economic significance for agricultural enterprises, where efficiency and cost reduction are priorities.

The practical value of the obtained results lies in their potential application for improving the design of potato harvesting machines, leading to increased productivity, economic efficiency, and a reduction in technical and energy costs.

The prospects for further research include the development of new materials for manufacturing the working organs to ensure increased wear and mechanical damage resistance. Furthermore, additional studies on adapting the working organs to various agronomic conditions should be conducted, which will allow achieving even greater results in the harvesting of root crops.

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ДОСЛІДЖЕННЯ ОСНОВНИХ КОНСТРУКТИВНИХ ХАРАКТЕРИСТИК РОТОРНОГО РОБОЧОГО ОРГАНУ МАШИНИ ДЛЯ ЗБИРАННЯ КОРЕНЕПЛОДІВ ТА БУЛЬБОПЛОДІВ

Удосконалення технічного оснащення для збирання коренеплодів і бульбоплодів залишається одним із ключових завдань сучасної агроінженерії. Це зумовлено потребою інтенсифікації виробництва, підвищення енергоефективності та зменшення механічних пошкоджень зібраної продукції. Вирішальна роль у цьому процесі належить роторному робочому органу, який безпосередньо взаємодіє з ґрунтом і забезпечує вилучення врожаю.

Метою цього дослідження є обґрунтування та визначення оптимальних конструктивних і технологічних параметрів роторного робочого органу, що впливають на повноту вилучення продукції, ефективність сепарації ґрунту, рівень пошкодження бульб і енергоємність процесу. Дослідження поєднує теоретичний аналіз, CAD/CAE-моделювання напружено-деформованого стану, DEM-моделювання руху частинок ґрунту та бульб, а також лабораторні випробування у ґрунтовому каналі за різних типів ґрунту та рівнів вологості. Також було проведено порівняльний аналіз вітчизняних і зарубіжних збиральних машин.

Основними досліджуваними параметрами були кількість, геометрія та розташування лопатей ротора, профіль захоплювальної поверхні, кут нахилу робочого органу, а також співвідношення між поступальною швидкістю машини та частотою обертання ротора.

Результати показали, що найефективнішою конструкцією є роторний робочий орган із чотирма спіральними лопатями. Теоретичні й експериментальні дослідження підтвердили, що встановлення лопатей під кутом 25° до горизонталі забезпечує плавне входження в ґрунт, зменшує лобовий опір і покращує розподіл навантаження. Така конфігурація зменшила механічні пошкодження бульб на 18 % порівняно з пасивними та дисковими робочими органами. Оптимальною частотою обертання ротора визначено 120 об/хв, що забезпечує баланс між продуктивністю, якістю сепарації ґрунту та енергоефективністю.

Практична цінність роботи полягає в розробленні інженерних рекомендацій щодо вдосконалення машин для збирання коренеплодів і бульбоплодів, зменшення втрат урожаю та підвищення надійності машин.

Ключові слова: *роторний робочий орган, конструктивні параметри, корензбиральна машина, коренеплоди, бульбоплоди, викопування, збирання, картопля, буряк.*

Ф. 5. Рис. 7. Літ. 29.

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