



## EXPERIMENTAL RESEARCH INTO OPERATION OF POTATO HARVESTER WITH ROTARY TOOL

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**ABSTRACT.** The experimental research was carried out on a specially designed laboratory-and-field test unit with the use of a hydraulic vertical rotor drive and strain-gauge equipment mounted on a tractor as well as the set of interchangeable coupling pieces for setting the machine's operating duty. Research into the process of breaking two adjacent potato row beds with the vanes of a vertical rotor has been undertaken. A design and process schematic model has been proposed for the operation of the potato harvester. Experimental research into the geometrical parameters of the potato row has been carried out to select the design parameters of potato harvesters. Based on the results obtained during the experimental investigations, the rational ranges have been established for the work process of the rotary potato harvester, the methods of engineering clod breaking tools have been developed. Following the completion of the full factorial experiment, regression functions have been generated. Their analysis has proved that the following factors have the greatest impact on the optimisation parameters: the rotor diameter and the clearance between the rotor and the spherical discs. The following parameters have been optimised based on the response surface analysis: soil separation ratio  $S = 93.5\%$ , tuber damage rate  $P_b = 0.97\%$ , total power consumption by unit operation  $N_a = 18.27$  kW, at the following pre-set values of the factors:  $n_p = 77$  min<sup>-1</sup>,  $V_m = 2.2$  m·s<sup>-1</sup>,  $d_p = 0.825$  m,  $l_2 = 0.3$  m. The maximum discrepancy between the results of the theoretical and experimental investigations for determining the design and process parameters of the potato harvester does not exceed 15%. The completed economic testing has proved the advantages of the experimental potato harvester as compared to the existing ones. That said, the separation ratio of the pilot machine is equal to  $S = 91.4\%$ , which is 23% higher than in the reference case, while its tuber damage rate is equal to 1.14%, which is 5.0% better than in the reference case. The recommendations for the selection of the rational operation duty of the rotary potato harvester as well as the methods for the engineering analysis of the design and process parameters of clod breaking tools have been developed.



## Introduction

Harvesting is one of the most complicated and energy-intensive process operations in the potato production structure (Wang *et al.* 2017; Xin, Liang, 2017). The quality, with which this operation is performed, has a significant impact on the labour intensity of the following operations and the storage life of the obtained product (Wei *et al.*, 2019a; Gulati, Singh, 2019). As distinct from many other crops, harvesting the ripe potatoes requires lifting soil slices of great volumes and then separating the tubers from the soil, achieving the cleanness rate in the combined unit hopper of at least 80% and the damage rate not exceeding 3% (Hevko *et al.*, 2016; Wei *et al.*, 2017; Bulgakov *et al.*, 2018).

When potatoes are cultivated in heavy loam soils, which are prone to compacting during tillage, by the time of harvesting, when the potato harvesters lift tuber-bearing soil slices, a great amount of clods is formed and these clods cannot be removed by the separating tools of the combined unit (Petrov, 2004, Kheiry *et al.*, 2018, Pshechenkov *et al.*, 2018; Wei *et al.*, 2019b).

In that case, the soil content in the potato heap arriving at the hopper exceeds 20%, which does not meet the agronomical standards. Because of the above-said, the industrially produced potato harvesters are capable of operating only on sandy, sandy loam and medium grain-size composition soils with optimal moisture contents. When operating on heavy loam soils, the potato heap cleanness rate does not exceed 55–74%, while the tuber damage rate varies within the range of 18–25% (Lü *et al.*, 2015; Bulgakov *et al.*, 2018; Ruzhylo *et al.* 2020).

That complicates the process of potato heap classification and makes it necessary for the farm businesses to use manual labour extensively in the harvesting operations, which significantly increases the production cost of the final output. All efforts before potato harvesting have to be focused on loosening the tuber-bearing soil slice structure, removing hard clods from it and establishing the conditions that provide for essentially reducing the arrival of the soil impurities sized commensurate with potato tubers to the potato harvester separating tools. Meeting these conditions will facilitate raising the efficiency of the use of combined units on heavy soils and reducing the potato tuber loss and damage rates (Bulgakov *et al.*, 2019).

After analysing the known designs of clod breaking tools as well as the results of the research into their operation (Misener, McLeod, 1989; Ruyschaert *et al.* 2006; Bishop *et al.* 2012; Ichiki *et al.* 2013; Lü *et al.*, 2017), it becomes obvious that it is necessary to explore the agronomical characteristics of the operation of such tools. Among the reviewed potato harvesters, the greatest attention is to be paid to rotary-type tools (Petrov, 2004). The analysis of the operation of finger and vane beaters has proved that it is a most promising direction to design the clod breaking devices, in which the tools produce an increased impact on the tuber-

bearing soil slice at the initial stage of the work process, at the same time taking into account the tuber damage rate (Brook, 1993; Blahovec, Židova, 2004; Gao *et al.*, 2011; Feng *et al.*, 2017; Bulgakov *et al.*, 2018; Issa *et al.*, 2020).

The experimental research into the operation of the rotary potato harvester has to find out the impact that different factors (shape and type of the rotary tool, machine's translational motion velocity, rotation frequency of the rotor, type and properties of the soil) have on the performance indices of the machine, such as the soil separation ratio, the tuber damage rate, the tuber-bearing heap distribution pattern on the raddle chain (Feller *et al.*, 1987).

The relevancy of carrying out the experimental research is proved by the absence in the available publications of any data on the investigation of the main parameters and operation duties of rotary tools as well as the data that would specify the efficiency of their operation in the vertical position in the inter-row spacing between two adjacent potato rows.

Taking into account the above-mentioned circumstances, the following targets were included in the experimental research programme:

- to explore the relations and patterns observed in the process of breaking clods in the potato row by the vanes of the vertical rotor and justify the positioning of spherical discs relative to the rotor as well as the other design and kinematic parameters of the machine's clod breaking tools;
- to determine experimentally the effect of the machine translation velocity, rotor rotation frequency, rotor diameter, spherical disc positioning, soil type and properties on the potato harvester's performance;
- to determine the tractive resistance of the experimental unit and the total power consumed in the work process;
- to test the operating efficiency of the vertical rotor on the soil contaminated with stones and plant debris;
- to carry out the comparative analysis of the economic and energy efficiency in the operation of the experimental unit and the commercial potato harvester KST-1.4.

The following tasks had to be performed to fulfil the above programme of experimental investigations:

- developing the techniques for carrying out individual stages of research;
- selecting the needed standard equipment;
- engineering and manufacturing the laboratory-and-field test unit;
- producing the necessary quantity of accessory parts for the performance of experiments;
- designing and manufacturing the equipment for the vertical rotor hydraulic drive installation as well as the calibration instruments;
- carrying out the calibration of measuring tools;

– organising the performance of the investigations following the experiment planning procedure and the processing of research results.

The research aimed to study the influence of the rational design, process and energetic parameters for clod crushing tools in the rotary-type potato harvester to improve its separating capacity.

### Materials and methods

The method of experimental investigations was developed regarding the GOST 28713-90 and the RD 10.8.5-89 "Testing of agricultural machinery". To carry out the experimental investigations, it was necessary to arrange the monitoring of the work process performance utilizing measurements. That said, the performance of the overall research was divided into two phases: exploratory tests and main experiments.

The exploratory tests were carried out after the following design:

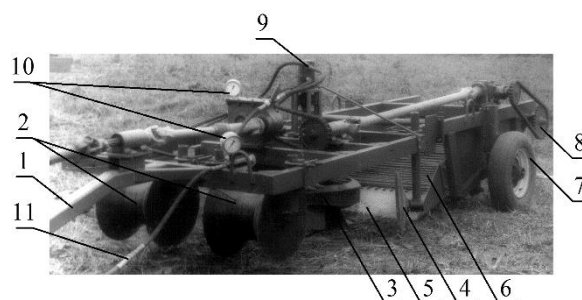
- determining the factors that have an effect on the process of soil separation and clod breaking by the vertical rotor in conjunction with the spherical discs and the riddle chain, i.e. selection of main factors;
- determining the effect the main factors have on the performance of the work process of breaking clods in the potato row bed;
- partially checking the testing method and conditions;
- checking the devices concerning the testing conditions;
- determining the data needed to calculate the number of experiments.

The exploratory tests do not provide for fully discovering the relations in the performance of the work process. They can be applied during the development of the research method, during the research or after it.

To carry out the exploratory and main tests, it was necessary to produce a pilot unit with an assortment of accessory parts, a set of measuring devices, strain-gauge equipment (Bulgakov *et al.*, 2021).

With provision for the above programme of experimental investigations, to explore the performance of the rotary tool operating in combination with the spherical discs and riddle chain, the experimental unit is shown in Fig. 1 and described further was designed and produced.

Frame 1 is used for mounting the components and mechanisms and comprises two parts: main and auxiliary. The main part of the frame carries the following components: depth rollers, vertical rotor, spherical discs and hydraulic drive. The auxiliary part of the frame carries a solid share, riddle chain, carrying wheels, which could be mounted on the main part of the frame. The depth rollers 2 mounted in the forepart of the unit are simultaneously the feeling and carrying members, which allow adjusting the depth of processing.

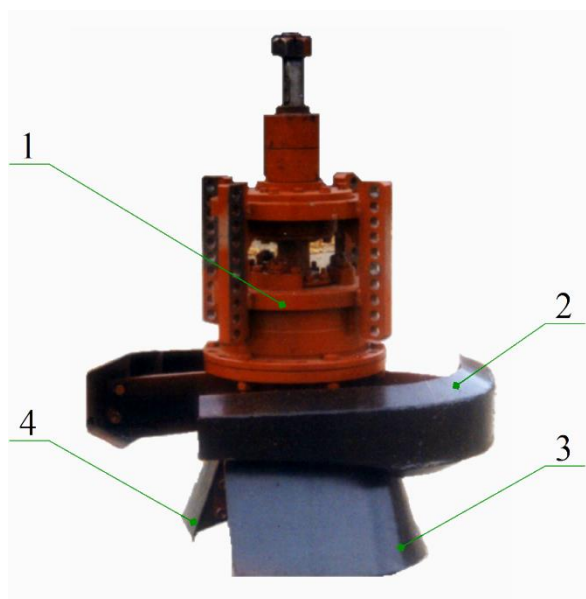


**Figure 1.** Field experiment unit for research into the operation of new potato harvester (the unit comprises the following components: frame 1, depth rollers 2, vertical rotor 3, spherical discs 4, solid share 5, riddle chain 6, carrying wheels 7, jolting device 8, vertical rotor hydraulic drive 9, pressure gauge 10, connection hoses 11)

The spherical discs 4 positioned at the angle of attack relative to the machine's line of travel overturn the two potato row beds broken by the vertical rotor towards the inter-row spacing centreline, thus forming the windrow to be picked up by the solid share 5.

The riddle chain 6 operates together with the jolting device 8 providing for the dispersion of the broken tuber-bearing soil slice and the separation of the tubers from the soil, the latter being then thrown off onto the field surface. It is to be noted that the travel rate of the conveyor belt and the amplitude of its jolting are equal to those of the conventional potato harvester riddle chains (Lovkis, 1991; Misener, McMillan, 1996). The carrying wheels 7 are used for adjusting the running depth of the unit's tools as well as for its transportation.

The vertical rotor 3 mounted on the centreline of the machine is used for breaking the two adjacent potato row beds by shifting them away from the inter-row spacing centreline, in order to disintegrate the soil clods. It is shown in more detail in Fig. 2.



**Figure 2.** Vertical rotor: 1 – planetary reduction gear, 2 – upper beater, 3 – lower beater, 4 – disk blade

The design of the vertical rotor is as follows. The top-mounted planetary reduction gear 1 changes the senses of rotation of the upper 2 and lower 3 beaters that rotate at different angular velocities with a reduction ratio of 2.39. The upper beater 2 and the lower beater 3 each feature two curved vanes. The vanes of the lower beater have a cone-shaped surface with the offset radius facilitating the smooth penetration and disintegration of the lower layer of the potato row. The vanes of the upper beater have a cylinder-like surface with the offset radius and change the direction of motion of the tuber-bearing soil slice broken by the lower beater. The disk blade 4 of the vertical rotor provides for the uniform penetration and smooth motion of the vertical rotor.

The tools in the pilot unit can be driven by the tractor's power take-off (PTO) shaft, so by its hydraulic system. In particular, an MGP-160 hydraulic motor has been installed for driving the vertical rotor.

The power transmission comprises a reduction gear, two transmission gears, three transmission shafts, a universal-joint drive, a V-belt drive and a chain gear.

After selecting the main factors, in the second phase of research, the experiments had to be carried out. For that purpose, it was necessary to prepare the design of a full factorial experiment  $2^n$ .

The measurement results were recorded in the test log, then processed with the use of the mathematical statistics methods (Brandt, 2014).

As is known, it is necessary to change during the experiments the machine's operating duty as well as the geometric parameters of its tools. Therefore, the rotor rotation frequency was changed with the use of a flow metering valve, the machine translation velocity – by shifting the tractor's gears, the rotor diameter – with the use of the assortment of accessory connection plates for the vanes of the lower and upper beaters, as shown in Fig. 3 and 4.

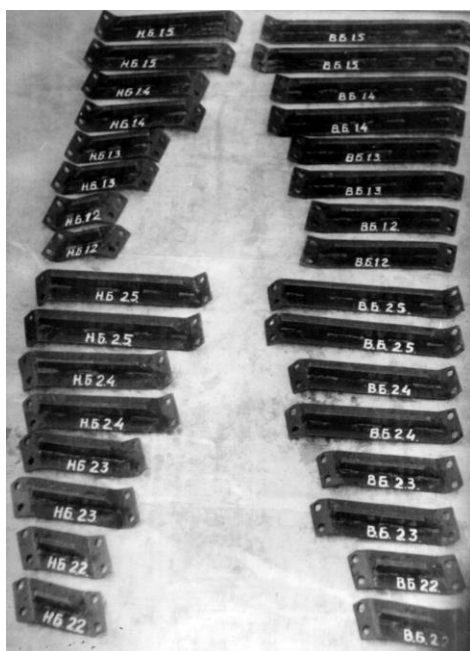


Figure 3. Assortment of accessory connection plates for vertical rotor

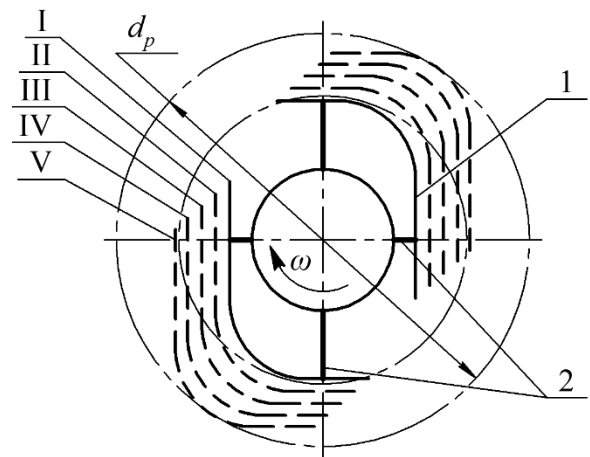


Figure 4. Schematic model of changing rotor diameter with the use of connection plates: 1 – rotor vane; 2 – connection plate

The spherical discs were mounted on the frame of the experimental unit and positioned in the longitudinal and transverse directions with the use of special brackets fastened with clamps (Fig. 5).

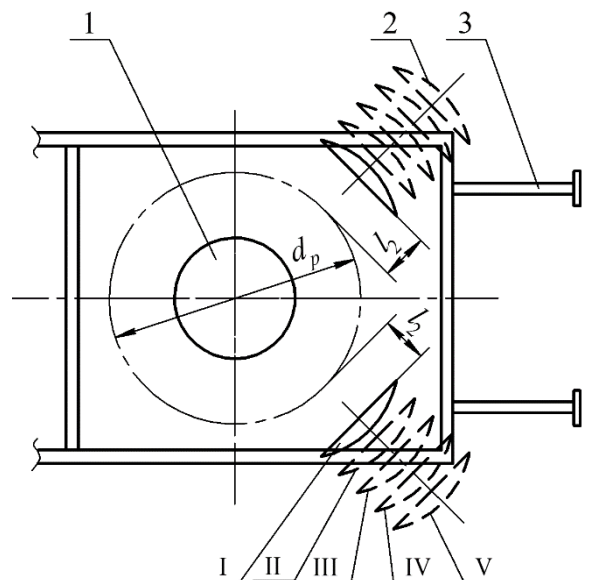
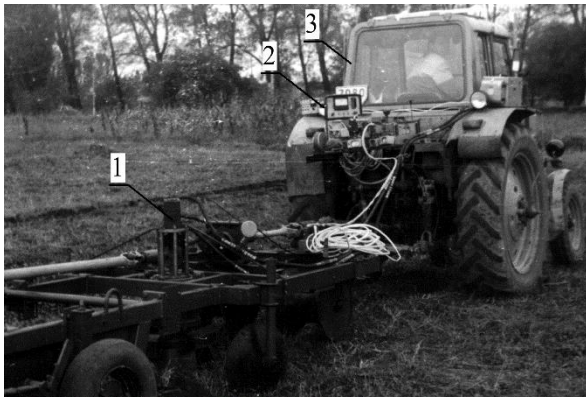


Figure 5. Schematic model of positioning spherical discs on experimental unit's frame: 1 – vertical rotor; 2 – spherical disc; 3 – frame

To determine the main relations between the performance indices and provide for the objective analysis of the experimental data, it was necessary to define the conditions for carrying out the research (Fig. 6).

Using the equipment installed in the tractor's cabin, the above-listed parameters, except for the tractive resistance, were synchronously recorded on the oscillograph tape. The traction resistance of the experimental unit was measured by the strain-gauge installation mounted in the rear part of the tractor's cabin.



**Figure 6.** Experimental unit with strain-gauge equipment during measurement of energy characteristics: 1 – experimental unit; 2 – strain-gauge equipment; 3 – carrying tractor MTZ-80

The experimental investigations were carried out taking into account the following analytic relations.

The hydraulic moment on the vertical rotor is equal to:

$$M_p = q_M \Delta P \eta_{g.g.} \frac{1}{2\pi}, \quad (1)$$

where  $q_M$  – constant of the hydraulic motor ( $\text{cm}^3 \text{rev}^{-1}$ );  $\Delta P = P_n - P_d$  – pressure drop on the hydraulic motor (MPa);

$\eta_{g.g.}$  – mechanical efficiency of the hydraulic motor.

Angular velocity of the rotor is equal to:

$$\omega = \frac{\pi n_p}{30}, \quad (2)$$

where  $n_p$  – rotation frequency of the rotor (according to the oscillogram)

$$n = \frac{60 K_0}{\Delta t n_0}, \quad (3)$$

where  $K_0$  – number of revolution marks on the oscillogram;

$\Delta t$  – time-division value on the oscillogram;

$n_0$  – number of time marks on the oscillogram.

The power rating of the rotor drive is equal to:

For the soil separation ratio  $S$ :

$$y_1 = 91.39 + 1.13x_1 + 2.06x_4 + 0.281x_1x_2 + 0.219x_2x_4 - 0.344x_3x_4 - 1.003x_1^2 - 1.288x_2^2 - 0.553x_3^2 - 0.445x_4^2 \quad (6)$$

For the tuber damage rate  $P_b$ :

$$y_2 = 2.159 - 0.557x_1 - 0.593x_2 + 0.245x_3 + 0.584x_4 - 0.258x_2x_4 + 0.108x_1^2 + 0.138x_3^2 \quad (7)$$

For the total power consumption by the unit operation  $N_a$ :

$$y_3 = 17.24 + 1.934x_2 - 0.813x_3 + 0.33x_4 + 0.625x_1x_3 + 0.813x_1x_4 + 0.275x_3x_4 - 1.72x_2^2 - 1.02x_3^2 \quad (8)$$

After a transition from the encoded form of the regression equations to the natural one, the following equations were obtained for each of the optimisation parameters, respectively:

$$N_p = M_i \omega_i, \quad (4)$$

Total power consumption by the experimental unit operation is equal to:

$$N_a = R_a V_m + N_p + N_{PTO}, \quad (5)$$

where  $R_a$  – tractive resistance of the unit (kN);  $N_{PTO}$  – power consumption by the tractor's power take-off shaft (kW).

## Results

### Design and operating parameters

Following the programme and methods of experimental investigations, to obtain reliable and full information about the process under consideration, the main experiments were carried out following the method of full factorial orthogonal central-composition planning.

After carrying out the theoretical analysis and exploratory screening tests, the following parameters had been identified as those having the greatest effect on the performance of the work process: machine translation speed  $V_m$ , rotor rotation frequency  $n_p$ , rotor diameter  $d_p$ , the distance between the spherical discs and the rotor's diameter  $l_2$ . Thus, the main experiments had to be carried out as four-factor full factorial experiments  $2^4$ .

The soil separation ratio  $S$  and the tuber damage rate  $P_b$  were taken as the optimisation parameters that represented the quality of operation of the experimental unit. Simultaneously with the assessment of the machine's operation quality, the energy characteristics were estimated. For that purpose, the unit's tractive resistance  $R_a$  and the rotation moment on the rotor shaft  $M_p$  were measured with the use of the strain-gauge installation mounted on the tractor, then the total power consumption by the unit operation  $N_a$  was determined taking into account the power output at the tractor's PTO, which was equal to 6.25 kW (Bulgakov *et al.*, 2020). The numbers of measurements needed to ensure the target reliability of experiments were determined from the table by Brandt (2014). The number of experiment replications was equal to five.

After processing the experimental data to determine the effect of the above-mentioned factors on the optimisation parameters, the following three regression equations were obtained in the encoded form:

$$S = 26.418 + 108.179d_p + 0.135n_p + 4.496d_p V_m + 9.713V_m + 0.018V_m n_p + 0.092l_2 n_p + 7.866l_2 - 64.171d_p^2 - 4.912V_p^2 - 24.577l_2^2 - 0.00071n_p^2 \tag{9}$$

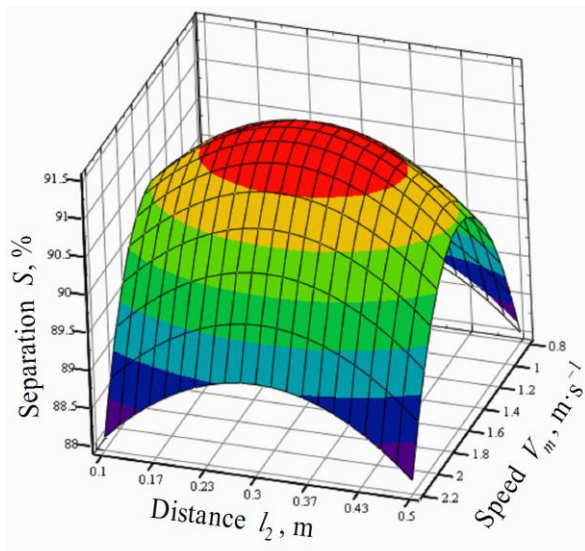
$$P_b = 8.308 - 15.861d_p + 0.362V_m - 2.047l_2 + 0.054n_p - 0.021V_m n_p + 6.912d_p^2 + 6.133l_2^2 \tag{10}$$

$$N_a = 18.511 + 24.508V_m - 11.22l - 0.223n_p + 33.333d_p l_2 - 29.511d_p + 0.26d_p n_p + 0.073l_2 n_p - 6.88V_m^2 - 45.333l_2^2 \tag{11}$$

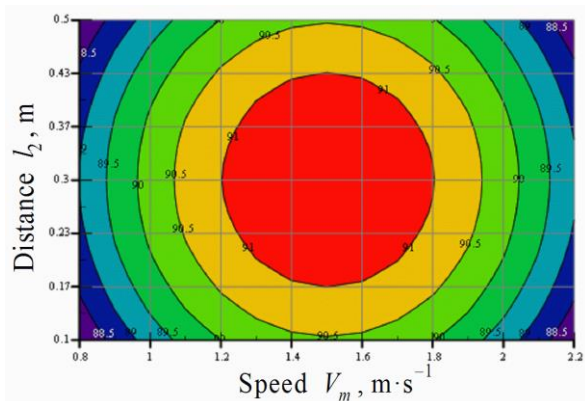
where 
$$x_1 = \frac{d_p - 0.825}{0.125}; \quad x_2 = \frac{V_m - 1.5}{0.5}; \quad x_3 = \frac{l_2 - 0.3}{0.15}; \quad x_4 = \frac{n_p - 75}{25}. \tag{12}$$

Testing the above relations by Fisher's ratio allowed us to state that the model adequacy hypothesis was not rejected at a significance level of 0.05.

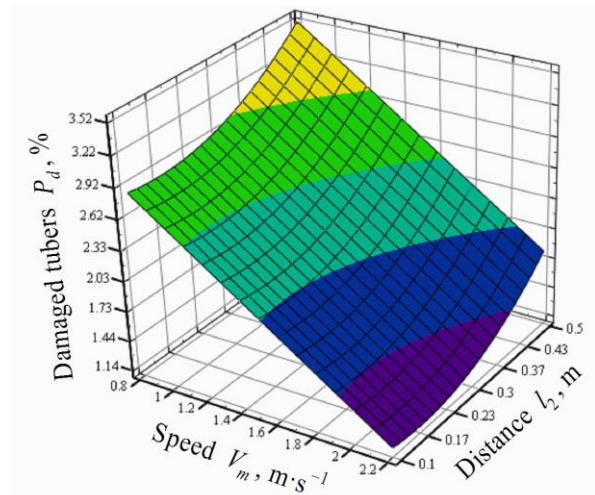
The obtained equations were analysed with the use of the path-of-steepest-ascent method applied on the PC in the MathCAD environment. For that purpose, two of the factors were fixed at pre-set values, while the other two were variable. The response surfaces for different cases and their analysis with fixed values of the factors of soil separation ratio  $S$  and tuber damage rate  $P_b$  are presented in Fig. 7–10.



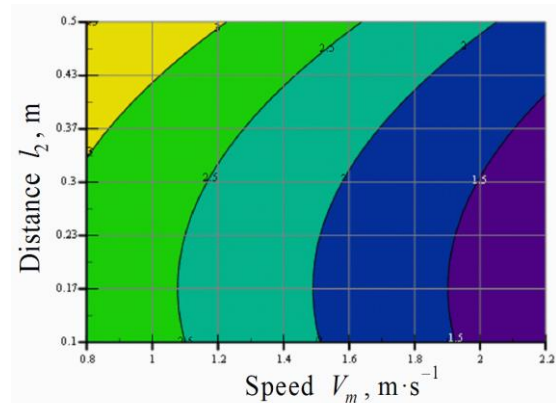
**Figure 7.** Relation between soil separation ratio  $S$ , on the one hand, and machine translation speed  $V_m$  and distance between rotor diameter and spherical discs  $l_2$ , on the other hand (at  $d = 0.825$  m,  $n_p = 75$  min<sup>-1</sup>)



**Figure 8.** Analysis of response surface for soil separation ratio  $S$



**Figure 9.** Relation between tuber damage rate  $P_b$ , on the one hand, and machine translation speed  $V_m$  and distance between rotor diameter and spherical discs  $l_2$ , on the other hand

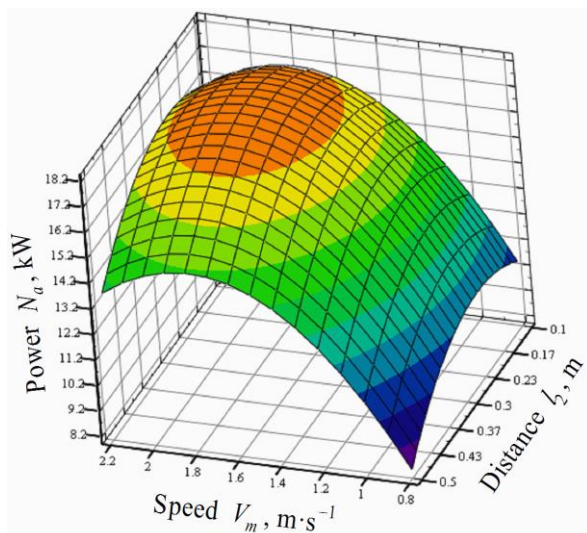


**Figure 10.** Analysis of response surface for tuber damage rate  $P_b$

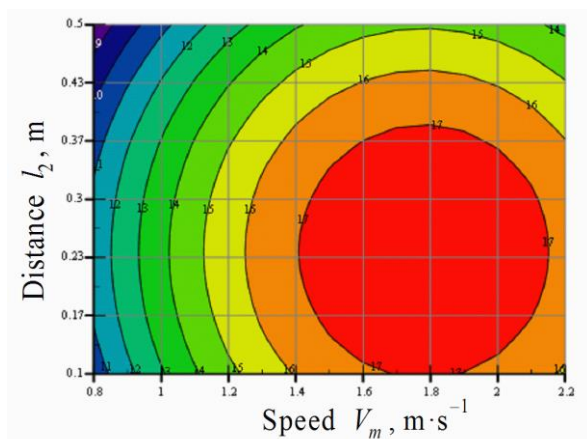
**Energetic parameters**

Following the method of research with the use of strain-gauge equipment, the following data were recorded: oil pressure in the pressure  $P_n$  and return  $P_z$  lines of the hydraulic rotor drive, rotor rotation frequency  $n_p$  as well as the tractive resistance of the experimental unit  $R_a$ . By the analytic relations described in the experiment procedure, the following parameters were determined: the rotor shaft rotation moment  $M_p$ , the power consumption by rotor drive  $N_p$ , as well as the power consumption by the unit operation  $N_a$  (Fig. 11, 12).

Basing on the analysis of response surfaces, the optimum value has been established for the total power consumption in the operation of the two-row tractor-hitched potato harvester developed by the authors. It is equal to  $N_a = 18.27$  kW at the following pre-set values of the other design and kinematic parameters:  $n_p = 77$  min<sup>-1</sup>,  $V_m = 2.2$  m·s<sup>-1</sup>,  $d_p = 0.825$  m,  $l_2 = 0.3$  m. That said, the maximum discrepancy between the results of the theoretical and experimental investigations does not exceed 15%..



**Figure 11.** Relation between total power consumption for unit operation  $N_a$ , on the one hand, and machine translation speed  $V_m$  and distance between rotor diameter and spherical discs  $l_2$ , on the other hand.



**Figure 12.** Analysis of response surface for total power consumption by unit operation  $N_a$

## Conclusions

1. In the completed exploratory tests, the factors that have the greatest effect on the performance of the potato harvester have been established: machine translation speed  $V_m$ , rotor rotation frequency  $n_p$ , rotor diameter  $d_p$ , the distance between the spherical discs and the rotor diameter  $l_2$ .

2. The working capacity of the machine has been established at different operating duties and the revealed deficiencies have been eliminated.

3. The main experiments have been carried out following the design of the full factorial experiment 2<sup>4</sup>. As a result, the rational design and process parameters of the potato harvester have been established.

4. The regression equations have been generated for the following three optimisation parameters: soil separation ratio  $S$ , tuber damage rate  $P_b$ , total power consumption by the unit operation  $N_a$ .

5. The response surfaces have been analysed with the use of the path-of-steepest-ascent method.

## Conflict of interest

The authors declare no conflict of interest, financial or otherwise.

## Author contributions

VB, YI – study conception and design;  
VB, JO – drafting of the manuscript;  
VB, VB, VM, JO, YI – analysis and interpretation of data;  
YI, ZR, AZ, VV – acquisition of data.  
JO – critical revision and approval of the final manuscript.

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