Improving the design of a root crop harvester in order to increase the sustainability of agriculture

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Abstract. Cultivating agricultural crops assumes the use of mechanical means to accelerate the performance of technical operations in a reasonable agrotechnical amount of time. Vegetable growing is one of the industries where it is necessary to use modern automated and robotized machinery. Technologies and technical means have been considered which are used in enterprises engaged in cultivating tuberous roots at the moment and the disadvantages have been revealed. As a result, a technology of harvesting tuberous roots has been proposed, which is based on the use of the combine-harvester developed. The design solutions of the combine-harvester have been considered, which allow to solve the problem of the vegetable growers, and the technical process of harvesting tuberous roots has been described. The substantiation of a drum cutter bar has been presented and the coefficient of chaff feed to the transporter, the traction force of the conveyor motion and the power at the drive of the chain slatted conveyors have been determined. As a result of the researches carried out, it was determined that the use of the combine-harvester for tuberous roots shall allow to increase the level of mechanization and the productivity at enterprises, which are engaged in cultivating vegetable crops.

1. Introduction
Harvesting tuberous roots continues remaining the most labour-intensive operation in the cultivation technology nowadays, as tuberous roots are in the soil. A combine-harvester must extract tuberous roots out of a soil layer by simultaneously performing the destruction and separation of the soil from the harvest and using technical solutions. Because the technical process of separation of tuberous roots from a soil layer is energy-consuming due to their low content volume of 1…3% [1], it follows thence that a combine-harvester must undercut, separate and extract up to 200 kg of soil per one second in order to extract 4…6 kg of tuberous roots from the soil. One should herewith take into account that the capabilities of the separating mechanisms of combine-harvesters are limited by the dimensions and strength properties of tuberous roots [2]. The separation of tubers from the soil is negatively influenced by the tops, which must be cut before digging out the tuberous roots and removed from the separating workign tools. Large tubers (with the weight exceeding 200 g) and those having a prolonged shape are damaged more when being separated.
The process of harvesting tuberous roots comprises the following operations: removal of the tops a few weeks before harvesting, extraction of the tuberous roots from the soil and their separation from it, and loading into a means of transport to move the harvest to the place of its sorting and storage.

In dependance to a technology used to cultivate tuberous roots, harvesting is finished by loading the harvest into storage facilities (the in-line technology) or placing the harvest into temporary storage clamps and then to a sorting station with its dispatch for storage [2].

The time when one must start harvesting is determined by the ripeness of a tuber, the destination of the potatoes, and the condition of the culture. The start of combine-harvesting is the moment of the top necrosis. The air temperature during harvesting must be at least +5 °C and, simultaneously, it must be approximately +10 °C in the soil at the level where the tuberous roots are [3]. The humidity of the soil is of a great importance in the course of harvesting as it must be in the range of 10…15% in the sandy loam soils and 16…22% in the clay loam soils. The tops must be therewith removed before the beginning of harvesting down to the height of the stalks of 6…8 cm for combine-harvesting and, when the harvesting is performed by lifters, it must not exceed 20 cm in height. On studying the literature sources, it was found out that the maximum depth of location of tuberous roots is 22 cm and the width of their location in a row is at most 40 cm. [3].

By using the technology of combine-harvesting of tuberous roots, it is necessary to observe the agricultural requirements, which correspond with machine-harvesting: the losses after a combine-harvester must not exceed 2% on the surface and 1% of tuberous roots in the soil, the volume of admixtures, which get into the bunker, must not exceed the following parameters: the total number – 20%, the remains of the tops – 0.5%, and no more than 0.1% of other admixtures, including soil clods and remains of the root system, with mechanical damage to tuberous roots not exceeding the following values: up to 4% in medium and light soils and not more than 10% in those heavy and stony.

Notwithstanding a method of harvesting, the preharvest tops destruction is an obligatory operation. The underripe and developed green tops are exposed to desiccant treatment two weeks before the beginning of harvesting and, after their decay, they are destroyed mechanically [4]. The conventional technical means and technologies for harvesting potatoes do not meet the agricultural requirements presented and need modernizing and improvement.

2. Materials and methods
As a result of the analysis of modern technologies and technical means for harvesting tuberous roots carried out, a design of a combine-harvester for tuberous roots has been developed, which is set out in Figure 1. The design of the combine-harvester for tuberous roots consists of basic carrying frame 1 with disc knives 2 installed vertically at the front, which have the external dimensions corresponding to the condition of cutting through the superior layer down to the depth of location of tuberous roots. The disc knives are located between the rows of tuberous roots and fastened to bearing units. Shovels 3, which are connected to lower conveyor 4, are installed in the rear part of knives 2. The spaces in the row of the slats of conveyor 4 were selected based upon the requirement to prevent losses of tuberous roots and spillage of minor soil fractions. Conveyor 5 is placed upon chain slatted conveyor 4, the distance between its slats being based upon the criterion of avoiding losses of tuberous roots between the slats. Lower chain slatted conveyor 4 is mounted on frame 1. It is possible to change its inclination angle and horizontal plane through the use of degree axis 6. Upper chain slatted conveyor 5 is mounted on frame 5 on degree axis 7. Lower chain slatted conveyor 4 is mounted on frame 8, and upper chain slatted conveyor 5 is mounted on frame 9. Upper chain slatted conveyor 5 is provided with clod destructors 10, which are made of elastic material preventing injuries to roots. The slats of conveyors 4 and 5 are covered with elastic material. The drive of lower 4 and upper 5 chain slatted conveyors is made from reducer 11 through cardan drive 12 and power takeoff shaft of the tractor. Top mounted conveyor 5 is set in motion through reducer 11 from chain gearing 1, and conveyor 4, which is installed at the bottom after the shovel, is set in motion by the same reducer 11 by means of chain 14. The motion speed of conveyor 4 has lower velocity \( V_1 \) than that of conveyor 5 \( (V_2) \), which is mounted at the top. The upper and lower conveyors finish in the internal plane of drum type loading belt 15, which consists of circular
rods 16 and blades 17, which are installed in its internal part and grip and hold tuberous roots. The distance between circular rods 16 is preset therewith based upon the condition of avoiding creeping of tuberous roots into the gap between them.

Figure 1. The diagram of the design and technical operation process of the combine-harvester for tuberous roots.

Frame 1 of the combine-harvester for tuberous roots is installed on axes with pneumatic wheels 18.; a guide groove is mounted at the top, in drum type loading belt 15. The drive shaft of upper conveyor 5 is installed in the bearings of disc knives 2. Carrier 20 with the drum of the top cutter bar, which is fastened to it, is installed before frame 1.

Side shields 21 are installed on the sides of lower conveyor 4 with the purpose of reducing the descend of tuberous roots aside off it. Reducer 22 of the drive of the cutter bar is installed on carrier 20 though chain gearing 23. Cutter bar 25 with gauge wheels 26 is mounted on drawbars 24. Soil destroying rollers 27 with teeth, which are located in multiple-thread spiral lines, with the left and right threads, are installed in the upper part of shovel 3 before the coupling with the lower conveyor. Top pulverizer 25 is set in motion by means of hydraulic cylinder 28. Lug 29 of the hitch is used to connect the combine-harvester with the tractor.

Soil destructing rollers 27 are installed on carriers 30 by means of plain bearings 31 in hole 12 of cutting shovel 3.

The technical process of operation of the combine-harvester for tuberous roots runs as outlined below.

By travelling along a field lot where the process of harvesting takes place, top cutter bar 25 chops and scatters about the tops, which are cut along the field lot, the tops having been exposed to desiccant treatment two weeks before the beginning of harvesting.

Disc knives 2, which are installed in the spaces between the rows, cut through the surface of the soils below the depth of location of the tuberous roots, and allow to reduce the traction force of shovel 3, owing to the absence of resistance to the separation of a soil layer from the side walls. Shovel 3 separates a soil layer with tuberous roots in the horizontal plane and passes it to the soil destroying rollers 27, under the impact of which the soil crumbles, with tuberous roots being separated. It is gripped by upper chain slatted conveyor 5 and moved along cutting shovel 3 to lower chain slatted conveyor 4, which also considerably reduces the drawbar resistance of the combine-harvester. Soil destroying rollers 27
grind the layer and separate tuberous roots from it due to the different direction of the spiral lines of the teeth. When soil with tuberous roots moves along the lower chain slatted conveyor 4, upper chain slatted conveyor 5 provides grinding of the soil and separation of the tuberous roots from it owing to the difference between the motion speeds of the conveyor slats.

Clod destroyer 10 impacts the soil clods, which are difficult to destroy, in the incoming layer, thus improving the separation of the combine-harvester. The separated tuberous roots go to drum type loading belt 15 where, owing to its rotation, they get under the impact of holding blades 17 and get into the guide groove, by means of which loading of containers or means of transport is performed.

The use of top cutter bar 25 in the design allows to reduce the labor intensity of harvesting and improves the conditions for separating the soil and tuberous roots. The use of disc knives in the design proposed allows to considerably decrease the traction force of the combine-harvester for tuberous roots. The soil layer, which is undercut therewith by shovel 3, is then carried by upper conveyor 5 and this also contributes to a reduction in the traction force.

The use of upper conveyor 4 and lower 5 with different motion speeds of their runs improves the process of destruction of a soil layer and increases the quality of separation of tuberous roots from the incoming layer, which enhances the output of the combine harvester and its productivity.

3. Results and discussion

When substantiating the parameters of the cutter bar, angles of setting the knife blade $\gamma$, cutter angle $\varphi$ of the knife, and angle of cutting $\theta$ were considered, which are in the plane, which is perpendicular to the cutting plane, being therewith in the following relationship [5]

$$\theta = \varphi + \beta = 90 - \gamma, \quad (1)$$

$\gamma$ means the angle of setting the blade; it is the angle between its rear surface and the direction of cutting.

The knife of the cutter bar has one sided sharpening and it is set edge forward. It allows to support the constant clearance between the knife blades and the cross bar, which facilitates sharpening of the knives on the surface of the edges without removing them from the drum. [6, 7].

The normal course of the technical process of cutting requires deflection of the blade edge for angle $\gamma$ from the direction of cutting (Figure 2). This deflection is oriented to the side of movement of the material fed and prevents it from excessive friction on the blade edge.

$$tg\gamma = \frac{V_{mat}}{V_{knife}}, \quad (2)$$

where $V_{mat}$ means the velocity of the tops feed; $V_{knife}$ means the knife speed.

The reaction of the cutting force of the tops of tuberous roots, which is applied to the knife blade edge, is deflected from the line of the angle of cutting for angle $\psi$ [8]

$$\psi = \gamma + \frac{\beta}{2}, \quad (3)$$

where $\beta$ means the angle of blade sharpening.

Top cutting force $P_{cut}$ can be distributed into the following elements: normal $P_n$, which is directed along the line of angle of sharpening $\theta$, and bending force $P_k$, which is perpendicular to it [9]

$$P_n = P_{cut} \cos \left(\gamma + \frac{\beta}{2}\right), \quad (4)$$

$$P_k = P_{cut} \sin \left(\gamma + \frac{\beta}{2}\right), \quad (5)$$
Figure 2. The diagram to substantiate the angles of fastening the knife in the top cutter bar.

The apex of the blade bends under the impact of bending stress $P_k$ and breaks off in a certain section thereof at distance $\ell$ from the cutting edge of the blade [10]. Bending moment $M$ of stress $P_k$ in the section shall be

$$M = P_k \cdot \ell. \tag{6}$$

The bending strain of the cutting edge can be written in this section as:

$$\sigma_l = \frac{P_k \ell}{bh^2} = \frac{6 P_k \ell}{h^2}, \tag{7}$$

where $b$ means the blade length, m. $h$ means the blade thickness in the section, m.

Value $\ell$ defines by itself the place of the point of fracture of the knife tip, it is proportional to bending stress $P_k$ and inversely proportional to allowable stress $\sigma_u$.

The blade thickness is determined by the formula:

$$\delta = \frac{3 P_k}{\sigma_l} \left(1 + \frac{1}{\sin \frac{B_0}{T}}\right). \tag{8}$$

It is necessary to use value $\Theta$ of the return of the rear knife edge $\Theta = t g \gamma B_0$ for the drum cutter bar, where $B_0 = \frac{B}{\cos \tau}$ means the section of the knife width in the plane, which is perpendicular to the axis of the top chopping drum:

Then $B$ means the knife width, m.; $\tau$ - means the gliding angle of the knife.

It is necessary to prevent the knife, which moves in the plane, from bumping so that its rear plane should be at a certain distance from the cylindric generatrix, which is described by the blades. It requires fastening of the knife blade at angle $\alpha$

$$\cos \alpha = \frac{r^2 + B_o^2 - (r + B_o t g y)^2}{2rB_o} \tag{9}$$

The angle of fastening of chopping knife $\gamma_\delta$ for the cutter bar of the combine-harvester for tuberous roots can be found from the difference between the angles of the rear plane of the knife and the tangent line, which forms a cylinder in the apex of the blade. [11].

$$\gamma_\delta = 90 - \alpha. \tag{10}$$

It has been experimentally established that the value of clearance between the blades of the cutting couple influences the process energetics and the quality of cutting off and chopping.

An empirical dependence has been established between specific work of cutting $A_{sp}$ and clearance $\Delta$.

$$A_{sp} = k \Delta^m + c, \tag{11}$$

where $k$, $m$ and $c$ mean the coefficients for potato tops; $k = 0.0735$, $m = 1.46$, and $c = 3$. 
The soil destroyed is gripped from the tuberous roots by the chain slatted conveyor and moved to digging shovel 3.

The productivity per hour can be determined by formula [12]

$$Y = \frac{3600 q_{tot}v}{1000} = 3.6 \ q_{tot} \cdot v \ (m^3/h),$$  \(12\)

where $q_{tot}$ means the average quantity of load per unit of length of a load-bearing element; $v$ means the motion speed.

Or by the adjusted formula:

$$v = h \ b \ p \ v k,$$  \(13\)

where $h$ means the size of the soil chaff to move, m; $b$ means the width of the moving conveyor, m; $p$ means the thickness of the soil chaff, kg/m$^2$; $v$ means velocity of the conveyor, m/s; $k$ means the feed coefficient of chaff soil to the conveyor.

In order to determine the coefficient of chaff feed to the conveyor, let us use the following formula:

$$k = k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot k_5,$$  \(14\)

where $k_1$ means the filling factor ($k_1 = 0.5$); $k_2$ means the coefficient, which considers thickening of the chaff when it is moved ($k_2 = 1.13$); $k_3$ means the velocity coefficient ($k_3 = 0.9\ldots0.95$); $k_4$ means the coefficient, which considers the volume, which is taken up by the chain and the slats ($k_4 = 0.97$); $k_5$ means the coefficient, which considers the angle of inclination of the inclined conveyor ($k_5 = 0.8\ldots0.9$).

The traction force, $N$, of the conveyor motion can be determined by the following formula:

$$P = P_1 + P_2 + P_3 + P_4 + P_5,$$  \(15\)

where $P_1$ means the resistance from friction of the chaff on the soil layer with tuberous roots, which is moved, $N$; $P_2$ means the resistance from friction of the chaff on the side walls; $P_3$ means the resistance from lifting the chaff by the inclined conveyor; $P_4$ means the resistance from the motion of the conveyor chain, $H$; $P_5$ means the resistance from the motion of the chaff in the direction towards the unloading to the drum conveyor, $N$ [13].

The resistance from friction of the chaff on the soil layer with tuberous roots, which is moved, $N$

$$P_1 = h \cdot b \cdot \ell \cdot g \cdot c \cdot \cos \beta,$$  \(16\)

where $\ell$ means the way made by the chaff, m; $g$ means the free fall acceleration ($g = 9.81$ m/s$^2$); $f$ means the coefficient of soil-on-soil friction; $\beta$ - means the angle of installation of the inclined conveyor, degree.

The resistance from chaff friction on the side walls of the fencing bords:

$$P_2 = h_2 \cdot p \cdot g \cdot \ell \cdot f \cdot \zeta \cdot \cos \beta,$$  \(17\)

where $\zeta$ means the coefficient of lateral pressure, which is equal to

$$\zeta = \psi \left(1 + f_m - \sqrt{(1 + f_m^2)(f_m + f^2)} - f_m \left(\sqrt{(1 + f_m^2)} - \sqrt{f_m^2 + f^2}\right)\right),$$  \(18\)

where $\psi$ means the dynamic coefficient ($1.5\ldots1.8$); $f_m$ means the coefficient of internal friction in the chaff.

The effort spent on lifting the chaff by the inclined conveyor, $N$

$$P_3 = h \cdot b \cdot \ell \cdot g \cdot \sin \beta.$$  \(19\)

The resistance to the motion of the chains of the empty conveyor, $N$

$$P_4 = 2 \cdot g_c \cdot l_0 \cdot \cos \beta,$$  \(20\)

where $g_c$ means the specific force of gravity of 1 m of the chains with slats, N/m; $l_0$ means the distance between the axes of the chain-wheels, m.

The resistance of the chaff, which is moved by the drum conveyor, $N$

$$P_5 = 0.25 P_4.$$  \(21\)

The power at the drive of the chain slatted conveyors, kW,

$$N = k P v / (102 \ \eta_t),$$  \(22\)

where $k$ means the coefficient, which provides for the tensile force of the chain of the drive chain-wheel ($k = 1.1$); $\eta_t$ - means the efficiency of the gearing.
4. Conclusion
The use of the technology and design of the combine-harvester for tuberous roots developed will allow to increase the level of mechanization in enterprises, which are engaged in cultivating vegetable crops, up to 80%, reduce the energy consumption of harvesting down to 20% and enhance the labor productivity up to 50%.

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