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Theoretical study on motion of potato tuber on surface of separator

V. Bulgakov[1], S. Nikolaenko[1], Z. Ruzhylo[1], I. Fedosiy[1], J. Nowak[2] and J. Olt[3,*]

[1]National University of Life and Environmental Sciences of Ukraine, 15 Heroyiv Oborony Str., Kyiv, UA03041, Ukraine
[2]University of Life Sciences in Lublin, 13 Akademicka Str., 20-950 Lublin, Poland
[3]Estonian University of Life Sciences, Institute of Technology, 56 F.R. Kreutzwaldi Str., EE51006 Tartu, Estonia
[*]Correspondence: jyri.olt@emu.ee

Abstract. The aim of the study was to determine the optimal design and kinematic parameters of the separator that cleans potatoes from impurities and has a design of the spiral type. The authors have devised a highly efficient design of the spiral type potato heap separator, in which the motion of the potato tubers takes place in the channel formed by two spiral members made in the form of cylindrical spiral springs. In order to substantiate the optimal kinematic and design parameters of the new spiral type potato heap separator, the authors have generated a mathematical model of the motion of a single potato tuber on the cleaning surface formed by two spirals. As a result of solving the obtained analytical expressions, the graphical relations between the parameters of the investigated process of the motion of a single potato tuber body situated between two adjacent spirals have been plotted, which has enabled selecting the optimal design and kinematic parameters of the spiral separator. It has been established in the completed investigation that the angular velocity of rotation of the cleaning rolls has to be within the range of 27–40 rad s^{-1} in order to ensure the efficient transportation and cleaning of the potato tuber with a diameter of 50 mm that moves on the surface of the spiral with a radius of 75 mm wound from the round bar with a diameter of 15 mm, in case the spirals are mounted with an eccentricity of 10 mm. By analysing the kinematics of motion of the potato tuber on the surface of the spiral type cleaning machine, in case the tuber contacts the spirals at two points, it has been established that the increase of the angular velocity of rotation of the spirals results in the respective growth of the transportation capacity of the cleaning tool, while the separating efficiency at the same time becomes reduced to some extent.

Key words: cleaning, impurity, potato, quality, separator efficiency, spiral, transportation.

INTRODUCTION

In the process of harvesting potatoes, their cleaning from soil and plant impurities is a highly important problem, in view of the fact that the mechanical harvesting results in the removal of fertile soil from the fields together with the harvested potatoes.

This phenomenon is caused by the situation, where the harvesting of potatoes with the use of lifting tools involves undercutting and lifting tubers together with considerable volumes of soil bed, in which the potato tubers themselves can hold as little as 10%. As the moisture content in the soil in the harvesting period reaches sometimes 20%, it becomes a great hindrance to the efficient separation of soil from the potato tubers. Hence, the search for new engineering solutions aimed at the improvement of the potato heap cleaning at the stage of harvesting is a topical research and technology task.

In order to improve substantially the performance indices of the lifting and separating tools of potato harvesters, in particular, to improve the efficiency of separating the potato heap lifted from soil, the authors have developed a new design of the spiral potato heap separator (Fig. 1).

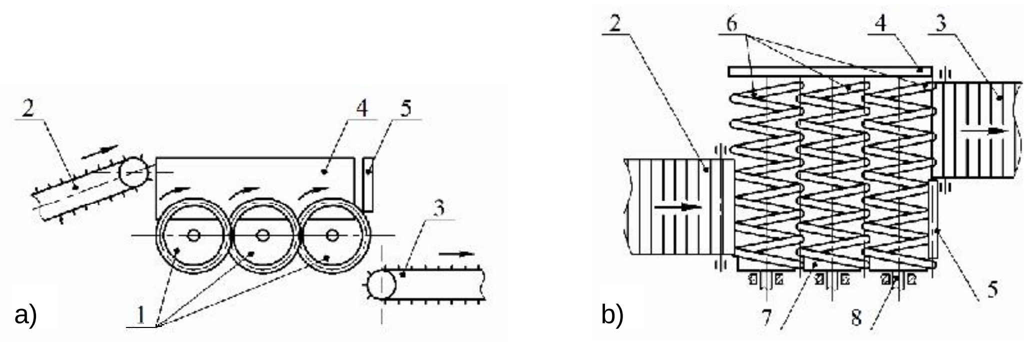


Figure 1. Structural layout of spiral potato heap separator: a – side view, b – top view; 1 – spirals; 2 – feeding conveyor; 3 – discharge conveyor; 4 – side protective apron; 5 – face protective apron; 7 – hub; 8 – drive shaft (Bulgakov et al., 2019).

The spiral potato heap separator comprises the three sequentially placed spirals 1, which form an even cleaning surface on top of them. The spirals 1 are installed as cantilevers in such a way that their first ends are fixed in the hubs 7 connected with the drive shafts 8, and their second ends overhang freely. At the same time, the spirals 1 are positioned with overlapping and the drive shafts 8 provide for their rotation at the same angular velocities and in the same sense. The feeding conveyor 2 leads to one of the sides of the above-mentioned cleaning surface, the discharge conveyor 3 starts at the opposite side. The side areas around the spirals 1 are covered with protective side apron 4 and face protective apron 5.

The spiral potato heap separator under consideration operates as follows. The feeding conveyor 4 continuously feeds the tuber-bearing bed lifted from the soil onto the cleaning surface formed by the three spirals 1. As a result of its fall from the small height, the soil bed with potato tubers disintegrates partially and spreads initially over the closest spiral 1, then proceeds to the other spirals 1. Since the spirals 1 are connected via the hubs 7 with the drive shafts 8, they rotate and entrain with their turns potato tuber bodies and soil clods and start transporting them both along the spirals' axes and along their radii. However, due to the large gaps (between the turns of each spiral 1 and spaces between the spirals 1), the smaller soil particles immediately sieve in considerable amounts down and outside of the separator.

The spiral potato heap separator comprises the several consecutively positioned power driven cleaning spiral rolls 1, which are designed as cantilever suspended spiral springs and form the cleaning surface, the feeding conveyor 2 positioned on the one side of it and the discharge conveyor 3 positioned on the other side. In order to prevent the loss of potato tuber bodies, the flat guard shield 4 is installed on the side of the free ends of the cantilevered spiral rolls 1, the flat guard shield 5 is installed beside the discharge conveyor 3. Each cleaning roll 1, that is, each spiral spring 6 is installed on the hub 7 connected with the drive shaft 8. The rotation of all the three spiral cleaning springs 6 actuated by the drive shafts 8 has the same sense, that is, in the direction towards the discharge conveyor 3.

In the proposed potato heap cleaning machine with power-driven cantilever spiral springs, there are openings with a significant area formed by the spaces between the own turns of the spirals and the spaces between the windings of adjacent spirals (Bulgakov et al., 2018a, 2018b, 2018c; 2019; Nowak et al., 2019). Due to that, the effective separation area (that is, the total area of all separating openings), in comparison with the total surface area, is significantly increased. Consequently, the machine's throughput capacity in the sieving of soil and plant impurities downwards, i.e. outside the separator, is also increased, which results in the improved quality indices of its operation.

Moreover, the absence of any shaft inside each cleaning spiral spring facilitates the unobstructed passage of all impurities downwards and also allows to avoid the undesirable wrapping of plant debris. The hollowness of the internal space in each spiral spring provides for a significant increase in the capacity of positively transporting the whole mass of soil and plant impurities that has entered the spring towards the outlet (cantilever) end of each spiral spring and dropping it through the free end face onto the surface of the field.

In order to prevent the soil caking on each separating roll and avoid the complete choking of the gaps between the spiral windings with wet soil, the rolls are installed with certain overlapping, that is, the turns of each roll partially enter the spaces between the turns of the adjacent roll.

The systems of cleaning tools used in potato combines and harvesters not always provide for a high level of the soil impurity separation (Petrov, 1984). The reduced quality of cleaning results most frequently from the heavy caking of wet soil on the surfaces of the cleaning tools. The engineering solutions based on the more active handling of the potato heap in the soil separation process have the increased level of tuber damage, which is an undesirable factor in view of the deteriorated consumer and storage qualities of the produced potatoes.

Therefore, the potato heap cleaning units not only have to deliver the reliable and high quality performance of the work process, but they also must clean themselves in the process of their operation. Obviously, the potato tuber damage has to be at the minimum level, if possible.

The problem of developing efficient and reliable potato heap cleaning units for the lifting stage as well as potato cleaning and grading machines for stationary potato-grading plants has been discussed in many papers (Petrov, 1984; Feller et, al., 1987; Misener & McLeod, 1989; Bishop et al., 2012; Ichiki et al., 2012; Guo & Campanella, 2017; Wang et al., 2017; Wei et al., 2017; Ye et al., 2017). However, despite the great variety of potato heap cleaning work processes used in the harvesting, the studies on the optimisation of the parameters and modes of operation of spiral separators that have been carried out by now are relatively few (Holland-Batt, 1989; Krause & Minkin, 2005).

The aim of the study was to determine the rational design and kinematic parameters for the spiral type unit that cleans potatoes from impurities.

MATERIALS AND METHODS

The movement of a potato tuber on the surface of the cleaning spiral spring takes place due to the pressure of the mass behind it, which is continuously fed to the cleaning unit. In order to ensure the uninterrupted progress of the separation process and avoid jamming, the bed of potato tubers along the length of the spiral tool has to have a thickness of one tuber.

The background experimental and theoretical research into the motion of a body on the surface of the spiral potato heap cleaning unit carried out by the authors suggests that, in order to describe the interaction between the body and the working surface of the cleaning spiral, it is necessary to analyse the relative motion of the single potato tuber as a solid body, which is approximated by the body that has a shape close to spherical (Peters, 1997). The equivalent schematic model devised by the authors (Fig. 2) features the said body situated on the surface of the spiral cleaning spring with a radius of R and an angle of helix of γ. The body has its own radius of R_K. It is assumed that to a first approximation the initial velocity of the body under consideration, that is, the initial velocity of the potato tuber, when it arrives onto the surface of the spiral cleaning spring in the machine for cleaning the potato heap from impurities, is equal to zero.

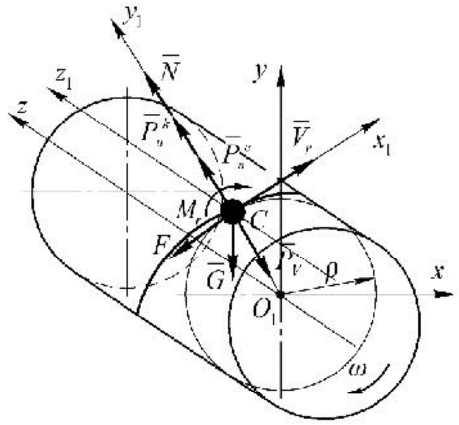


Figure 2. Equivalent schematic model of motion of potato tuber on surface of spiral cleaning spring.

At the same time, the body (potato tuber) is under the action of the following forces shown in the equivalent schematic model:

$G = mg$ – force of gravity of the potato tuber with a mass of m, which rotates together with the moving system of coordinates at an angular velocity of ω;

$\bar{N}$– force of normal reaction of the surface of the spiral coil directed normally to the path of the spiral relative motion of the body;

$\bar{F} = fN$– force of the sliding friction between the body and the surface of the spiral coil directed opposite to the direction of the relative motion of the body, where f – coefficient of sliding friction of the body on the material of the spiral coil. For potato tubers, it can be assumed (in case of metal spiral surface) that f = 0.2–0.3 (Bulgakov et al., 2018a);

$\bar{P}_n^e$– centrifugal force of inertia directed normally to the motion path, its magnitude being equal to

$$\bar{P}_n^e = m\omega^2\rho,$$

where ρ – radial parameter of the position of the centre of gravity of the body with respect to the spiral's longitudinal axis; $\bar{P}_u^k$ – Coriolis force directed normally to the relative motion path, i.e. opposite to the direction of the Coriolis acceleration vector, its magnitude being equal to:

$$P_u^k = 2m \cdot \omega \cdot V \sin\left(\widehat{\omega, \bar{V}}\right);$$

$\bar{P}_V$ – force of pressure applied by the potato heap fed onto the spiral separator; $\bar{M}_r$ – moment of rolling friction force, the magnitude of which is found with the use of the formula:

$$M_r = \delta N,$$

where $\delta = R_K \cdot \tan \mu$ – coefficient of rolling friction, μ – rolling friction angle.

MATHEMATICAL MODELLING

The equivalent schematic model (Fig. 2) features two frames of reference. It is, first of all, the fixed system of coordinates xO_1yz, the O_1z axis of which coincides with the longitudinal axis of the spiral, while the O_1x axis is directed towards the adjacent spiral, the same as the motion of the potato tuber. Also, it includes the moving system of coordinates $x_1Cy_1z_1$, the origin of which (point C_1) coincides with the centre of gravity of the potato tuber.

Using the above-said and basing on Newton's second law, the differential equation of motion of the body (potato tuber) on the surface of the cleaning spiral spring can be generated (Grote & Antonsson, 2008).

The equation of motion of the potato tuber on the surface of the spiral in the vector notation appears as follows:

$$m\bar{a} = \bar{G} + \bar{N} + \bar{F} + \bar{P}_n^e + \bar{P}_u^k + \bar{P}_V, \qquad (1)$$

where $\bar{a}$ – acceleration of the centre of the potato tuber moving on the surface of the cleaning spiral spring.

The motion of the centre of the potato tuber in the O_1xyz coordinate system can be represented by the projections of the vector equation (1) on the respective coordinate axes. They appear as follows:

$$\left.\begin{aligned} m\ddot{x} &= -\left(P_n^e + N + P_u^k - P_V\right) \cdot \cos\left(\widehat{x, \bar{n}}\right) - F\cos\left(\widehat{\dot{x}, \bar{V}}\right), \\ m\ddot{y} &= \left(P_n^e + N + P_u^k - P_V\right) \cdot \cos\left(\widehat{y, \bar{n}}\right) - F\cos\left(\widehat{\dot{y}, \bar{V}}\right) - G. \end{aligned}\right\} \qquad (2)$$

Further, the differential equation of the potato tuber rotation about its centreline has to be written down:

$$I\ddot{\theta} = M_r - F \cdot R_K, \qquad (3)$$

where I – moment of inertia of the potato tuber body with respect to the central axis.

For a spherical body: $I = \frac{2}{5} m \cdot R_K^2$ (Grote & Antonsson, 2008); $\ddot{\theta}$ – angular acceleration of the rotary motion of the potato tuber; $\cos\left(\widehat{x, \bar{n}}\right)$ and $\cos\left(\widehat{y, \bar{n}}\right)$ – direction cosines, which are defined in accordance with (Petrov, 1984) by the following expressions:

$$\cos\left(\widehat{x, \bar{n}}\right) = \frac{\frac{\partial p}{\partial x}}{\Delta p}, \quad \cos\left(\widehat{y, \bar{n}}\right) = \frac{\frac{\partial p}{\partial y}}{\Delta p}, \qquad (4)$$

where $\Delta p=\sqrt{\left(\frac{\partial p}{\partial x}\right)^2+\left(\frac{\partial p}{\partial y}\right)^2+\left(\frac{\partial p}{\partial z}\right)^2}$ – modulus of the gradient of the function $p(x,y,z)$; $p=p(x,y,z)$ – equation of constraint corresponding to the equation of the surface of the spiral winding. For a cylindrical spiral with an outside diameter of $2R$ wound from a round bar with a radius of r with a winding pitch of S, the equation of the unit gradient function (accordingly, the equation of constraint) appears as follows (Vasilenko, 1996):

$$p=\frac{S^2}{4\pi^2}\cdot\left|\frac{x\cdot\sin\frac{2\pi\cdot z}{S}-y\cdot\cos\frac{2\pi\cdot z}{S}}{\sqrt{x^2+y^2}}\right|\cdot\cos\left(\frac{S}{2\pi\sqrt{x^2+y^2}}\right)+ \qquad (5)$$

$$+\left(\sqrt{x^2+y^2}-R\right)^2-r^2=0.$$

After differentiating the equation of constraint and substituting into it the respective expressions from the kinematic analysis, the following values of the direction cosines are obtained:

$$\cos\left(x,\hat{\bar{n}}\right)=\frac{\frac{1}{4}\cdot\frac{S^2}{\pi^2}\cdot\frac{\sin\psi}{R+\varepsilon}\cdot\cos\left[\frac{1}{2}\cdot\frac{S}{\pi\cdot(R+\varepsilon)}\right]+2\varepsilon\cdot\cos\psi}{\sqrt{\frac{1}{4}\cdot\frac{S^2}{\pi^2}\cos^2\left(\frac{1}{2}\cdot\frac{S}{\pi(R+\varepsilon)}\right)\cdot\left[\frac{S^2}{4\pi^2(R+\varepsilon)^2}+1\right]+4\varepsilon^2}},$$

$$\cos\left(y,\hat{\bar{n}}\right)=-\frac{\frac{1}{4}\cdot\frac{S^2}{\pi^2}\cdot\frac{\cos\psi}{R+\varepsilon}\cdot\cos\left[\frac{1}{2}\cdot\frac{S}{\pi\cdot(R+\varepsilon)}\right]+2\varepsilon\cdot\sin\psi}{\sqrt{\frac{1}{4}\cdot\frac{S^2}{\pi^2}\cos^2\left(\frac{1}{2}\cdot\frac{S}{\pi(R+\varepsilon)}\right)\cdot\left[\frac{S^2}{4\pi^2(R+\varepsilon)^2}+1\right]+4\varepsilon^2}}. \qquad (6)$$

Here, the angular parameter represented by an angle of ψ, which defines the position of the spherical potato tuber body on the two turns of the cleaning spiral, depends on the geometrical parameters of the said spiral and varies as a function of the radial parameter ρ that represents the position of the potato tuber with respect to its own centreline, the spiral radius R and the spiral winding parameter γ. However, this angular parameter is exactly the factor that determines the motion of the potato tuber entrained by the spiral turns over the surface of the cleaning unit.

The direction cosines $\cos\left(\dot{x},\hat{\bar{V}}\right)$ and $\cos\left(\dot{y},\hat{\bar{V}}\right)$ can be found with the use of the following expressions:

$$\cos\left(\dot{x},\hat{\bar{V}}\right)=\frac{\dot{x}}{V}=\frac{\dot{x}}{\sqrt{\dot{x}^2+\dot{y}^2+\dot{z}^2}}, \qquad \cos\left(\dot{y},\hat{\bar{V}}\right)=\frac{\dot{y}}{V}=\frac{\dot{y}}{\sqrt{\dot{x}^2+\dot{y}^2+\dot{z}^2}}. \qquad (7)$$

After substituting the obtained values of all the components (4)–(7) into the differential Eqs (2) and (3), the system of differential equations representing the motion of the potato tuber on the spiral spring of the potato heap cleaning unit is obtained. It appears as follows:

$$
\left.\begin{aligned}
&m\ddot{x} = -\left(m\cdot\omega^2\cdot\rho + N + 2m\cdot\omega\cdot V\sin\left(\omega,\hat{\bar{V}}\right) - P_V \right)\times \\
&\times\frac{\frac{1}{4}\cdot\frac{S^2}{\pi^2}\cdot\frac{\sin\psi}{(R+\varepsilon)}\cdot\cos\left[\frac{1}{2}\cdot\frac{S}{\pi\cdot(R+\varepsilon)}\right]+2\varepsilon\cdot\cos\psi}{\sqrt{\frac{1}{4}\cdot\frac{S^2}{\pi^2}\cos^2\left(\frac{1}{2}\cdot\frac{S}{\pi(R+\varepsilon)}\right)\cdot\left[\frac{S^2}{4\pi^2(R+\varepsilon)^2}+1\right]+4\varepsilon^2}} - \\
&- fN\frac{\dot{x}}{\sqrt{\dot{x}^2+\dot{y}^2+\dot{z}^2}}, \\
&m\ddot{y} = -\left(m\cdot\omega^2\cdot\rho + N + 2m\cdot\omega\cdot V\sin\left(\omega,\hat{\bar{V}}\right) - P_V \right)\times \\
&\times\frac{\frac{1}{4}\cdot\frac{S^2}{\pi^2}\cdot\frac{\cos\psi}{(R+\varepsilon)}\cdot\cos\left[\frac{1}{2}\cdot\frac{S}{\pi\cdot(R+\varepsilon)}\right]+2\varepsilon\cdot\sin\psi}{\sqrt{\frac{1}{4}\cdot\frac{S^2}{\pi^2}\cos^2\left(\frac{1}{2}\cdot\frac{S}{\pi(R+\varepsilon)}\right)\cdot\left[\frac{S^2}{4\pi^2(R+\varepsilon)^2}+1\right]+4\varepsilon^2}} - \\
&- fN\frac{\dot{y}}{\sqrt{\dot{x}^2+\dot{y}^2+\dot{z}^2}} - G, \\
&I\cdot\ddot{\theta} = N\cdot R_K\cdot\tan\mu - fN\cdot R_K.
\end{aligned}\right\} \quad (8)
$$

At the same time:

$$
\sin\left(\omega,\hat{\bar{V}}\right) = \sin(90^{\circ}-\gamma) = \cos\gamma \quad (9)
$$

When the motion state becomes steady, all points of the potato tuber (in particular, the points of contact between the tuber and the surface of the spiral spring) retain the constant value of their motion velocity. That means that it is reasonable to substitute $\ddot{x} = 0$ and $\ddot{y} = 0$ into the equations of the system (8).

After that, it is possible to derive from the first two equations of the system of Eqs (8) the normal reaction of the surface. Following the appropriate transformations, the result is:

$$
N = -\frac{mg\sqrt{\dot{x}^2+\dot{y}^2+\dot{z}^2}}{f\cdot\dot{x}}\cdot\left[\frac{\frac{1}{4}\cdot\frac{S^2}{\pi^2}\cdot\frac{\sin\psi}{(R+\varepsilon)}\cdot\cos\left[\frac{1}{2}\cdot\frac{S}{\pi\cdot(R+\varepsilon)}\right]+2\varepsilon\cdot\cos\psi}{\frac{1}{4}\cdot\frac{S^2}{\pi^2}\cdot\frac{\cos\psi}{(R+\varepsilon)}\cdot\cos\left[\frac{1}{2}\cdot\frac{S}{\pi\cdot(R+\varepsilon)}\right]+2\varepsilon\cdot\sin\psi}\right] \quad (10)
$$

The obtained value of the normal reaction of the surface N has to be substituted into the third equation of the system (8), then, after certain mathematical transformations are carried out, the following formula is obtained for the angular acceleration of the potato tuber about its centreline:

$$\ddot{\theta} = \frac{2.5\left(R_K \cdot \tan\mu - f \cdot \rho\right) g \cdot \sqrt{\left(R+\varepsilon\right)^2 + \dfrac{S^2}{4\pi^2}}}{R_K^2\left(R+\varepsilon\right)\cdot f\left[\dfrac{-\dfrac{1}{4}\cdot\dfrac{S^2}{\pi^2}\cdot\dfrac{\cos\psi}{\left(R+\varepsilon\right)}\cdot\cos\left[\dfrac{1}{2}\cdot\dfrac{S}{\pi\cdot\left(R+\varepsilon\right)}\right]+2\varepsilon\cdot\sin\psi}{\dfrac{1}{4}\cdot\dfrac{S^2}{\pi^2}\cdot\dfrac{\sin\psi}{\left(R+\varepsilon\right)}\cdot\cos\left[\dfrac{1}{2}\cdot\dfrac{S}{\pi\cdot\left(R+\varepsilon\right)}\right]+2\varepsilon\cdot\cos\psi} - \cos\psi\right]} \qquad (11)$$

at $\psi = \omega \cdot t$.

After integrating the expression (11) on time, the angular velocity $\dot{\theta}$ of the potato tuber's rotation about its centreline during its motion on the surface of the spiral spring in the potato heap cleaning unit is obtained and it appears as follows:

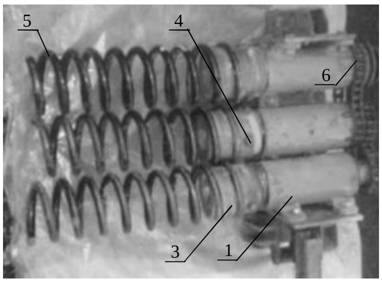
$$\dot{\theta} = \int \frac{2.5\left(R_K \cdot \tan\mu - f \cdot \rho\right) g \cdot \sqrt{\left(R+\varepsilon\right)^2 + \dfrac{S^2}{4\pi^2}}}{R_K^2\left(R+\varepsilon\right)\cdot f\left[\dfrac{-\dfrac{1}{4}\cdot\dfrac{S^2}{\pi^2}\cdot\dfrac{\cos\psi}{\left(R+\varepsilon\right)}\cdot\cos\left[\dfrac{1}{2}\cdot\dfrac{S}{\pi\cdot\left(R+\varepsilon\right)}\right]+2\varepsilon\cdot\sin\psi}{\dfrac{1}{4}\cdot\dfrac{S^2}{\pi^2}\cdot\dfrac{\sin\psi}{\left(R+\varepsilon\right)}\cdot\cos\left[\dfrac{1}{2}\cdot\dfrac{S}{\pi\cdot\left(R+\varepsilon\right)}\right]+2\varepsilon\cdot\cos\psi} - \cos\psi\right]} dt \qquad (12)$$

RESULTS AND DISCUSSION

In view of the complexity of integrating the above expression, the integration has been done graphically with the use of the PC. In these calculations, the authors have used as the input data the dimensions of a single potato tuber (mean value of the radius) as well as the design parameters of the spiral cleaning unit designed by the authors and subjected to field testing and experimental investigations (Fig. 3). For example, the radius of the potato tuber is assumed to be equal to $R_K = 25$ mm, the radius of the spiral – $R = 75$ mm, the spiral winding pitch – $S = 30$ mm, the spirals are mounted with an eccentricity of $\varepsilon = 10$ mm, the radial parameter of the potato tuber's position relative to its centreline is assumed at $\rho = 120$ mm, the coefficient of sliding friction – $f = 0.55$, rolling friction angle – $\mu = 17$ deg (or 0.297 rad). Thus, in the PC-assisted numerical calculations the authors have used the parameters of the spiral-type potato cleaning unit for removal of impurities designed by the authors, which is shown in Fig. 3.

By carrying out PC-assisted calculations with the use of the specially developed programme as well as the assumed values, the diagrams have been plotted for the variation of the angular velocity of rotation $\dot{\theta}$ of the potato tuber, when the angular coordinate ψ varies from 0 to 1 rad at the spirals' angular velocities of $\omega = 10$, 20, 30, 40, 50 rad s^{-1}. As is proved by the obtained graphs (Fig. 4), when the angular velocity ω of the cleaning spiral increases, the angular velocity $\dot{\theta}$ of the potato tuber's rotation about its centreline decreases, coming close to zero, that is, the motion of the body without rolling is observed.

It is quite evident that increasing the angular velocity $\dot{\theta}$ of the potato tuber's rotation about its centreline provides the conditions for the improvement of the quality of cleaning its surface from the stuck soil.



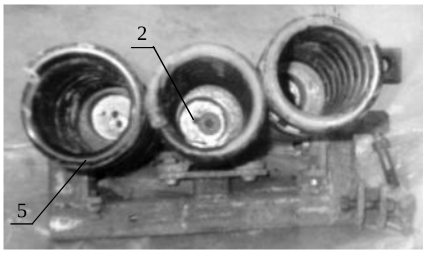


Figure 3. Spiral-type potato cleaning unit of authors' design (a – top view; b – side view): 1 – bearing assembly for mounting spirals; 2 – hub; 3 – holder; 4 – fastening bolt; 5 – spiral spring; 6 – chain drive.

The next step is to determine the effect that certain design parameters of the spiral separator have, by means of analysing the graphs of variation of the angular velocity of motion of the tuber, when the angular coordinate varies from 0 to 1 rad, the angular velocity of the spirals is equal to 40 rad s^{-1} and the parameters under consideration have the following different values (one parameter changes, all other remain constant, the same as in the previous case):

1) R = 75 mm, ε = 10 mm, S = 35 mm; 2) R = 100 mm, ε = 10 mm, S = 35 mm; 3) R = 75 mm, ε = 15 mm, S =35 mm; 4) R = 75 mm, ε = 10 mm, S = 45 mm.

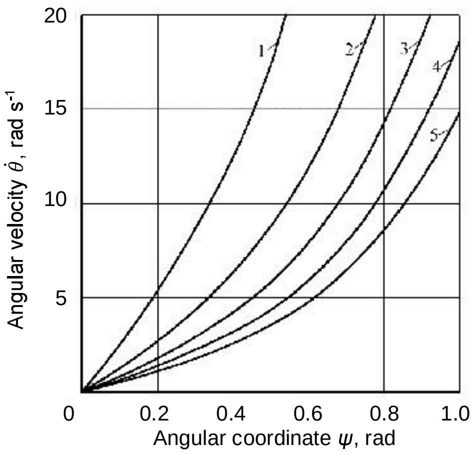


Figure 4. Relation between angular velocity $\dot{\theta}$ of rotation of potato tuber and angular coordinate ψ at different angular velocities ω of cleaning spiral spring:
1) ω = 10 rad s^{-1}; 2) ω = 20 rad s^{-1};
3) ω = 30 rad s^{-1}; 4) ω = 40 rad s^{-1};
5) ω = 50 rad s^{-1}.

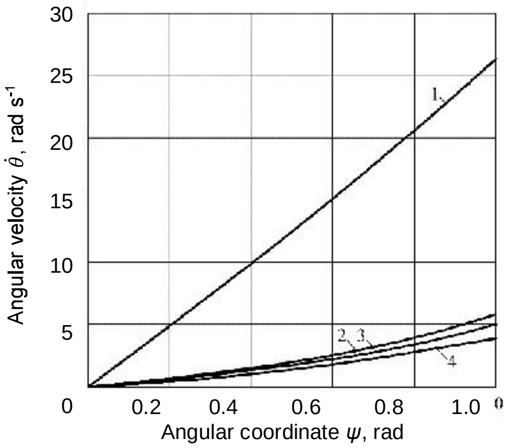


Figure 5. Relation between angular velocity $\dot{\theta}$ of rotation of potato tuber and angular coordinate ψ, when angular velocity ω of cleaning spiral spring is set at 40 rad s^{-1}:
1) R = 75 mm, ε = 10 mm, S = 35 mm;
2) R = 100 mm, ε = 10 mm, S = 35 mm;
3) R = 75 mm, ε = 15 mm, S = 35 mm;
4) R = 75 mm, ε = 10 mm, S = 45 mm.

The obtained diagrams (Fig. 5) show the effect that the radius of the spiral (curve 2), the eccentricity in the mounting of the spirals (curve 3) and the winding pitch (curve 4) have on the angular velocity of the potato tuber's rotation about its centreline.

When the above-listed parameters increase, the angular velocity of rotation of the potato tuber decreases. The greatest effect on the tuber's angular velocity is observed in case of the variation of the winding pitch, the smallest – when the eccentricity changes. Consequently, it can be concluded from the above-said that these parameters have to be increased in order to achieve the minimum angular velocity of rotation of the potato tuber.

For the work process of cleaning the potato heap with the use of the potato heap cleaning unit under consideration to take place it is necessary to ensure that the centreline velocity of the potato tuber is below zero. Therefore, the minimum value of the angular velocity of the cleaning spiral spring's rotary motion has to be in accordance with the following relation:

$$\omega_{\min} = \dot{\theta}\left(1 + \frac{2\pi\left(R_K + \frac{d_n}{2}\right)}{S}\cos\gamma \cdot \cos\theta\right). \quad (13)$$

For example, if the tuber has a radius of R_K = 25 mm, the spiral has a radius of R = 75 mm, the winding has a pitch of S = 35 mm, the round bar, from which the spiral coil is made, has a radius of r = 7.5 mm, the spiral is mounted with an eccentricity of ε = 10 mm, $\dot{\theta}$ can be found with the use of the graphic relation (Fig. 5) at a value of ψ = 0.8 rad. After substituting the value of $\dot{\theta}$ into the expression (13), it has been found that the magnitude of the angular velocity ω_{min} of the spiral's rotary motion has to be equal to at least 27 rad s^{-1}.

Table 1. Data on quality performance of spiral-type unit for cleaning potatoes from impurities obtained during field experiment investigations

Indicator	Spiral-type potato cleaning unit
Potato yield (t ha^{-1})	10.0
Effective width of cleaning unit (1 row) (m)	0.7
Operating rate of travel of lifter equipped with cleaning unit under study (km h^{-1})	2.41
Mass of cleaning unit (kg)	78.0
Entirety of potato tubers passing through cleaning unit (%)	100
Potato tubers damaged by cleaning unit (%)	1.8–3.2
Severely damaged potato tubers (%)	1.6–2.4
Potato tubers lost while passing through cleaning unit (%)	1.6–1.38
Contamination of potato tubers with soil impurities (%)	1.9–3.2
Contamination of potato tubers with plant impurities (%)	1.5–1.9

The authors have carried out field experiment investigations with the spiral-type potato cleaning unit of the design developed by them. Table 1 contains the data on the quality, with which the potato tubers lifted from the soil were cleaned from soil and plant impurities, as well as the conditions, in which the field experiment investigations were conducted. In the experiments, the cleaning unit of the design developed by the authors was installed in a single-row potato lifter attached to a Class 1.4 wheeled tractor. The general view of the single-row potato lifter (a share-type lifting implement and a raddle chain conveyor, which feeds the heap to the cleaning unit) complete with the installed cleaning unit of the design developed by the authors is shown in Fig. 6.

The data in Table 1 prove that the spiral-type potato cleaning unit developed by the authors delivers the quality, the indices of which not only meet the agronomical requirements, but also exceed by far the similar indices of the other types of devices for cleaning potatoes from soil and plant impurities.

That is due to the fact that the cleaning spirals sieve with a high efficiency the soil and plant impurities through their own gaps and the clearances between the spirals. The new spiral cleaning unit completely rules out any positive entrainment of potato bodies as well as their strong compression, which virtually eliminates their damaging. The parameters obtained by the authors during the theoretical investigations with the use of PC-assisted calculations provide for the transportation of potato bodies by the spirals (especially their upper and side surfaces) at a high rate and that means the small duration of the contacts between the potato tuber bodies and the spirals. It should be noted that, in case the turns of the cleaning spirals are coated with rubber or some other elastic material, the rate of potato tuber damage will be even lower. On the contrary, the soil and plant impurities, which virtually immediately fall into the space inside the turns, are transported by the spiral turns at a significantly lower rate. At the same time, the impurities, unlike the potato bodies, are actively entrained and compressed by the spiral turns. As a result of that, they are very efficiently positively carried down and outside the working space of the cleaning unit, which allows the potato bodies to move freely along the windings of the cleaning spirals and further onto the discharge conveyor. The contamination of the potato tubers with soil impurities also stays under 3.5% (and that contamination is caused not by free soil particles but by the soil caked on the tubers), while plant impurities are virtually absent in the cleaned potato heap.

Figure 6. General view of experimental unit with mounted spiral-type potato cleaning unit.

CONCLUSIONS

1. The mathematical model of the motion of a single potato tuber on the cleaning spiral spring of the spiral potato heap cleaning unit has been generated. The model enabled obtaining the system of differential equations that describes the motion of the potato tuber on the cleaning unit's spiral spring.

2. As a result of the performed integration, the analytical expressions have been obtained for the angular velocity of rotation of the potato tuber about its centreline and the angular velocity of rotation of the cleaning spiral spring.

3. Using the specially developed computer programme and assuming the selected main values of the parameters of the work process under consideration, PC-assisted

numerical calculations have been carried out and the diagrams have been plotted for the variation of the angular velocity of rotation of the potato tuber in relation to the design and kinematic parameters of the spiral cleaning unit.

4. Basing on the completed analytical study, it has been established that, when a potato tuber (approximated by a spherical-shape body) with a diameter of 50 mm moves on the surface of the cleaning spiral with a radius of 75 mm wound from the round bar with a diameter of 15 mm, in case the spirals are mounted with an eccentricity of 10 mm, it is necessary to maintain the angular velocity of rotation of the spirals within the range of 27-40 rad s^{-1} in order to ensure the efficiency of transporting and cleaning the tuber.

5. The results of the undertaken experimental investigations indicate the following indices of cleaning quality for the spiral-type cleaning unit of the design developed by the authors, the design and kinematic parameters of which have been determined theoretically: the damage rate does not exceed 3.5% (including severe damage – 2.4%), the loss rate is 1.5% or less, while the rate of contamination with impurities is not more than 3.3%, which is significantly lower, than the similar indices of other types of potato cleaning units, and does not exceed the agronomical requirements to the potato harvesting process.

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