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Theory of retaining potato bodies during operation of spiral separator

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Abstract. The increase of the efficiency and quality of performance of the work process of potato heap separation can be achieved by means of improving the design of the vibrational spiral separator and substantiating theoretically its rational parameters under the condition of eliminating damage to the potato tubers. An equivalent schematic model of the interaction between the potato tuber and the surface of the cantilever spiral springs has been devised. On the basis of the model, the kinematic characteristics of the tuber's flight and its impact contact with the elastic surface of the over mounted rebounding conveyor have been investigated. A new analytical mathematical model of the potato tuber's flight from the surface of the spiral separator and its subsequent encounter with the rebounding conveyor mounted above the spiral springs has been developed. New analytical dependences have been obtained for finding out the distance and height of the potato tuber's flight to the point of impact contact as well as the trajectory equation for the travel to the said contact, which makes it possible to obtain the kinematic constraints imposed on the allowed rate of travel under the condition of not damaging the tuber. On the basis of the obtained analytical dependences, the kinematic parameters of the improved design of the spiral potato harvester separator in its interaction with a potato tuber under the condition of not damaging the latter have been investigated.

Key words: potato, tuber, harvester, spiral separator, rebounding.

INTRODUCTION

Cultivation and harvesting of potatoes is one of the most power- and material-intensive production processes in agriculture. For example, regarding the power consumption, it features about 4–5 times greater specific energy costs as compared to the energy spent for the production of a unit of cereal crops (Petrov, 2004). Therefore, the issue of cutting down those parameters in the production of potatoes is urgent and, in the continued process of developing and improving the tools of potato harvesters and optimising their parameters, it is necessary not only to increase their quality indicators, but at the same time to provide for the reduction of their material and energy consumption rates.

The analysis of the process design and structural layout of a majority of potato harvesters and potato combines has shown that the largest share of their total weight is accounted for their separating tools, since the required level of cleanliness of the output product is achieved through the increase of the potato heap separation duration, which implies the respectively greater number and complexity of the tools. This is explained by the fact that the cleaning tools are effectively the main element in the process of ensuring the qualitative indicators of performance of the potato harvester as a whole.

For the purpose of improving the potato harvester's operation quality indicators through the intensification of the process of cleaning the potato tubers from soil impurities and plant debris, we have developed the new design of the spiral potato heap separator (UA43907).

The spiral separator comprises three driven cylindrical spirals mounted in parallel, which are made in the form of spiral springs cantilever-fitted on their drive hubs. During the operation of the spiral separator under consideration, the potato heap to be cleaned is fed to the upper work face created by the spiral springs, the rotation of which results in the entrainment and subsequent sifting downwards of significant masses of soil. At the same time, the potato tubers are moving along the axes of the springs' spiral windings, mostly in the troughs formed by the neighbouring springs, and, due to their violent contacts with the rotating and, at the same time, vibrating spiral springs, the stuck soil is efficiently separated from their side surfaces.

Thus, the main distinctive feature of the spiral potato heap separator under consideration is the presence of sizable gaps between the coils of the springs, in order to let the soil impurities and plant debris immediately pass through and fall down. Also, such a design provides for a significant increase of the effective cleaning area (i.e. the total area of the separating gaps) as compared to the total area of the separator's cleaning surface. This, in its turn, results in the rise of the throughput capacity of the separating surface, which contributes to the growth of the quality indicators of the process of cleaning the heap of tuberous roots from impurities. Moreover, the absence of driving shafts inside the cleaning spirals makes impossible for plant debris to wind on the shafts, while the free space inside each spiral is capable of transporting the soil impurities falling into it along the axis towards the unobstructed face end of the cantilevered spring, then further outside from the separator.

The obstruction of the separating gaps in the spiral separator by caked humid soil is eliminated, because the cleaning spirals are positioned with overlapping and the coils of each cleaning spiral partially enter the gaps between the coils of the neighbouring spiral. Such an arrangement facilitates self-cleaning of the spirals during the operation of the spiral separator.

The undertaken experimental laboratory and field studies of the spiral separator (Bulgakov et al., 2017) mounted on the test unit modelling a single-row potato-digger have shown the high efficiency of its operation.

However, the results of the experimental studies have also proved that some part of potato tubers and also firm soil lumps with the size and mass characteristics similar to those of the tubers overflies the separator's spirals, which results not only in the deterioration of tuber cleaning quality, but in some cases even in the loss of tubers. This happens not only at the initial stage, just as the potato heap is fed to the cleaning surface, but also during the later transfer of the potato bodies from one spiral to the other. Besides, the mentioned effect hinders the further improvement of the separator's performance, because it imposes limitations on the angular velocities of the rotating spirals.

In order to eliminate the overflight of potato tubers across the spiral separator, an improved design of the latter has been proposed with the introduction of the rebounding plain belt conveyor mounted above the cleaning spirals at a certain angle to the line passing through the centres of axes of the separator spirals (Fig. 1).

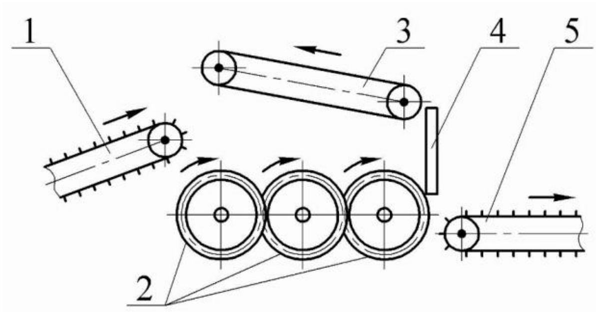

Figure 1. Potato heap separator of improved design (side view): 1 – feeding conveyor; 2 – cantilevered spiral springs of cleaning rolls; 3 – rebounding belt conveyer; 4 – protecting apron; 5 – discharge conveyor.

Due to such an arrangement, during the operation of the improved-design separator, when a potato tuber takes off from the surface of the cleaning spiral and flies up, it hits eventually the down side of the belt of the rebounding conveyor and returns again onto the separating spiral surface.

It has become evident from the analysis of a large number of scientific publications and patent studies that the potato heap separators must be capable of not only reliably performing the work process with good quality, but also continuously self-cleaning during the operation. It is common knowledge that the systems of separating tools used on conventional potato combine harvesters not always ensure the high level of soil impurities separation (Petrov, 2004; Wei et al., 2013). The most frequent cause of the shortcoming is the intensive blockage of the separating tool surfaces by the sticking humid soil.

The problem of developing high-efficiency and reliably operating potato heap separators for the harvesting process as well as cleaning systems for fixed-site potato dressing stations is covered in studies (Zaltzman & Schmilovitch, 1985; Feller et al., 1987; Misener & McLeod, 1989; Ichiki et al., 2013; Klindtworth, 2016; Feng et al., 2017). However, despite the great variety of potato heap cleaning work processes and studies on them, the papers on the optimisation of kinematic and design parameters specifically of spiral separators are relatively scarce.

The aim of this study was increasing the efficiency and quality of performance of the potato heap separation work process by means of providing for the retention of potato bodies in the improved design of the vibrational spiral separator and substantiating theoretically its rational parameters under the condition of eliminating potato damage.

MATERIALS AND METHODS

The theoretical study of the potato body retention by the improved potato heap separator has been carried out with the use of fundamental provisions of the mathematics, theoretical mechanics as well as the methods of composing programmes for numerical computation on the PC, plotting graphical dependences and their analysis.

The theoretical substantiation of the parameters of the improved spiral potato heap separator is based on the development of the mathematical model (France & Thornley, 1984) of behaviour of the potato tuber that is first ejected from the surface of the spiral separator, then performs flight upwards and finally interacts with the elastic surface of the rebounding belt conveyor mounted above.

For that purpose it is necessary, first of all, to form the equivalent schematic model of the ejection, subsequent flight and rebound of the potato tuber during the operation of the improved-design spiral separator (Fig. 2). The equivalent schematic model shows the structural elements of the improved spiral separator (two spiral springs mounted alongside each other and rebounding conveyor mounted above them) and designations of their kinematic and design parameters. It shows the potato tuber modelled as a material point, to which the forces acting after the tuber reached the surface of the spiral spring (winding) and started interacting with it are applied.

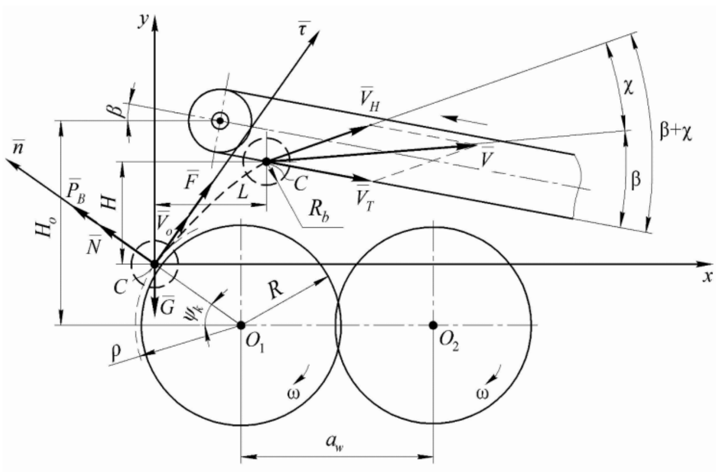

Figure 2. Equivalent schematic model of potato tuber's flight in spiral separator of improved design.

In this model, the potato tuber is analysed sequentially in its two positions: at the point of ejection from the spiral separator and at its impact contact with the surface of the rebounding belt conveyor. In order to simplify the analytical calculations, the potato tuber body is approximated by a full sphere.

RESULTS AND DISCUSSION

First, the motion of the potato tuber with a shape close to the sphere with a determined radius of R_b on the surface of the spiral separator with an outer radius of R, a winding pitch of S and a spiral wire diameter of d_n is examined. The separator's spirals are installed in series with a center-to-center distance of a_W and some overlapping. The spirals rotate about their figure axes clockwise with equal angular velocities of ω. It is assumed that the separator's spiral at a first approximation is a plain cylindrical surface. The position of the potato tuber on the surface of the spiral is defined by certain radial parameter ρ and angular parameter ψ. The interaction between the potato tuber and the spiral's surface can take place in either of the following two ways (Bulgakov et al., 2017):

– tuber moving on the surface of the spiral coil with a one-point contact;
– tuber moving in the intercoil space of the spirals.

Therefore, the radial parameter ρ for these options is equal to, respectively:

– in case of motion in the intercoil space:

$$\rho = \left(R - \frac{d_n}{2} \right) + \frac{1}{2}\sqrt{\left(d_n - 2R_b\right)^2 - S^2}, \tag{1}$$

– in case of motion on the outer surface of the spiral:

$$\rho = R + R_b. \tag{2}$$

When a certain critical value $\psi = \psi_k$ of the angular parameter is reached, the potato tuber takes off from the spiral surface. This becomes possible, when the normal reaction of the spiral coil is $N = 0$. In order to consider that, the schematic diagram of the forces acting on the potato tuber with a specified mass of m and the centre in the point C during its motion on the surface of a spiral in the cleaning unit (Fig. 3) is to be examined. In this schematic diagram $\bar{G}$ – force of gravity; $\bar{N}$ – force of spiral's normal reaction vectored normally to the trajectory of relative motion of the tuber body on the spiral; $\bar{F}$– force of sliding friction of the tuber body on the surface of the spiral; $\overline{P_b}$ – centrifugal force of inertia vectored normally to the trajectory of motion.

Let's investigate the relative motion of the potato tuber on the spiral's surface at the moment of its take-off from the said surface in the natural system of coordinates $\bar{\tau} C \bar{n}$ with the origin set at the point C – the centre of the potato tuber.

In accordance with the set up schematic diagram of forces, the equations of the relative motion in its projections on the axes $\bar{\tau}$ and $\bar{n}$ of the mentioned natural system of coordinates can be written in the form of the following system of differential equations:

$$\left. \begin{aligned} m a_\tau &= F, \\ m a_n &= N + P_B - G \sin\psi_k. \end{aligned} \right\} \tag{3}$$

Since the potato tuber's motion takes place only along the tangential axis τ, then $a_n = 0$ and, consequently, the following is derived from the second equation of the system (3):

$$N + P_B - G \sin\psi_k = 0. \tag{4}$$

Hence, taking into account the condition that the potato tuber takes off from the spiral's surface ($N = 0$), the value of the angular parameter ψ_k, at which the potato tuber takes off from the spiral's surface, can be found. It is obtained as follows:

$$\sin\psi_k \geq \frac{P_B}{G}. \tag{5}$$

As

$$G = mg \tag{6}$$

and

$$P_B = m\omega^2\rho_i, \tag{7}$$

then:

$$\psi_k \geq \arcsin\frac{\omega^2\rho_i}{g}. \tag{8}$$

As regards the first equation in the system (3): at the moment, when the tuber takes off from the spiral's surface, the force $\bar{F}$ goes to zero; accordingly, the tangential acceleration a_t also becomes equal to zero. Hence, when the potato tuber starts moving away from the separator's spiral, the initial velocity of its motion V_0 has a specific value. Having completed its flight in the space between the spiral and the rebounding conveyor, the potato tuber reaches the lower flight of the rebounding belt conveyor. It is possible to determine the point of (impact) contact between the potato tuber and the rebounding conveyor as well as the velocity attained by the tuber by that point. For that purpose, it is assumed that the potato tuber, taking off from the spiral's surface at an angular position of ψ_k, has the initial motion velocity V_0 of the following value:

$$V_o = \omega\rho. \tag{9}$$

In accordance with the known relations (Petrov, 2004), the distance and height of the potato tuber's flight are determined on the basis of the following formulae:

$$L = V_o t \cdot \cos\psi_k \tag{10}$$

and

$$H = V_o t \cdot \sin\psi_k - \frac{gt^2}{2} \tag{11}$$

After the time parameter t is eliminated from the relations (10) and (11) and they are combined with each other, the expression describing the potato tuber centre's motion trajectory in the form of the relation between the height and the distance of its flight is obtained:

$$H(L) = L\tan\psi_k - \frac{gL^2}{2V_o^2\cos^2\psi_k}. \tag{12}$$

Whereby at the point situated at a height of H the potato tuber will have the following rate of travel:

$$V_H = \sqrt{V_o^2 - 2gH} = \sqrt{V_o^2 - 2g\left(L\tan\psi_k - \frac{gL^2}{2V_o^2\cos^2\psi_k}\right)}. \tag{13}$$

If a fixed Cartesian coordinate system xCy with the horizontal axis x, the vertical axis y and the origin at the potato tuber's centre C at the moment, when the tuber takes off from the spiral's surface, is set and the parameters L and H in the expression (12) are replaced by the current coordinates x and y, respectively, then the law of the tuber's flight in this coordinate system will assume the following appearance:

$$y(x) = x \cdot tg\psi_k - \frac{gx^2}{2V_o^2\cos\psi_k}. \tag{14}$$

In the design of the improved spiral potato heap separator, a rebounding belt conveyor is installed at a height of H_o relative to the centre of the first spiral at an angle of β to the horizon with a tilt towards the process mass conveyor. Its surface (the working lower flight) in the same coordinate system is described by the following equation:

$$y(x) = H_o - (\rho + R_b)\sin\psi_k - x\tan\beta \tag{15}$$

Obviously, the point C of the contact between the potato tuber and the rebounding conveyor is the point of intersection of the tuber's flight trajectory (14) and the conveyor's surface (described by the expression (15)). Therefore, the coordinates of the mentioned point of contact in the reference system *xCy* can be determined by solving the system of equations (14)–(15). Since the left-hand sides of the said equations are in this case equal to each other, then the right-hand sides of the equations can be equated and, after certain transformations, the following quadratic equation in the unknown coordinate x is obtained:

$$\frac{gx^2}{2V_o^2\cos^2\psi_k} - (\tan\beta + \tan\psi_k)x + \\ + \left[H_o - (\rho + R_b)\sin\psi_k\right] = 0. \tag{16}$$

By solving the obtained equation, the value of the distance of the tuber's flight to the point of contact and interaction with the rebounding belt conveyor is found:

$$x = \frac{V_o^2\cos^2\psi_k}{g}\cdot\left\{\tan\left(\tan\beta + \tan\psi_k\right) + \right. \\ \left. + \sqrt{(\tan\beta + \tan\psi_k)^2 - \frac{2g\left[H_o - (\rho + R_b)\sin\psi_k\right]}{V_o^2\cos^2\psi_k}}\right\}. \tag{17}$$

The height of the potato tuber centre's flight and the velocity of its motion at the point of contact *C* is determined by means of substituting the solution (17) into the expressions (15) and (13), respectively.

The potato tuber's velocity V_H at the point of contact *C* is vectored at an angle of χ to the horizon; its tangent is determined as the derivative of the function (14) with respect to the argument *x*:

$$\tan\chi = \frac{dy}{dx} = \tan\psi_k - \frac{gx}{V_o^2\cos^2\psi_k}. \tag{18}$$

The resulting velocity $\bar{V}$ of the potato tuber at the impact is equal to the vector sum of the tuber's velocity $\bar{V}_H$ at the point of contact *C* and the linear velocity $\bar{V}_T$ of the rebounding conveyor:

$$\bar{V} = \bar{V}_H + \bar{V}_T \tag{19}$$

or

$$V = \sqrt{V_H^2 + V_T^2 - 2V_H V_T \cos\left(V_H \hat{,} V_T\right)}, \tag{20}$$

where $\cos\left(V_H \hat{,} V_T\right)$ – direction cosine of the potato tuber's velocity vector $\bar{V}_H$ at the moment of its contact with the rebounding conveyor's velocity vector V_T.

According to the schematic model (Fig. 2):

$$\cos\left(V_H \hat{,} V_T\right) = -\cos(\beta + \chi) \cdot \qquad (21)$$

Hence, the resulting velocity V of the potato tuber is equal to:

$$V = \sqrt{V_H^2 + V_T^2 + 2V_H V_T \cos(\beta + \chi)} \cdot \qquad (22)$$

In order to meet the condition of undamaged potato tubers at the output, it is necessary for their resulting velocity V after the impact not to exceed the maximum acceptable value, which, according to Petrov (2004), is assumed to be equal to 4–5 m s^{-1}. After the expression (13) is substituted in the expression (20) and the above-mentioned limitation on the potato tuber's velocity V after the impact is taken into account, the following kinematic condition, which ensures the tuber remaining undamaged during its impact on the rebounding conveyor's surface, is obtained:

$$V = \sqrt{\omega^2\rho^2 - 2g\left[L \cdot \tan\psi_k - \frac{gL}{2\omega^2\rho^2\cos^2\psi_k}\right] + V_T^2 + 2\sqrt{\omega^2\rho^2 - 2g\left[L \cdot \tan\psi_k - \frac{gL}{2\omega^2\rho^2\cos^2\psi_k}\right]} V_T \cos(\beta + \chi)} \leq [V]. \qquad (23)$$

The implementation of the obtained relation (23) with the use of application software for the PC has allowed to determine the parameters of the improved design of the spiral separator that would operate without damaging the potato tubers or losing them; that, in its turn, would result in the increase of the spiral separator's productivity.

Using the specially developed PC programme, numerical calculations have been performed in the Mathcad environment, which has enabled plotting the following curves (Fig. 3–5).

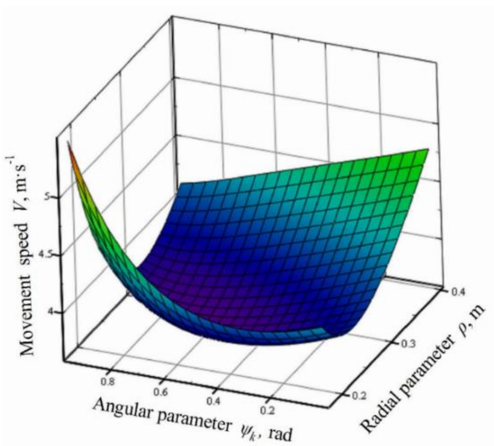

Figure 3. Relation between potato tuber's velocity and angular parameter ψ_k and radial parameter ρ.

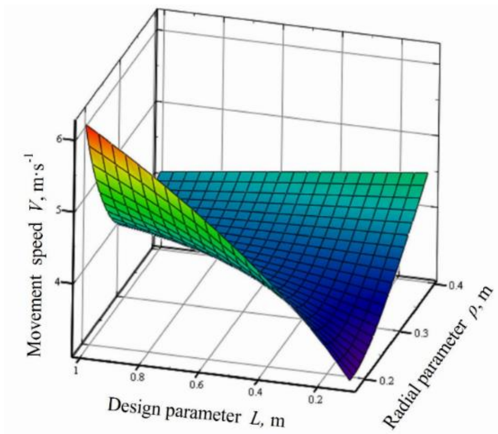

Figure 4. Relation between tuber's velocity and design parameter L and radial parameter ρ.

As may be inferred from the curves in Fig. 3, the angular parameter ψ_k can be selected on the basis of the values of the radial parameter within a range of ρ = 0.24…0.27 m, which corresponds to the values of the former within a range of 0.4...0.6 rad. Any other values of ρ are undesirable, as they bring about the increase of the spiral separator's overall dimensions. The results presented in Fig. 4 prove that preference is to be given to lengths L within a range of 0.2...0.5 m, based on the earlier accepted values of ρ. Also, on the assumption of the above-accepted design parameters of the spiral separator (ρ and L), the radial parameter ψ_k is to have the values indicated earlier, i.e. ψ_k = 0.4…0.6 rad, which becomes obvious from Fig. 5.

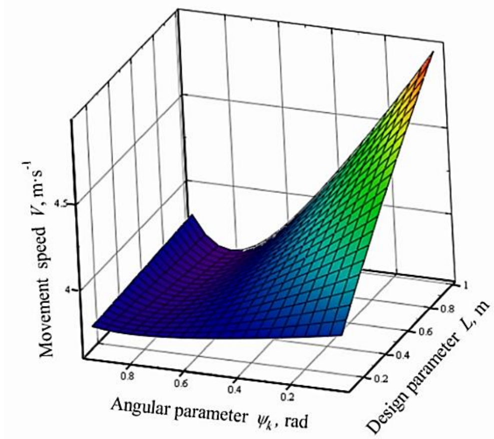

Figure 5. Relation between tuber's velocity and angular parameter ψ_k and design parameter L.

During the experimental studies, the quality characteristics of the cleaning of potato tubers from soil impurities and plant residues as well as their loss and damaging in relation to the spiral separator's design and kinematic parameters (Bulgakov et al., 2017) were assessed. The statistical analysis of the results of the experimental studies provided for obtaining the graphical dependences that show the potato tuber loss and damage rates as functions of the pilot unit's travel speed (Fig. 6).

The dependences between the potato tuber loss and damage rates and the linear velocity of the separator's spiral coils in the presence of the rebounding belt conveyor mounted above are shown in Fig. 7.

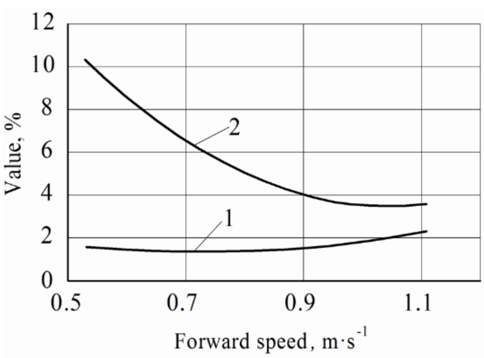

Figure. 6. Relation between potato tuber loss (1) / damage (2) rates and field pilot unit travel speed (Bulgakov et al., 2017).

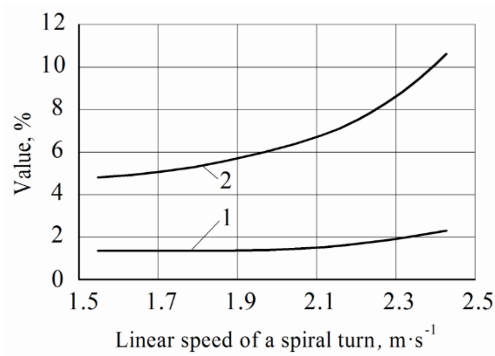

Figure 7. Relation between potato tuber loss (1) / damage (2) rates and linear (circumferential) velocity of spiral's outside surface.

As is seen from the curves in Fig. 7, the rebounding conveyor recovers virtually 100% of the departing potato tubers. Their loss rate stays below 2%. As regards the tuber damaging, its rate does not exceed 4…6% as long as the linear velocity of the spiral coils' working surfaces stays within a range of up to 2 m s^{-1}. Thus, the damage to tubers is caused mainly by the initial impacts of the fed potato tubers on the spirals and not by their "tossing" or their impacts on the belt of the rebounding conveyor.

The repulsion of potato tubers and their subsequent flying are most probable and possible only during the initial loading of the spiral separator or in case of the potato body transfer from one spiral to the next one, i.e. when it moves perpendicular to the axis. But, in the latter case the transfer of single potato tubers from one spiral to the other one takes place virtually without the tuber departing from the coil surface or hitting it (there is simply no cause for any other kind of movement, such as take-off and flight), the adjacent spirals rotate at equal angular velocities, the potato bodies in this scenario travel only for negligible distances and virtually in continuous contact with the surface. It has been established by experiments that the transfer from one spiral to the other one is possible only under the impact of the new inflow of the fed heap, which in effect propels the cleaned potato heap forward.

On the other hand, if the progression of the potato body along the spiral's axis has already started, the take-off and flight of the potato body towards the rebounding conveyor is impossible. In that event, the potato body captured by the coils of the two adjacent spirals will travel in continuous contact and without impacts along the spirals' axes towards their ends.

CONCLUSIONS

1. A new analytical mathematical model of the potato tuber's flight from the surface of the spiral separator with an improved design up to its impact on the above-mounted rebounding conveyor has been developed.
2. On the basis of the obtained analytical dependences, the kinematic parameters of the improved-design spiral potato harvester separator during its interaction with the potato tuber subject to a condition of not damaging the product have been theoretically investigated.
3. The following design parameters of the spiral separator are to be considered reasonable under the condition of not damaging the potato tubers: ρ = 0.24…0.27 m, ψ_k = 0.4…0.6 rad and $L \leq 0.5$ m.

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