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Theoretical study on sieving of potato heap elements in spiral separator

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Abstract. One of the principal problems in the harvesting of potatoes is the cleaning of the lifted heap from soil and plant impurities. The low quality in the performance of this harvesting work process operation is the main cause of the withdrawal from fields of considerable amounts of fertile soil. In order to facilitate choosing the optimal parameters for the new design of the spiral potato heap cleaning unit, a mathematical model of sieving the soil impurities through its cleaning spirals has been developed. The obtained analytical expressions have been solved with the use of a PC and the results have been used for plotting the graphic relations between the parameters of the examined process of a variable-mass body's motion on the surface of a spiral, which have made it possible to select the optimal design and kinematic parameters of the spiral cleaning unit under consideration. The obtained graphic relations indicate that the rate of sieving in the spiral separator depends on many factors, including the initial mass, the design dimensions (spiral's radius, helix angle etc.), the frictional properties of the surface, the angular parameters of the position of the potato heap elements on the spiral's surface, and the angular velocity of the rotational motion of the spiral roll itself.

Key words: cleaning, digging, mathematical model, potato, spiral roll.

INTRODUCTION

The industrial production of potatoes is among the energy and material intensive sectors in the agricultural industry, in view of the fact that just with regard to its energy costs per unit of output product it exceeds the production of grain crops 4 to 5 times (Vasilenko, 1996). The most undeveloped area in the mechanized technologies of potato production is its harvesting, in particular, the achievement of the standard quality in the output product. Therefore, in the further development and improvement of the tools for potato harvesters and the optimization of their parameters it is necessary, first of all, not only to provide for reducing their material and energy intensity, but substantially raise the quality of the potato tubers lifted from the soil as well (Misener & McLeod, 1989;

Peters, 1997; Bishop et al., 2012; Ichiki et al., 2013; Guo & Campanella, 2017; Wang et al., 2017).

The accomplished theoretical and experimental investigations (Bulgakov et al., 2018a) as well as the numerous trials of various types of potato harvesters (Petrov, 2004) have proved that the high quality of the cleaning of potato tubers from soil and plant impurities is achievable, when a considerable amount of the soil and other heap components (haulm residues, rootstock, hardened soil bodies, stones etc.) is separated from the tubers in the process of digging the potato bed or immediately after their lifting. In that case a significant mass of the dug heap will not be fed into the harvester together with the potato tubers. However, the widely used elevators, the units for loosening and breaking the dug bed installed immediately after the passive and active vibrational type lifting tools, screens, clod smashers, while demonstrating sufficient transporting capacity, have relatively low separating performance. As a result of that, considerable quantities of soil impurities and plant residues are still fed into the potato harvesters and reach their other separating tools.

At the same time, the various kinds of cleaning tools in the majority of potato harvesters, such as agitators, open-web elevators, grading screens as well as drum and rotary separators mostly perform what is known as passive or without power driven separation' of impurities (Petrov, 2004). That implies that despite the fact that these tools can vibrate, be equipped with various actuators (for example, rotary-vane, auger etc.), perform other types of forced motions, the removal of impurities in them is not directly intended and enforced. Even though various cleaning forces, which have different lines of action and magnitudes, are applied to potato tuber bodies as well as to the accompanying impurities, in the majority of cases the up-to-date separators of impurities from potato heaps do not establish the conditions for exactly their positive capture and forced evacuation from the separation zone. Therefore, in the well-known separation facilities (Feller et al., 1987), the impurities are not always suitable for their efficient separation, especially in the conditions of wet soil, which heavily clogs almost all separating spaces. When the dug heap contains rootstock and other plant residues (dry and green), they close the said separating gaps even more. Moreover, the currently known potato heap separators can feature such sieving gaps, which do not rule out the entrapment and damaging of potato tuber bodies.

The design and process schematic model of the discussed spiral unit (Bulgakov et al., 2018b) for cleaning the potato heap from impurities is presented in Fig. 1.

In this potato heap cleaning unit (Fig. 1) with driven cantilevered spirals 5, its cleaning surface features large-area sieving gaps formed by the spacing between the own turns of the spirals 5 and the spacing between the coils of the adjacent spirals 5. Overall, such a considerable increase of the effective separating area (i.e. the total area of all sieving gaps) relative to the total area of the whole cleaning surface not only provides a marked increase in the throughput capacity of the cleaning machine under consideration, but also facilitates the improvement of the quality indicators of its performance. For example, the fast and efficient sieving of the soil and plant impurities that fall down through the horizontal cleaning surface outside from the cleaning unit results in the increase of the time of contact between the potato tubers themselves and the turns of the spirals 5, which improves the cleaning of their side surfaces from the stuck soil. Moreover, the absence of a shaft inside any of the spirals 5 ensures the unobstructed passing down of all impurities input with the heap and also eliminates the wrapping of plant residues, which would be possible in case the drive shafts resided inside the spirals 5. The hollow interior space inside each spiral 5 enables raising significantly its capacity of positively transporting all the mass of the soil and plant impurities that have fallen here towards the output (cantilever) end of the spiral 5 and discharge it through the open end to the field surface. At the same time, the bodies of potato tubers cannot enter the interior spaces of the spirals 5.

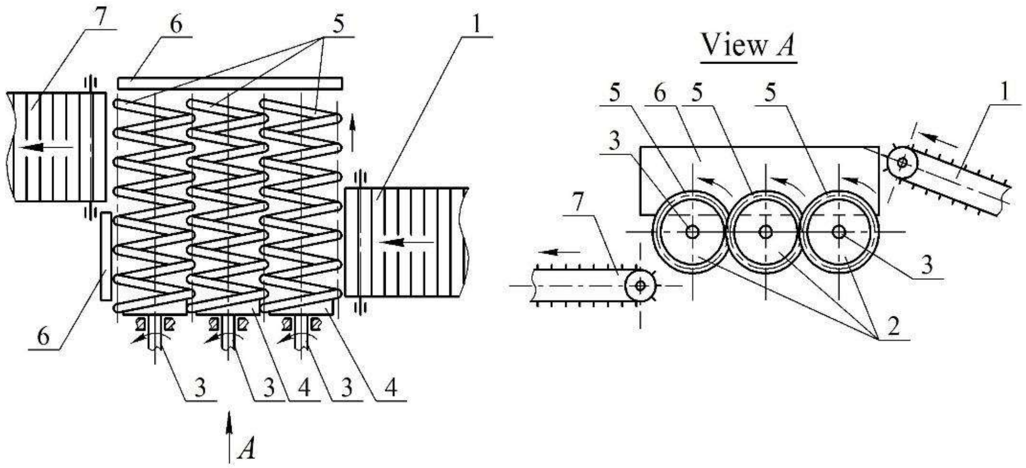

Figure 1. Schematic model of the potato heap separator of improved design: a – top view, b – side view; 1 – feeding conveyor; 2 – cantilevered spiral springs of cleaning rolls; 3 – power axle; cleaning roll; 4 – hub; 5 – spirals; 6 – protective apron; 7 – discharge conveyor.

In order to prevent the caking of the soil on each cleaning roll 2 and avoid complete sealing of the gaps between the spirals 5 with wet soil, the spirals are positioned with certain overlapping, i.e. the turns of the spiral 5 of each roll 2 partially enter the gaps between the turns of the spiral of the adjacent roll 2.

The work process of the spiral cleaning unit under consideration progresses as follows. The mass of the heap of the potato tubers dug out from the soil together with a considerable quantity of soil and plant impurities is fed by the conveyor 1 and arrives to the separating surface formed by the spirals 5 rotating in the same sense. Due to that rotation, the said mass of the potato heap is further transported along the coils of the spirals 5 (i.e. along their centrelines) and during that motion smaller soil impurities immediately spill through the separating gaps between the coils of the spirals 5. When the soil mass enters in greater quantities, it can fall down, but be accumulated in the interior spaces of the spirals 5, which will result in the situation, where the bottom inside surfaces of the spirals 5 are also unable to sieve the soil impurities down and outside of the cleaning unit at their full capacity. But the coil of each spiral 5 will transport the impurities already contained inside the spiral, which have been detained in the interior space of the spiral, and they will be positively transported to its free cantilever end and in the same way always, without exception fall down and outside of the cleaning unit. The arrangement of cleaning rolls 2 so that their spirals 5 overlap provides for the spirals 5 mutually cleaning each other from the stuck wet soil.

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.

The research objective of this study was to determine theoretically the optimal design and kinematic parameters of the potato heap cleaning unit that ensure the efficient evacuation of soil impurities.

MATERIALS AND METHODS

It is obvious that the satisfactory progress of the separation process, i.e. the sieving of the elements of the potato heap in the spiral separator to a considerable extent depends on the dimensions of the heap elements - soil impurities fed to the spiral cleaning unit (Krause & Minkin, 2005). For that reason, an important factor in the said process is the reduction of the size of the said heap elements resulting from their displacement on the working surface of the spiral cleaning unit (Holland-Batt, 1989).

In view of the fact that the soil clods of different size input together with the potato tubers are the principal component of the potato heap lifted from the soil, the research into the process of sieving the potato heap elements, i.e. the soil impurities, which is equivalent to reducing the mass of the soil clod moving along the working surface of the spiral cleaning unit as a result of its dynamic (force) interaction with the said spiral surface is of considerable interest. As a consequence of the said interaction, the mass separated from the soil clod sifts without fail through the gaps in the working spirals and thus the continuously fed stream of the heap with potato tubers is overall cleaned from the accompanying mass of soil impurities.

In view of the aforesaid, it is reasonable to give consideration to a single soil clod moving on the separating spiral surface of the spiral cleaning unit as a variable mass body under the effect of the system of forces arising as a result of the interaction between the said body and the working surface of the spiral cleaning unit. For that purpose, the first step is to generate an equivalent schematic model, in which the conditions described above are represented (Fig. 2). This aim can be achieved by considering two cleaning spirals. In this case, the equivalent schematic model contains two driven spiral springs 1 and 2 installed as cantilevers at points D and D_1, their longitudinal axes being parallel to each other, which are in rotational motion at same angular velocities of ω and in the same sense. The spiral springs 1 and 2 are shaped like cylinders with the same radii of R, their coils have the same helix pitches of S and the same hands of helix (right-handed looking from the cantilever end of the spiral, which is shown by the arrows) and the springs are positioned so that they overlap. The helix angle (angle between the plane of the spiral's cross-section and the helical line) of spirals 1 and 2 is the same and is equal to γ. The centres of the spiral springs 1 and 2 are designated by the points O and O_1 respectively.

The particle (arbitrary-shape clod) of soil designated M in the equivalent schematic model is considered to be a variable-mass body, which at an arbitrary instant of time t is situated on some turn of spiral 1, and is in contact with the turn at the point K.

In order to investigate the process of motion of the said body M on the surface of the spiral cleaning unit, the principles of the dynamics of the variable-mass body movement are to be applied. For the purpose of generating the differential equation of the variable-mass body movement, it is necessary to choose the three-dimensional Cartesian coordinate system $xOyz$. The point of origin of the system of coordinates $xOyz$ (point O) is located on the longitudinal axis of the spiral 1, the axis Oz is aligned along the longitudinal axis of the spiral 1, the axes Ox and Oy are situated in the plane of cross-section of the spiral 1, in which case the axis *Ox* is directed horizontally to the right and perpendicular to the axis *Oz*, the axis *Oy* is directed vertically up and perpendicular to plane *zOx*. The described system of coordinates is assumed absolute (fixed) and the movement of the above-mentioned variable-mass body *M* is assumed to take place in this system of coordinates.

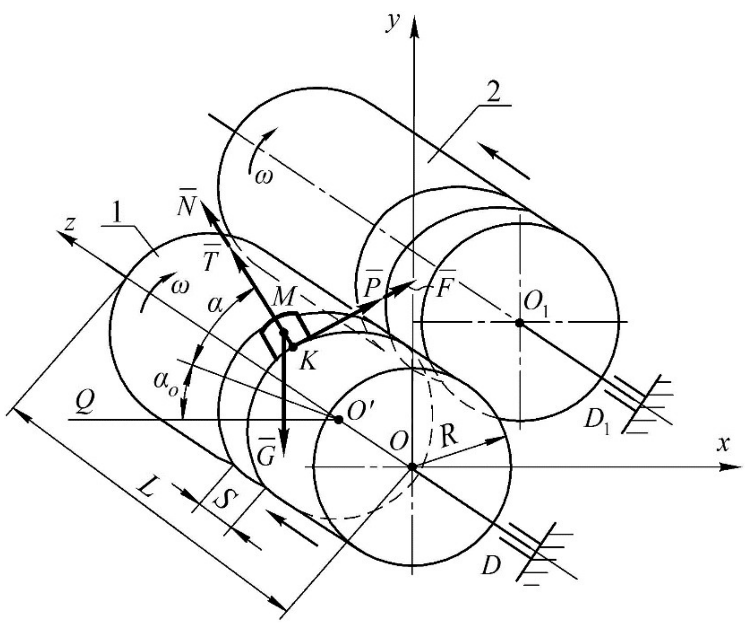

Figure 2. Equivalent schematic model of interaction between soil particle from potato heap with surface of spiral cleaning unit: 1 – first cleaning spiral; 2 – next cleaning spiral.

Apart from the coordinates *x*, *y* and *z*, which define the position of the variable-mass body *M* on the cleaning surface, taking into account the fact that the spiral 1 has a shape of cylinder, additional parameters are introduced – the angles α_0 and α, which define the position of the variable-mass body *M* in the cross-section of the spiral 1. The said cross-section passes through the point *K* of contact between the soil clod *M* and the turn of the spiral 1 and crosses the axis of the spiral 1 at the point O′.

Hence, α_0 is the angle that indicates the initial (at $t = 0$) position of the point *K* of contact between the soil clod *M* and the turn of the spiral 1 in the cross-section under consideration. Then, the angle $\alpha_0 + \alpha$ indicates the position of the point of contact *K* of the soil clod *M* at an arbitrary instant of time t. The angle α_0 is measured from the horizontal half line *O′Q*, which is parallel to the axis *Ox*, in the same direction, in which the spiral 1 rotates (clockwise). The angle α is measured in the same direction after measuring angle α_0. Under the given conditions, if $t = 0$, then also $\alpha = 0$.

RESULTS AND DISCUSSION

It is assumed that the length of the spiral 1 is equal to *L*. Also, the current value of the mass of the body under consideration *M* is assumed to be a function of time, i.e. $m = m(t)$, its initial value being equal to m_0.

The next step is to designate the forces acting on the variable-mass body *M*. They are, first of all: $\bar{G}$ – weight force of the variable-mass body. The force is applied at the body's centre of mass, directed vertically downwards and has the following magnitude:

$$G = m(t) \cdot g, \tag{1}$$

where g – acceleration of gravity; $\bar{F}$ – force of friction. It is directed at a tangent to the surface of the spiral and along the helical line (at an angle of γ with the plane of cross-section of the spiral), applied at the point of contact *K*, is vectored opposite to the relative velocity of the body *M* and, as is known, has the following magnitude:

$$F = f \cdot N, \tag{2}$$

where f – coefficient of sliding friction of the body on the surface of the spiral; $\bar{N}$ – normal reaction of the working surface of the spiral; $\bar{T}$ – acceleration force of the oscillatory motion of the spiral, which arises due to the deflection of the longitudinal axis of the spiral caused by the weight of the potato heap fed onto the cleaning surface.

The magnitude of the force *T* can be determined as follows.

As a result of the deflection of the longitudinal axis of the spiral 1, the centre of each cross-section of the spiral becomes displaced from the axis *Oz* by a certain distance varying from zero at the beginning of the spiral (point *O*) to a certain maximum distance at the cantilever end of the spiral. The magnitude of this displacement at a specific cross-section will be designated *A*. Thus, when the spiral rotates about the axis *Oz* at an angular velocity of ω, its deflected longitudinal axis circumscribes in space a certain surface of revolution, the cross-sections of which (perpendicular to the axis *Oz*) are concentric circles with their centres lying on the axis *Oz*. In the earlier mentioned specific cross-section the radius of such a circle is equal to *A*. Therefore, the centre of the said cross-section moves on the above-mentioned circle with a radius of *A*. In view of the smallness of the *A* value, it can be assumed that the centre of the cross-section oscillates during the operation of the unit following the sinusoidal law with an amplitude of *A* about the axis *Oz* along the diameter of the said concentric circle with a radius of *A*.

Accordingly, it can be assumed that the law of the oscillatory motion of the cleaning unit's spiral in its radial direction can be represented by the following expression:

$$l = -A\sin(\alpha_0 + \omega t), \tag{3}$$

where l – deflections of the cross-section centre from the axis Oz at an arbitrary instant of time t; *A* – amplitude of oscillation; ω – angular velocity of the spiral's rotation (it is assumed to be pre-set and have a fixed value).

By taking the first derivative of the expression (3), the following is obtained:

$$\dot{l} = -A \cdot \omega \cdot \cos(\alpha_0 + \omega t). \tag{4}$$

The acceleration of the spiral's oscillatory motion is equal to the first derivative of the expression (4) or the second derivative of the expression (3):

$$\ddot{l} = A \cdot \omega^2 \sin(\alpha_0 + \omega t). \tag{5}$$

Hence, the value of the force T is finally determined by the following formula:

$$T = m(t) \cdot \ddot{l} = m(t)\omega^2 \cdot A \cdot \sin(\alpha_0 + \omega t). \tag{6}$$

The force T at an arbitrary instant of time t is vectored normally to the spiral's helical line.

In order to generate the differential equation of motion of the variable-mass body M, the principle of the linear momentum of a particle in its differential form (Bulgakov et al., 2018c) is to be used:

$$\frac{d}{dt}\left(m\bar{V}\right)=\sum_{k=1}^{n}\bar{F}_k, \tag{7}$$

where m – mass of the particle (in this particular case the mass of the body M), $m = m(t)$ in the general case; $\bar{V}$ – velocity of the particle, $\bar{V} = \bar{V}(t)$ in the general case; $\sum_{k=1}^{n}\bar{F}_k$ – vector sum of the forces acting on the particle (body M) at an arbitrary instant of time t.

After substituting all above-listed forces into the expression (7), the following is obtained:

$$\frac{d}{dt}\left[m(t)\cdot\bar{V}(t)\right]=\bar{G}+\bar{N}+\bar{F}+\bar{T} \tag{8}$$

or

$$m\frac{d\bar{V}}{dt}+\bar{V}\frac{dm}{dt}=\bar{G}+\bar{N}+\bar{F}+\bar{T} \tag{9}$$

As the mass of the body on the surface of the spiral cleaning unit with the passage of time t decreases, the following can be stated:

$$\frac{dm}{dt}<0 \tag{10}$$

Taking into account (10), the expression (9) can be written in the following form:

$$m\frac{d\bar{V}}{dt}=\bar{G}+\bar{N}+\bar{F}+\bar{T}-\bar{V}\frac{dm}{dt}. \tag{11}$$

The last member of the sum in the expression (11), that is $-\bar{V}\frac{dm}{dt}$, represents the reactive force $\bar{P}$ generated by the change (in this case, decrease) of the body's mass. As a result of the mass decrease, this force $\bar{P}$ is vectored together with the displacement of the body and serves to increase its acceleration. Since the variable-mass body M moves on the cylindrical surface, the said force $\bar{P}$ is also directed at a tangent to that surface, which is shown in Fig. 2.

Thus, the expression (11) is the differential equation of motion of the variable-mass body – particle M (soil clod), on the surface of the spiral of the cleaning unit in the vector form.

The next step is to write the differential equation (11) in its projections on the axes of the Cartesian coordinate system $xOyz$.

Prior to doing that, it is to be noted that, since the projections of the vector of velocity $\bar{V}$ on the coordinate axes Ox, Oy and Oz are equal to $\dot{x}$, $\dot{y}$ and $\dot{z}$ respectively, the projections of the vector of force $\bar{V}\frac{dm}{dt}$ on the mentioned coordinate axes are equal to $\dot{x}\frac{dm}{dt}$, $\dot{y}\frac{dm}{dt}$ and $\dot{z}\frac{dm}{dt}$ respectively. Taking into account also the earlier statement about the direction of the friction force vector $\bar{F}$, it can be concluded that the projection of the said vector on the plane of cross-section of the spiral is equal to $\bar{F}\cos\gamma$, while on the axis Oz it is equal to $-F\sin\gamma$.

In view of the last remark as well as the obtained schematic model of forces (Fig. 2), the vector equation (11) in the projections on the assumed coordinate axes is resolved into the following system of differential equations:

$$\left.\begin{aligned} & m\ddot{x} = -N\cos(\alpha_0+\alpha) + F\cos\gamma\cdot\sin(\alpha_0+\alpha) - \\ & -T\cos(\alpha_0+\alpha) - \dot{x}\frac{dm}{dt}, \\ & m\ddot{y} = N\sin(\alpha_0+\alpha) + F\cos\gamma\cdot\cos(\alpha_0+\alpha) + \\ & +T\sin(\alpha_0+\alpha) - \dot{y}\frac{dm}{dt} - mg, \\ & m\ddot{z} = -F\sin\gamma - \dot{z}\frac{dm}{dt}. \end{aligned}\right\} \tag{12}$$

Taking into account the fact that in the general case the variable-mass body (soil clod) can move (slip) relative to the cylindrical surface of the spiral, the value of angle α is equal to:

$$\alpha = (\omega t + \varphi), \tag{13}$$

where φ – angle, through which the variable-mass body can move in the cross-section of the spiral relative to its surface.

It is obvious that the value of the angle φ depends on many factors, especially taking into account the oscillatory motion of the spiral due to the existence of eccentricity resulting from the deflection of the longitudinal axis of the spiral. The said angle φ can change both with regard to its value and its sign as a consequence of the change of the normal reaction N, and, accordingly, the force of friction $F = f\cdot N$, also under the action of the weight force G. There are grounds for suggesting that the angle φ in the most general case is a random variable.

Taking into consideration the expressions (1), (2) and (6) as well as the above statements about the angle α, which has a value of $\alpha = (\omega t + \varphi)$, the system of differential equations (12) can be transformed into the following representation:

$$\left.\begin{aligned} & m\ddot{x} = -N\cos(\alpha_0+\omega t+\varphi) + fN\cos\gamma\cdot\sin(\alpha_0+\omega t+\varphi) - \\ & -m\cdot\omega^2\cdot A\cdot\sin(\alpha_0+\omega t)\cdot\cos(\alpha_0+\omega t+\varphi) - \dot{x}\frac{dm}{dt}, \\ & m\ddot{y} = N\sin(\alpha_0+\omega t+\varphi) + fN\cos\gamma\cdot\cos(\alpha_0+\omega t+\varphi) + \\ & +m\cdot\omega^2\cdot A\cdot\sin(\alpha_0+\alpha)\cdot\sin(\alpha_0+\omega t+\varphi) - \dot{y}\frac{dm}{dt} - mg, \\ & m\ddot{z} = -fN\sin\gamma - \dot{z}\frac{dm}{dt}. \end{aligned}\right\} \tag{14}$$

Thus, the system of differential equations (14) of the motion of the variable-mass body M (soil clod) in the most general view has been obtained. The determination of the angle φ for this system involves considerable difficulties for the reasons indicated earlier.

It ought to be noted that the obtained system of differential equations (14) has been generated for describing the motion of a single (isolated) soil clod.

However, considering the fact that the discussed soil clod is inside the heap stream, i.e. surrounded by other elements of the heap, the mass (and, accordingly, the inertia) of which in total considerably exceeds the mass of the single soil clod under consideration, also, the total force of friction of which again considerably exceeds the force of friction of the said soil clod, it can be assumed in a first approximation that this soil clod slips in the cross-section of the spiral insignificantly and, therefore, it can be assumed within the practically sufficient accuracy that $\varphi \approx 0$. That results in the assumption that the angle α is equal to $\alpha = \omega t$, which to some extent simplifies the system of differential equations (14). Hence, after assuming the conditions stipulating that $\varphi = 0$, the following system of differential equations of motion is obtained:

$$\left.\begin{aligned}
&m\ddot{x} = -N\cos(\alpha_0+\omega t) + fN\cos\gamma\cdot\sin(\alpha_0+\omega t) - \\
&-m\cdot\omega^2\cdot A\cdot\sin(\alpha_0+\omega t)\cdot\cos(\alpha_0+\omega t) - \dot{x}\frac{dm}{dt}, \\
&m\ddot{y} = N\sin(\alpha_0+\omega t) + fN\cos\gamma\cdot\cos(\alpha_0+\omega t) + \\
&+m\cdot\omega^2 A\sin^2(\alpha_0+\omega t) - \dot{y}\frac{dm}{dt} - mg, \\
&m\ddot{z} = -fN\sin\gamma - \dot{z}\frac{dm}{dt}.
\end{aligned}\right\} \tag{15}$$

Since the rate of the soil clod mass reduction with the passage of time, i.e. the value $\frac{dm}{dt}$ is of prime importance at this stage, it has to be determined with the use of the system of differential equations (15).

For that purpose, the following is to be done. First, from the first two equations of the system (15) the expressions for the derivative $\frac{dm}{dt}$ are found and, after equating them to each other and then making a number of simple transformations, the expression for determining the normal reaction N is obtained in the following form:

$$N = \frac{B}{C}, \tag{16}$$

where

$$\begin{aligned}
B = m\Bigg[&\frac{\ddot{x}}{\dot{x}} - \frac{\ddot{y}}{\dot{y}} + \frac{\omega^2 A}{2\dot{x}}\sin 2(\alpha_0+\omega t) + \\
&+\frac{\omega^2\cdot A}{\dot{y}}\sin^2(\alpha_0+\omega t) - \frac{g}{\dot{y}}\Bigg],
\end{aligned} \tag{17}$$

and

$$C=\frac{-\cos\left(\alpha_0+\omega t\right)+f\cos\gamma\cdot\sin\left(\alpha_0+\omega t\right)}{\dot{x}}-$$
$$-\frac{\sin\left(\alpha_0+\omega t\right)+f\cos\gamma\cdot\cos\left(\alpha_0+\omega t\right)}{\dot{y}}. \tag{18}$$

The value of $\frac{dm}{dt}$ is also to be found from the third equation of the system (15). It is equal to:

$$\frac{dm}{dt}=-\frac{m\ddot{z}+fN\cdot\sin\gamma}{\dot{z}}. \tag{19}$$

After that, the value of the normal reaction N in accordance with the earlier obtained expression (16) can be substituted into the formula (19). The following is obtained:

$$\frac{dm}{dt}=-\frac{m\ddot{z}+f\cdot\frac{B}{C}\sin\gamma}{\dot{z}}, \tag{20}$$

where B and C are determined with the use of the expressions (17) and (18) respectively.

Considering the earlier made assumption about the sufficiently small displacement (slipping) of the soil clod M in the cross-section of the spiral relative to its surface, it can be assumed within the practically acceptable accuracy that the movement of the body on the surface of the spiral is described in this way. In view of the fact that the displacement of the soil clod M is effected under the action of the turn of the spiral, the equation of which is a helical line equation in the parametric form, it can be represented, according to (Ye et al., 2017), as follows:

$$\left.\begin{aligned}
x&=-R\cdot\cos\left(\alpha_0+\omega t\right),\\
y&=R\cdot\sin\left(\alpha_0+\omega t\right),\\
z&=\frac{S}{2\pi}\cdot\left(\alpha_0+\omega t\right),
\end{aligned}\right\} \tag{21}$$

Hence, it is possible to determine the projections of the velocity and acceleration of the soil clod M onto the axes x, y and z of the Cartesian coordinate system.

At the beginning, the projections of the velocity of the said body M on the respective coordinate axes in the assumed coordinate system $xOyz$ are to be determined. For that purpose, the equations (21) are differentiated with respect to the time t. The result is as follows:

$$\left.\begin{aligned}
\dot{x}&=\omega R\cdot\sin\left(\alpha_0+\omega t\right),\\
\dot{y}&=\omega R\cdot\cos\left(\alpha_0+\omega t\right),\\
\dot{z}&=\frac{S}{2\pi}\cdot\omega.
\end{aligned}\right\} \tag{22}$$

Further, after differentiating the components of the expression (22) with respect to the time t, it becomes possible to obtain the values of the projections of the spiral turn acceleration on the respective coordinate axes:

$$\left.\begin{aligned}\ddot{x} &= R\omega^2\cdot\cos\left(\alpha_0+\omega t\right),\\ \ddot{y} &= -R\omega^2\cdot\sin\left(\alpha_0+\omega t\right),\\ \ddot{z} &= 0.\end{aligned}\right\}\tag{23}$$

In view of the assumption that the body M moves on the working surface without slipping, which assumption, as indicated earlier, can be made within the practically sufficient accuracy, there are good reasons to conclude that the acceleration of the body M is equal to the acceleration of that turn of the spiral, on which the body resides at the current instant of time.

Substituting the obtained values (22) and (23) into the expressions (17) and (18) respectively, the following is arrived at:

$$\begin{aligned}B = m\Bigg[&\frac{\omega}{\tan\left(\alpha_0+\omega t\right)}+\omega\cdot\tan\left(\alpha_0+\omega t\right)+\\ &+\frac{\omega\cdot A\cdot\cos\left(\alpha_0+\omega t\right)}{R}+\frac{\omega\cdot A\cdot\sin^2\left(\alpha_0+\omega t\right)}{R\cdot\cos\left(\alpha_0+\omega t\right)}-\\ &-\frac{g}{\omega\cdot R\cdot\cos\left(\alpha_0+\omega t\right)}\Bigg],\end{aligned}\tag{24}$$

and

$$\begin{aligned}C = &\frac{-\cos\left(\alpha_0+\omega t\right)+f\cos\gamma\cdot\sin\left(\alpha_0+\omega t\right)}{\omega\cdot R\cdot\sin\left(\alpha_0+\omega t\right)}-\\ &-\frac{\sin\left(\alpha_0+\omega t\right)+f\cos\gamma\cdot\cos\left(\alpha_0+\omega t\right)}{\omega\cdot R\cdot\cos\left(\alpha_0+\omega t\right)}.\end{aligned}\tag{25}$$

Further, substituting the values of $\dot{z}$ and $\ddot{z}$ found in (22) and (23) into the equation (20), the following is finally obtained:

$$\frac{dm}{dt}=-\frac{2\pi f\cdot\dfrac{B}{C}\cdot\sin\gamma}{S\cdot\omega}\tag{26}$$

where the values of B and C are determined in accordance with the expressions (24) and (25) respectively.

Thus, the differential equation of the variation (in this case decreasing) of the mass of the soil clod M with the time t under the action of the forces shown in the equivalent schematic model (Fig. 2) taking into account the design and kinematic parameters of the spiral potato heap cleaning unit has been obtained.

Solving and analysing the solution of the obtained differential equation enables finding the rational design and kinematic parameters of the cleaning unit that ensure the efficient reduction of the mass of the soil clods arriving together with the potato heap lifted from the soil and fed onto the top cleaning surface of the spiral cleaning unit.

The differential equation (26) is nonlinear. It can be solved only with the use of numerical methods and the assistance of a PC.

In order to perform the numerical computation, the first step is to write down the initial conditions required for solving the problem.

At $t = 0$:

$m = m_0$;

$\alpha_0 = \dfrac{\pi}{4}$;

$x = x_0 = -R\cos\alpha_0$;

$y = y_0 = R\sin\alpha_0$;

$z = z_0 = \dfrac{S}{2\pi}\alpha_0$;

$\dot{x} = \dot{x}_0 = \omega R \cdot \sin\alpha_0$;

$\dot{y} = \dot{y}_0 = \omega R \cdot \cos\alpha_0$;

$\dot{z} = \dot{z}_0 = \dfrac{S}{2\pi} \cdot \omega \cdot$

For the PC-assisted numerical computation, the design and kinematic parameters of the spiral potato heap cleaning unit of our design that has been tested in production conditions and subjected to laboratory and field laboratory experimental investigations have been used. The main parameters of the potato heap cleaning unit input in the PC-assisted numerical computation have been as follows:

$m_0 = 0.2$ kg; $R = 0.15$ m; $S = 0.035$ m; $\gamma = 20°$; $\omega = 10, 20, 30, 40, 50$ rad·s^{-1}; $f = 0.5$; $A = 0.005$ m.

On the basis of the results of solving the differential equation (26) on a PC with the use of the specially developed programme in the Mat Lab environment, the diagram of the function $m = m(t)$ presented in Fig. 3 has been plotted.

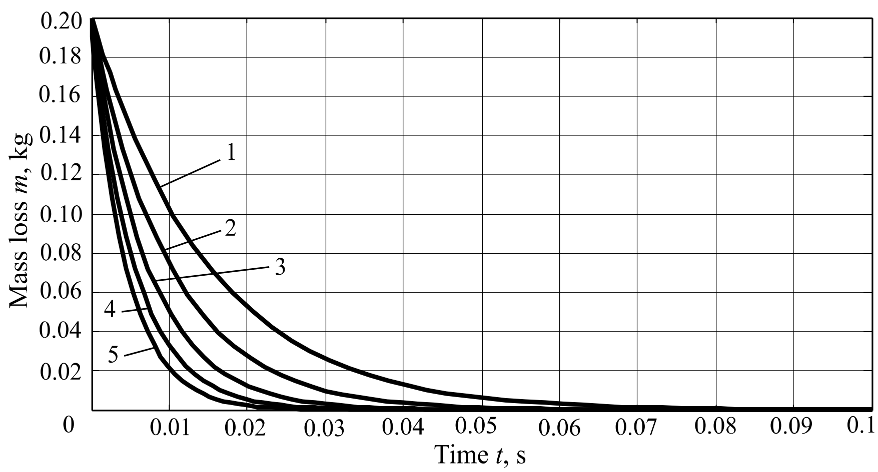

Figure 3. Reduction of soil clod mass $m = m(t)$ as function of time t at different values of spiral roll's angular velocity ω: 1 – ω = 10 rad·s^{-1}; 2 – ω = 20 rad·s^{-1}; 3 – ω = 30 rad·s^{-1}; 4 – ω = 40 rad·s^{-1}; 5 – ω = 50 rad·s^{-1}.

As is seen from the graphs shown in Fig. 3, when the angular velocity ω of rotation of the spiral roll increases, the mass m_0 of the soil clod fed to the top working surface is reduced at a higher rate. That is, at ω = 10 rad·s^{-1} the mass of the soil clod decreases from its initial value of m_0 = 0.2 kg to zero in 0.07 s, at ω = 20 rad·s^{-1} the soil clod mass falls from a value of $m_0 = 0.2$ kg to zero in 0.05 s, at $\omega = 30$ rad·s^{-1} – in 0.035 s, at $\omega = 40$ rad·s^{-1} – in 0.030 s, at $\omega = 50$ rad·s^{-1} – in 0.025 s. Therefore, it is obvious that the separating capacity (rate of separation) of the spiral cleaning unit increases together with the increase of the angular velocity ω of rotation of the spiral roll.

At the same time, the value $\Delta m(t) = m_0 - m(t)$ represents the mass of the soil sieved through the surface of the spiral separator at an arbitrary instant of time t.

In Fig. 4 and Fig. 5, the diagrams that represent the three-dimensional relations between the time t of the separation of a soil clod with a mass of m_0 and the radius of the spiral R and the amplitude of the oscillations of the spiral A, as well as the radius of the spiral R and the helix angle of the spiral γ respectively are shown.

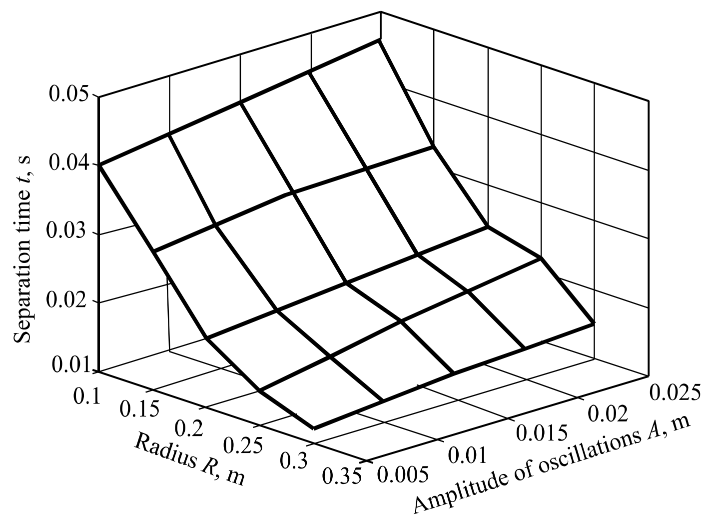

Figure 4. Relation between time t of separation of soil clod with mass m_0 and radius R of spiral and amplitude A of oscillations of spiral.

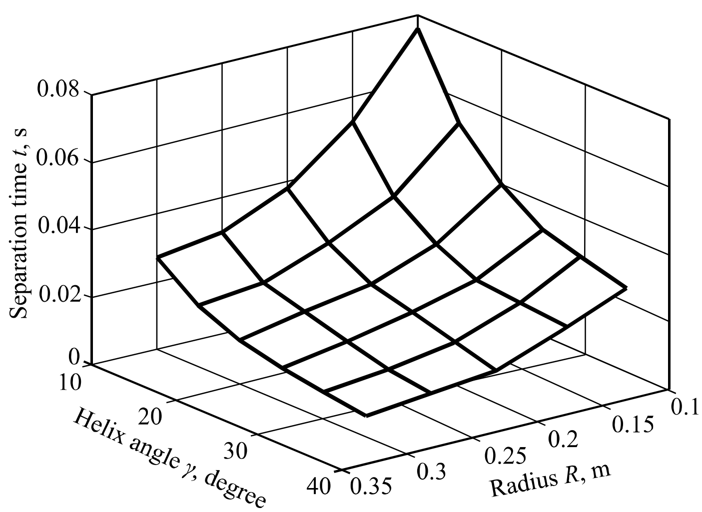

Figure 5. Relation between time t of separation of soil clod with mass m_0 and radius of spiral R and helix angle of spiral γ.

It can be concluded from the graph shown in Fig. 4 that with the increase of the spiral roll's radius R from 0.10 m to 0.30 m the time of the complete disintegration of the soil clod and, accordingly, its final sieving out is reduced from 0.04 s to 0.01 s, which gives evidence of the substantial effect that the radius R of the spiral has on the disintegration of the soil arriving to the working surface of the cleaning unit. At the same time, the increase of the amplitude of the oscillatory motion of the spiral from 0.005 m to 0.025 m has only an insignificant effect on the process of breaking down the soil clod and, accordingly, on the separation rate.

As is seen from the graph shown in Fig. 5, with the increase of the helix angle γ of the helical line of the spiral from 10° to 30° the time t of the separation of the soil clod under consideration at a spiral radius of R = 0.28 m decreases from 0.028 s to 0.005 s, at R = 0.10 m – from 0.075 s to 0.026 s. Hence, a greater value of helix angle γ in the spiral of the spiral roll contributes to the improvement of the separating capacity of the spiral cleaning unit.

In Fig. 6 – Fig. 8, the diagrams of the relations between the residual mass m on the surface of the cleaning roll and the radius R of the spiral, its helix angle γ and the amplitude A of the oscillations of the spiral in the process of the unit's operation are presented.

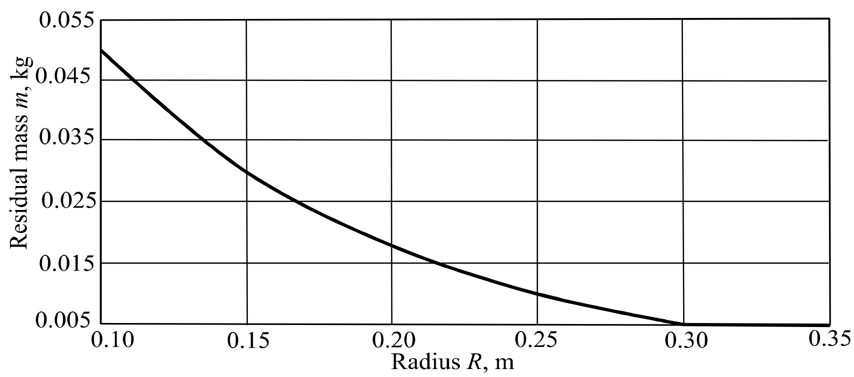

Figure 6. Relation between residual mass $m = m(R)$ and radius R of spiral.

As is evident from the graph plotted in Fig. 6, the increase of the radius R of the spiral to 0.30 m ensures the virtual absence of the residual mass m in the soil clod residing on the surface of the spiral cleaning unit.

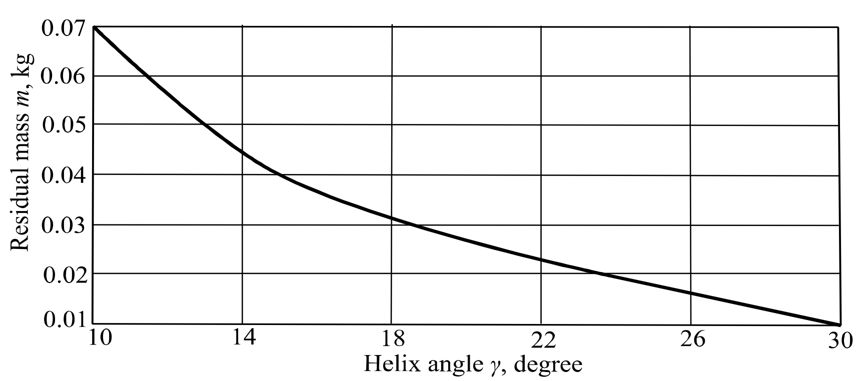

Figure 7. Relation between residual mass $m = m(\gamma)$ and helix angle γ of spiral.

The diagram shown in Fig. 7 indicates that the increase of the spiral's helix angle γ similarly provides for the virtual absence of the residual mass m of the soil clod on the surface of the cleaning roll.

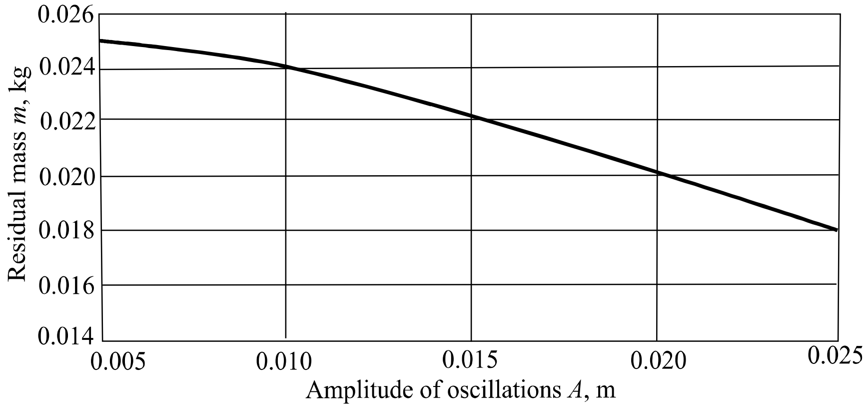

Figure 8. Relation between residual mass $m = m(A)$ and amplitude A of oscillations of spiral.

However, the variation of the amplitude A of the oscillations of the spiral does not, as is obvious from the graph presented in Fig. 8, produce any substantial effect on the reduction of the residual mass m of the soil clod fed onto the surface of the spiral roll in the spiral cleaning unit.

CONCLUSIONS

1. A mathematical model of the process of sieving the elements of the potato heap lifted from the soil in the spiral cleaning unit has been generated.
2. The differential equation of the process of gradually reducing the mass of the soil clod fed to the working surface of the spiral cleaning unit considering it as a function of the time of the soil clod's movement on the spiral of the cleaning roll has been generated taking into account the design and kinematic parameters of the cleaning unit.
3. The PC-assisted calculations carried out in the Mat Lab environment have shown that the increase of the angular velocity of rotation of the spiral roll results in the considerable decrease of the time, in which the process of reducing the mass of the investigated soil clod is completed. That is, when the angular velocity changes from 10 to 50 rad·s^{-1}, the time of complete sieving out decreases from 0.07 to 0.025 s.
4. The increase of the spiral's radius R also leads to the significant reduction of the time t spent for the complete sieving out of a single soil clod. Thus, when the spiral's radius R increases from 0.10 m to 0.30 m, the time of complete sieving out becomes reduced from 0.04 s to 0.01 s.
5. The increase of the cleaning spiral's helix angle γ has a substantial effect on the process of the complete sieving out of soil clods. When the said helix angle increases from 10° to 30°, the time spent for the complete sieving out of the soil at $R = 0.10$ m is reduced from 0.75 s to 0.026 s, at $R = 0.28$ m – from 0.028 s to 0.005 s.
6. It has also been established that the change of the spiral's radius R and its helix angle γ has a substantial effect on the residual mass of the soil clod. The amplitude A of

the oscillatory motion of the spiral has an effect of no significance on the residual mass of the soil clod.

7. Therefore, the rational design and kinematic parameters of the spiral cleaning unit that provide for the high-rate separation of the potato heap have been theoretically substantiated.

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