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Numerical modelling of process of cleaning potatoes in spiral separator

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Abstract. Cleaning potato tubers from soil and plant residues after their digging from the soil is a topical problem in the industrial production of potatoes. Taking into account the fact that the cleaning spirals are positioned with overlapping and rotate in the same sense, the potato tuber that has landed on the surface of the spiral separator in the trough between two adjacent spirals will perform translational motion towards the output ends of the spirals. As a result of solving the said system of equations, the graphical relations between the values of the normal reactions and friction forces generated during the translation of the potato tuber along the mentioned spirals, on the one hand, and the design and kinematic parameters, on the other hand, based on the requirement of not damaging tubers when performing the said work process of transportation and cleaning, have been obtained. The limitations for the normal reactions and friction forces at the points of contact between the tuber and the surface of the cleaning spiral are set in accordance with the requirement that they do not exceed the force of scraping (damaging) the tuber's external surface permissible for potato tubers. That has provided an opportunity to obtain the rational values of the design and kinematic parameters of the separator's operating spirals, in particular, the value of the angular velocity of the rotating cleaning spirals as well as their radius and helix lead.

Key words: post-harvest processing, potato, rational parameters, surface of the spiral separator.

INTRODUCTION

The advancement of the work process of potato production is a topical problem worldwide. One of the most important phases in the said work process is the cleaning of potato tubers from soil and plant residues after their digging out from the soil (Misener & McLeod, 1989; Peters, 1997; Veerman & Wustman, 2005; Bishop et al., 2012; Ichiki et al., 2013; Gou & Campanella, 2017; Wang et al., 2017). This phase provides for the high quality of the harvested product, while the possibility of damaging the product in it must be ruled out (Petrov, 2004).

The spiral separator of our design (Bulgakov et al., 2018a & 2018b) delivers, according to the results of the implemented experimental investigations, a sufficiently high level of cleaning the potato tubers from soil impurities and plant debris and at the same time ensures not damaging the tubers in terms of the established agricultural technology requirements. The simple design together with the low metal and energy intensity make this potato heap separator a promising engineering solution.

However, the varying conditions of harvesting, including the condition of the dug potato bed (the humidity and hardness of the soil in the ridge area, the presence of rhizomae, stones and hardened soil bodies, haulm residues) as well as the quantity of potato tubers differing in their weights, dimensions and shapes, necessitate repeatedly changing the engineering and process characteristics of the above-mentioned separator in order to ensure the achievement of the described performance of the work process of cleaning (Feller et al., 1987).

Such a situation gives rise to a problem of scientific substantiation of such rational design and kinematic parameters of the spiral potato heap separator under consideration that would provide for the high quality of cleaning under different physical and mechanical properties of the soil and the potato tubers themselves. Carrying out fundamental theoretical research into the process of interaction between the potato heap and, in particular, the potato tubers and the operating components of the spiral separator under consideration is an important step towards solving the above-mentioned problem (Krause & Minkin, 2015). Therefore, earlier in paper (Bulgakov et al., 2018c), we developed a mathematical model of cleaning potato tubers from soil and plant residues with the use of the spiral separator subject to the requirement of not damaging the potato tubers. In particular, the conditions, in which a single potato tuber approximated by a body shaped similar to a sphere was situated in the space between two adjacent spiral springs of the separator, were determined. All the relevant existing forces were applied to the potato tuber's body and the conditions were determined for the movement of the potato tuber in the said space as in the only place, where its displacement along the axes of the spiral cleaning springs, i.e. its cleaning from impurities and discharge from the area of cleaning, is ensured. As a result of the mathematical modelling, a system of differential equations was generated, its transformations were carried out and the necessary conditions were found that provide for the guaranteed movement of a single potato tuber on the cleaning surface of the spiral separator under consideration.

In the present study, the mathematical model developed in paper (Bulgaov et al., 2018c) has been used to perform the numerical calculations on a PC in order to substantiate the rational and practical parameters of the earlier developed new design of a spiral separator. At the same time, in the said calculations provisions have been made for the movement of the potato tuber without being damaged.

The aim of the study is to raise the quality of the cleaning of potato tubers from soil and plant impurities taking into account the requirement of not damaging them by means of analytically substantiating the design and kinematic parameters of the spiral separator on the basis of the calculation and analysis of the mathematical model of the interaction between the potato heap and the separator's operating surface.

MATREIALS AND METHODS

The investigations have been carried out with the use of techniques from the theoretical mechanics (Vasilenko, 1996), in particular, the dynamics of constrained particle, the higher mathematics, the techniques of designing computer programmes and performing numerical calculations on a PC as well as analysing the obtained results.

As already mentioned, in paper (Bulgakov et al., 2018c) a new mathematical model of the movement of a single tuber in the space between two adjacent cleaning spiral springs was developed on the basis of the earlier elaborated pattern of forces acting in the interaction between a potato tuber and the operating surface of a spiral separator. Nevertheless, in that study the process of the movement of the potato tuber approximated by a spherical body on the surface of the spiral separator was not investigated fully, because the conditions of such a movement were not represented in their final form and PC-assisted calculations were not carried out for the generated differential equations of motion.

In order to perform further analytical investigations, the equivalent schematic model of a potato tuber's motion has been refined in order to most fully take into account all the forces supporting the movement of a single potato tuber in the trough between two spiral springs. The resulting equivalent schematic model is shown in Fig. 1.

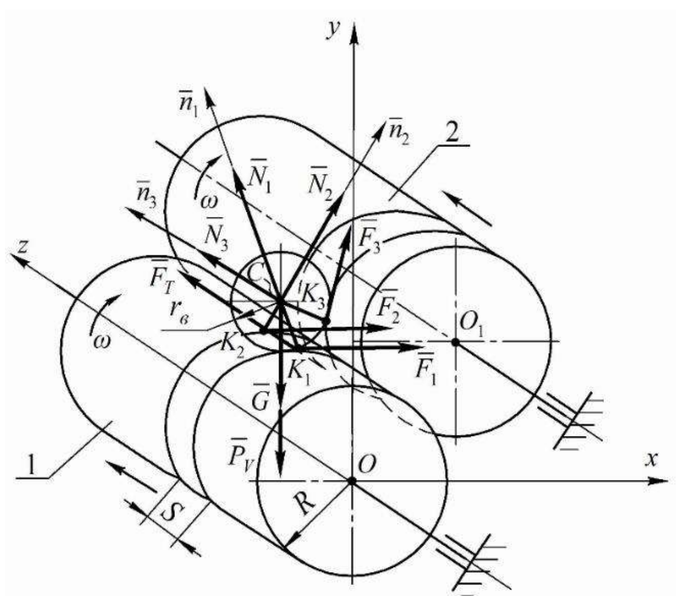

Figure 1. Equivalent schematic model of interaction between single potato tuber and two spiral springs, when tuber is situated in trough between springs

As is seen from the presented refined equivalent schematic model, the motion of the single potato tuber along the longitudinal axes of the spirals has to be guaranteed by the main propelling force $\bar{F}_T$ that appears at the point of contact K_1 with supporting spiral turn 1. At the same time, forces propelling the tuber can arise to some extent also at other points of contact between the single potato tuber and the spirals, such as K_2 on spiral 1 and point K_3 on the supporting turn of spiral 2. But, for the purposes of solving this particular problem, the potato tuber propelling forces that appear on the coils at points

K_2 and K_3, by reason of their smallness, can be neglected at a first approximation and it can be assumed that it is exactly point K_1 where the force $\bar{F}_T$ must be applied. It is also assumed that the vector of the said force $\bar{F}_T$ is parallel to the longitudinal axes of spirals 1 and 2.

Complex mechanical and mathematical investigations and transformations have been carried out and on their basis a mathematical model of a single potato tuber's motion comprising three differential equations of motion has been developed. The model appears as follows (Bulgakov et al., 2018c):

$$\left.\begin{aligned}
&m\ddot{x} = \left(N_1 + N_2 - N_3\right)\times \\
&\times\frac{A\sin(\omega t) + B\cos(\omega t)\cdot\sin(2\omega t)}{\sqrt{\left[A\sin(\omega t) + B\cos(\omega t)\cdot\sin(2\omega t)\right]^2 + \left[A\cos(\omega t) + B\sin(\omega t)\cdot\sin(2\omega t)\right]^2 + C^2\cos^2(2\omega t)}} - \\
&-\left(F_1 + F_2 + F_3\right)\frac{2\pi R\sin(\omega t)}{\sqrt{4\pi^2R^2 + S^2}}, \\
&m\ddot{y} = \left(N_1 + N_2 + N_3\right)\times \\
&\times\frac{A\cos(\omega t) + B\sin(\omega t)\cdot\sin(2\omega t)}{\sqrt{\left[A\sin(\omega t) + B\cos(\omega t)\cdot\sin(2\omega t)\right]^2 + \left[A\cos(\omega t) + B\sin(\omega t)\cdot\sin(2\omega t)\right]^2 + C^2\cos^2(2\omega t)}} - \\
&-\left(-F_1 - F_2 + F_3\right)\frac{2\pi R\cos(\omega t)}{\sqrt{4\pi^2R^2 + S^2}} - mg - P_V, \\
&m\ddot{z} = \left(N_1 - N_2 + N_3\right)\times \\
&\times\frac{C\cos(2\omega t)}{\sqrt{\left[A\sin(\omega t) + B\cos(\omega t)\cdot\sin(2\omega t)\right]^2 + \left[A\cos(\omega t) + B\sin(\omega t)\cdot\sin(2\omega t)\right]^2 + C^2\cos^2(2\omega t)}} - \\
&-\left(F_1 + F_2 + F_3\right)\frac{S}{\sqrt{4\pi^2R^2 + S^2}},
\end{aligned}\right\} \quad (1)$$

where

$$A = -\frac{S^2}{4\pi^2R}\cdot\cos\left(\frac{S}{2\pi R}\right)$$

$$B = \frac{S^2}{4\pi^2R}\cdot\cos\left(\frac{S}{2\pi R}\right) - \frac{S^3}{8\pi^3R^2}\cdot\sin\left(\frac{S}{2\pi R}\right)$$

$$C = \frac{S}{2\pi}\cdot\cos\left(\frac{S}{2\pi R}\right)$$

R – radius of spiral; S – lead of helix; m – mass of potato tuber; f – coefficient of sliding friction of the potato tuber's surface on the operating surface of the spiral; g – acceleration of gravity; P_V – force of impact of the fed potato heap on the spiral separator (vectored vertically down); ω – angular velocity of the rotating spiral about its figure axis; N_1, N_2 – normal reaction forces generated by the two adjacent turns of the first spiral, with which the potato tuber is in contact, when it is situated in the trough between the two adjacent spirals; N_3 – normal reaction force generated by the turn of the second spiral, with which the tuber is in contact at the given moment; F_1, F_2 and F_3 – forces of friction acting at the respective points of contact K_1, K_2 and K_3.

RESULTS AND DISCUSSION

The analysis of the obtained mathematical model includes first of all the solving of the system of differential Eqs (1) for the unknown functions $x = x(t)$, $y = y(t)$ and $z = z(t)$. The values of the normal reactions N_1, N_2 and N_3 can be determined on the basis of the conditions of the equilibrium of the potato tuber situated in the trough between the two adjacent spirals. These conditions were obtained earlier in (Bulgakov et al., 2018b) in the form of a system of linear equations with variable coefficients and unknown quantities N_1, N_2 and N_3. The solving of the mentioned system of linear equations could provide the values of the normal reactions N_1, N_2 and N_3 with an accuracy that is sufficient for practical purposes.

The solving of the above equations was carried out with the use of a PC, which resulted in obtaining the following mean values of the normal reactions: $N_1 = 1.50$ N, $N_2 = 1.50$ N and $N_3 = 1.00$ N. These theoretically obtained mean values of the normal reactions were later proved by the respective experimental investigations.

Also, experimental investigations and theoretical research have been undertaken in order to determine the value of the propelling force F_T that is responsible for the displacement of the potato tuber along the longitudinal axis of the cleaning spiral. Thus, from the results of the accomplished field experiment research into the operation of the spiral separator, its energy characteristics have been determined, in particular, the power consumption P by the drive of the spiral separator as during its idle run, so when the heap of cleaned potato tubers is fed onto the cleaning surface at a rate of 30 kg s^{-1} (Bulgakov et al., 2017).

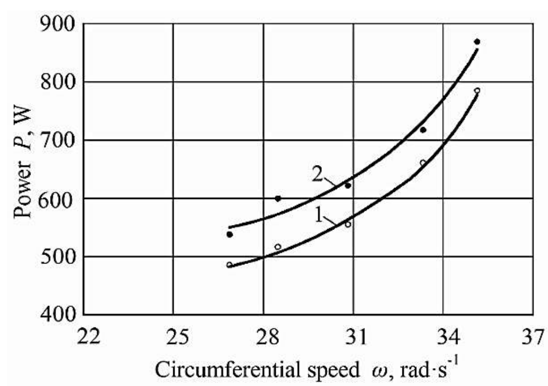

Figure 2. Relation between consumed power P required for driving rotational motion of three spirals of separator and angular velocity ω of its rotating spirals: 1 – idle running; 2 – heap feeding at a rate of 30 kg·s^{-1}.

The results obtained in the course of the experimental investigations and processed with the use of a PC have made it possible to determine the relation between the consumed power P and the angular velocity ω of the cleaning spiral rolls and plot the diagrams showing the relation (Fig. 2).

As is seen from the diagrams (Fig. 2), the power P consumed for driving the spiral rolls (3 pcs) under the operating load can reach the order of 850 W at an angular velocity

ω of the rotating rolls of about 40 rad·s^{-1}, when the heap of the cleaned potato tubers is fed to the rolls at a rate of 30 kg s^{-1}.

Meanwhile, in order to determine the value of the power P needed for the calculation of the propelling force F_T applied by only one turn of one spiral, it is necessary to subtract the power consumed by the separator during its idle running from the total power consumed by the separator, take the adjusted value of the power into account in the feeding of the potato heap to the complete cleaning surface of the separator and then, on the basis of the fact that the propelling force is generated by only one of the spiral rolls, the maximum value of the power P needed for the calculation of the propelling force F_T is assumed to be not exceeding 85.00 W on an average.

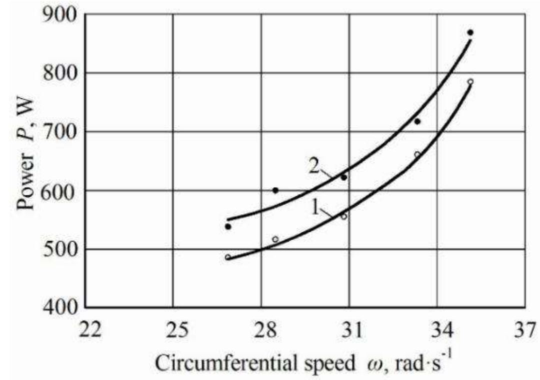

Figure 2. Relation between consumed power P required for driving rotational motion of three spirals of separator and angular velocity ω of its rotating spirals: 1 – idle running; 2 – heap feeding at a rate of 30 kg·s^{-1}.

Proceeding from the value of the consumed power P determined from the results of the experimental investigations, it is necessary to find the torque M_{kw} of the drive shaft of one of the separator's spirals. For that purpose, the following relation can be used:

$$M_{kw} = \frac{P}{\omega}, \quad (2)$$

where M_{kw} – torque of the drive shaft of a single cleaning spiral; ω – angular velocity of the rotating spiral.

Hence, taking into account (2), the value of the propelling force F_T is equal to:

$$F_T = \frac{M_{kw}}{R}\sin\gamma = \frac{P}{\omega \cdot R}\sin\gamma, \quad (3)$$

where R – spiral's radius; γ – lead angle of the helical line of the separator's spiral.

Further, the results of the experimental investigations have been used to determine the value of the force P_V that is a member of the system of differential Eqs (1). It has been proved by the results of the experimental investigations that the maximum mass of a soil lump that can be found in the potato heap coming into the separator is in the majority of cases two times greater than the average mass of a potato tuber (Bulgakov et al., 2017). Therefore, following the results of the done measurements, the force P_V of the impact of the fed potato heap on a single potato tuber situated in the trough between two adjacent spirals is assumed to be equal to:

$$P_V = 2mg, \quad (4)$$

where m – mass of the potato tuber.

Thus, all the data necessary for the transformation of the system of differential Eqs (1) into the following new form have been finally obtained:

$$\left.\begin{aligned}
&m\ddot{x} = \left(N_1 + N_2 - N_3\right)\times \\
&\times\frac{A\sin(\omega t) + B\cos(\omega t)\cdot\sin(2\omega t)}{\sqrt{\left[A\sin(\omega t) + B\cos(\omega t)\cdot\sin(2\omega t)\right]^2 + \left[A\cos(\omega t) + B\sin(\omega t)\cdot\sin(2\omega t)\right]^2 + C^2\cos^2(2\omega t)}} - \\
&-\left(F_1 + F_2 + F_3\right)\frac{2\pi R\sin(\omega t)}{\sqrt{4\pi^2 R^2 + S^2}}, \\
&m\ddot{y} = \left(N_1 + N_2 + N_3\right)\times \\
&\times\frac{A\cos(\omega t) + B\sin(\omega t)\cdot\sin(2\omega t)}{\sqrt{\left[A\sin(\omega t) + B\cos(\omega t)\cdot\sin(2\omega t)\right]^2 + \left[A\cos(\omega t) + B\sin(\omega t)\cdot\sin(2\omega t)\right]^2 + C^2\cos^2(2\omega t)}} - \\
&-\left(-F_1 - F_2 + F_3\right)\frac{2\pi R\cos(\omega t)}{\sqrt{4\pi^2 R^2 + S^2}} - 3mg, \\
&m\ddot{z} = \frac{P}{\omega\cdot R}\sin\gamma + \left(N_1 - N_2 + N_3\right)\times \\
&\times\frac{C\cos(2\omega t)}{\sqrt{\left[A\sin(\omega t) + B\cos(\omega t)\cdot\sin(2\omega t)\right]^2 + \left[A\cos(\omega t) + B\sin(\omega t)\cdot\sin(2\omega t)\right]^2 + C^2\cos^2(2\omega t)}} - \\
&-\left(F_1 + F_2 + F_3\right)\frac{S}{\sqrt{4\pi^2 R^2 + S^2}},
\end{aligned}\right\} \quad (5)$$

Specifically for our design of the spiral potato heap separator (Bulgakov, et al., 2018a), the system of differential Eqs (5) has been solved using the following values of the design and kinematic parameters included in the said system of equations: $R = 0.025…0.25$ m; $S = 0.035$ m; $m = 0.40$ kg; $g = 9.81$ m·s^{-2}; $f = 0.2$; $\omega = 20…40$ rad·s^{-1}; $N_1 = 1.50$ N; $N_2 = 1.50$ N; $N_3 = 1.00$ N; $P_V = 85$ N; $\gamma = 20°$.

As a result of solving the above system of Eqs (5) with the use of the Runge-Kutta method on a PC in the MathCad environment, the graphical representations of the relations between the values of the variables $x = x(t)$, $y = y(t)$ and $z = z(t)$, on the one hand, and a number of values of the initial design and kinematic parameters of the spiral separator, on the other hand, which show the displacements of the potato tuber along the *Ox*, *Oy* and *Oz* axes at an arbitrary instant of time t, have been obtained.

The obtained graphical relations are presented in Fig. 3, Fig. 4, Fig. 5 and Fig. 6. In Fig. 3, the variation of the z coordinate of the potato tuber's centre of mass C with the time t for different values of the angular velocity ω of the rotating spiral is shown.

In Fig. 4, the variation of the z coordinate of the potato tuber's centre of mass C with the time t is plotted for different values of the spiral's radius R.

According to the diagrams in Fig. 3, under the above-mentioned parameters of the spiral separator, the displacement of the potato tuber along the *Oz* axis, i.e. longitudinally, in $t = 0.3$ s is equal to 0.60 m at an angular velocity value equal to $\omega = 30$ rad s^{-1}. At an angular velocity equal to $\omega = 30$ rad s^{-1}, the said displacement is equal to 0.44 m, at an angular velocity of $\omega = 40$ rad s^{-1} – 0.33 m.

Also, as is seen from the presented graphical relations, the displacement of the potato tuber along the *Oz* axis, i.e. along the spiral's figure axis, changes following a law that is close to parabolic. Moreover, when the angular velocity ω of the rotating spirals increases, the value of the tuber's displacement in the same time *t* decreases.

That is due to the fact that, at the pre-set consumed power *P*, the value of the torque M_{kw} produced by the spiral's drive shaft and, accordingly, of the propelling force F_T generated by the spiral's supporting turn decreases with the increase of the angular velocity ω, which results in the reduction also of the velocity and displacement of the potato tuber along the line under consideration.

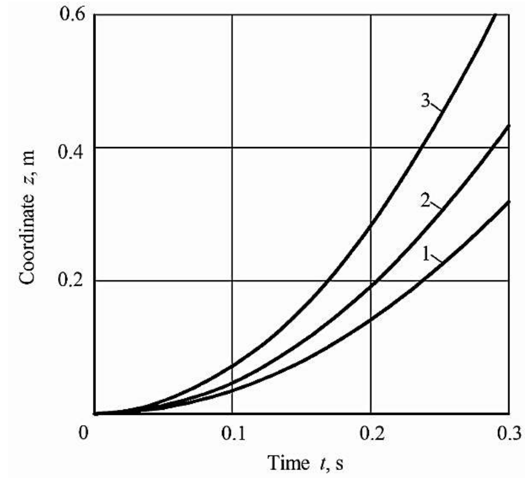

Figure 3. Cases of variation of *z* coordinate, i.e. displacement of potato tuber's centre of mass *C* along longitudinal axis of spiral spring with time *t*, for: 1) $\omega = 20$ rad·s^{-1}; 2) $\omega = 30$ rad·s^{-1}; 3) $\omega = 40$ rad s^{-1}.

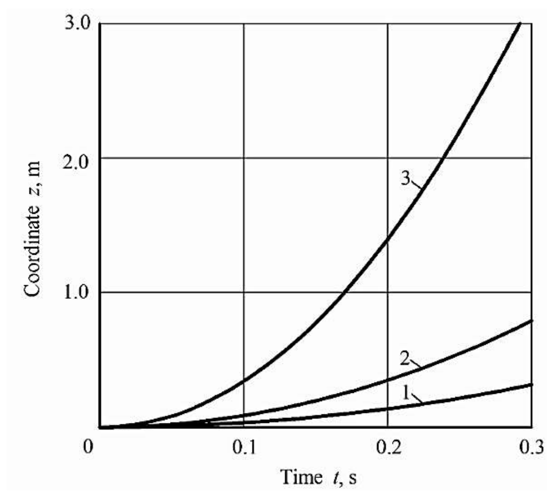

Figure 4. Cases of variation of *z* coordinate, i.e. displacement of potato tuber's centre of mass *C* along longitudinal axis of spiral spring, with time *t* for: 1) $R = 0.025$ m; 2) $R = 0.10$ m; 3) $R = 0.25$ m.

The diagrams in Fig. 4 show that the displacement of the potato tuber along the *Oz* axis, i.e. along the spiral's figure axis, in a time interval of $t = 0.3$ s is equal to 3.2 m, when the spiral's radius has a value of $R = 0.025$ m, in case of $R = 0.10$ m it is equal to 0.75 m, in case of $R = 0.25$ m– 0.30 m. Hence, the increase of the spiral's radius *R* results in the decrease of the value of the tuber's displacement along the spiral's longitudinal axis.

The reason for such a relation is the fact that the increase of the spiral's radius *R* causes the torque M_{kw} of the spiral's drive shaft and, accordingly, the propelling force F_T to decrease, which results in the reduction of both the velocity and displacement of the potato tuber along the trough between the two adjacent spirals.

The analysis of the diagrams presented in Fig. 3 and Fig. 4 provides evidence that the spiral potato heap separator under consideration possesses a high transporting capability along the longitudinal axes of its spirals.

In Fig. 5 and Fig. 6, the diagrams are shown for the variation of the *y* and *x* coordinates of the potato tuber's centre of mass *C* with the time *t*, i.e. the displacement of the potato tuber across the trough between the two adjacent spirals.

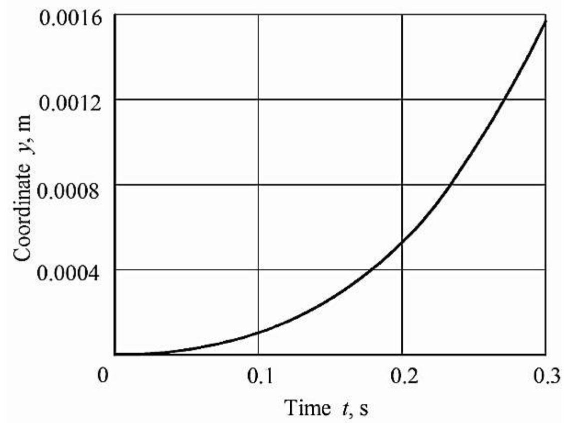

Figure 5. Variation of *y* coordinate, i.e. vertical displacement of potato tuber's centre of mass *C*, with time *t*.

As is seen from the graphical relation presented in Fig. 5, the vertical displacement of the potato tuber, i.e. its motion along the *Oy* axis in a time interval of $t = 0.3$ s is equal to 0.0016 m, which implies that the tuber moves virtually without losing the contact with the turns of the spirals.

The diagram in Fig. 6 shows that the displacement of the potato tuber along the *Ox* axis in the same time $t = 0.3$ s is negligible, being equal to mere 0.0018 m.

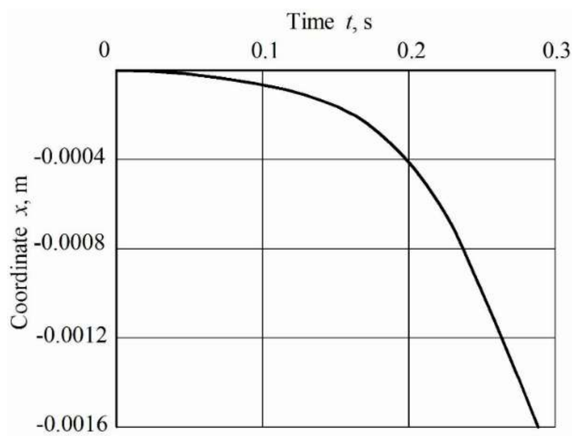

Figure 6. Variation of *x* coordinate, i.e. lateral displacement of potato tuber's centre of mass *C*, with time *t*.

Therefore, as can be concluded from the diagrams shown in Fig. 3–Fig. 6, the potato tuber moves along the trough between the two adjacent spirals smoothly, in virtually constant contact with the spirals and with great stability. The results of the PC-assisted calculations prove that the potato tuber in no case can be trapped or compressed between the turns of adjacent spirals. That, in its turn, ensures not damaging potato tubers during their cleaning in the spiral separator under discussion.

CONCLUSIONS

1. The PC-assisted analysis of the mathematical model of the process of cleaning potato tubers from soil and plant impurities with the use of a spiral separator subject to not damaging them has been completed. As a result of the analysis, the rational design and kinematic parameters of the separator have been substantiated.

2. The graphical relations between the displacement of a potato tuber situated in the trough between two adjacent spirals at an arbitrary instant of time and the design and kinematic parameters of the separator have been obtained.

3. The longitudinal displacement of the potato tuber (along the *Oz* axis) in 0.3 s at $\omega = 20…40$ rad s^{-1} is proved to be equal to 0.60…0.33 m, at the spiral's radius of $R = 0.025…0.250$ m – 3.20…0.30 m respectively, which implies the good transportation capability of the developed spiral separator of a new design.

4. As is seen from the obtained graphical relations, the vertical (along the *Oy* axis) and transverse (along the *Ox* axis) displacements of the potato tuber are fairly negligible and are equal to 0.0016 m and 0.0018 m respectively. That signifies that the movement of the potato tuber along the trough between the two adjacent spirals is stable and smooth, which ensures not damaging the tuber.

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