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Theory of impact interaction between potato bodies and rebounding conveyor

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Abstract. In order to increase substantially the quality of the potato heap separation, it is necessary to carry out the theoretical substantiation of the spiral separator's parameters with regard to the impact interaction between the product and the tools of the unit under the condition of not damaging the tubers. An equivalent schematic model of the impact interaction between a potato tuber and the surface of the rebounding conveyor has been devised. Taking into account the coefficient of restitution of the tuber's velocity in case of an impact, new analytical expressions have been obtained for determining the magnitude and direction of the potato tuber's velocity after the impact. They provided the basis for applying the principle of momentum at impact and obtaining the analytical expressions that allow determining the impact impulse and impact force at the impact of the tuber on the surface of the rebounding conveyor and, eventually, the dynamic constraints on the permitted velocity of the tuber prior to the impact interaction under the condition of not damaging it. A new analytical mathematical model of the impact interaction of the potato tuber during the potato heap separation has been developed. On the basis of the obtained theoretical results, studies have been carried out on the rational kinematical parameters of the high-quality performance of the above-mentioned work process under the condition of keeping the potato tubers undamaged.

Key words: potato, tuber, heap separation, impact interaction, impact impulse, rational parameters.

INTRODUCTION

As is known the potato growing is one of the agriculture sectors, where the energy consumption rates are rather high. Hence, in the development of new tools for potato harvesters and the improvement of the existing ones it is necessary to provide for the significant reduction of their energy consumption rates and the substantial increase of the output quality coupled with the minimal loss of product in the harvesting operations. One of the essential process operations in the harvesting of potatoes is the separation of the potato heap, which ensures the cleanliness of the delivered product. Thus, the cleaning tools play the principal role in securing the high performance quality indicators of potato harvesters. With that objective in mind, a new design of the potato heap separator has been developed (patent UA43907).

The experimental studies have shown that some part of the potato tubers, as well as the ground impurities with the size and mass characteristics similar to those of the tubers, overflies the cleaning tools and falls either on the field surface or on the discharge conveyor (Bulgakov et al., 2017). That results, on the one hand, in yield losses and, on the other hand, in the contamination of the obtained product with ground impurities.

Therefore, in order to eliminate the overflight of tubers above the separator, it is proposed to install a rebounding plain rubber belt conveyor. With such an arrangement, the tuber that has taken off from the separating surface will hit the elastic surface of the rebounding conveyor and returns back to the separating surface. Though, the impact interaction between the tuber and the conveyor's surface can result in damage to the former and that can reduce the overall quality of the product. Thus, to provide for the potato tubers remaining intact after the impact interaction is a rather relevant task, which is impossible to solve without carrying out theoretical research, in particular, developing the necessary mathematical model of the impact interaction. That model will provide the basis for substantiating the rational kinematic parameters of the separator's operation under the condition that potato tubers remain undamaged during the harvesting operations.

The separating tools used in state-of-the-art potato harvesters must not only ensure the reliable, high-quality performance of the work process of cleaning potato tubers from ground impurities, plant residues and stuck ground, but also be capable of self-cleaning during operation, which would provide for the required performance rate. However, it is known that the majority of separating tool systems employed in conventional potato harvesters not always ensure the high level of separation of ground impurities (Petrov, 2004). Most often this happens because of the heavy clogging of the separating tools' cleaning surfaces with wet ground.

Quite a few scientists and designers have worked on the problem of developing efficient and reliable potato heap separators as well as various cleaning systems for the use in stationary potato cleaning facilities (Zaltzman & Schmilovitch, 1985; Feller et al., 1987; Ichiki et al., 2013; Wei et al., 2013; Feng et al., 2017). Spiral separators are considered to be the most promising and technologically appropriate for the performance of the potato tuber cleaning process during the extraction of the tubers from soil under various edaphic and climatic harvesting conditions. However, while there is quite a number of existing potato heap cleaning technologies, the studies on the optimisation of the kinematic and design parameters of spiral separators are relatively few. That is especially true as regards the issue of establishing the conditions for preventing damage to potato tubers during their interaction with spiral windings, rebounding from various surfaces and further impact contacts with other tools.

The aim of this study was improving the efficiency and quality of the potato heap separation through the theoretical substantiation of the separator's rational parameters subject to the condition that the tubers are not damaged during their impact interactions.

MATERIALS AND METHODS

The theoretical studies of the impact interaction have been carried out with the use of fundamental provisions of the higher mathematics and theoretical mechanics.

The theoretical substantiation of the kinematic parameters of operation of the potato heap separator is based on the development of the mathematical model of the impact interaction between a potato tuber and the moving elastic surface of the rebounding conveyor. That requires, first of all, setting up the equivalent schematic model of the mentioned impact interaction (Fig. 1).

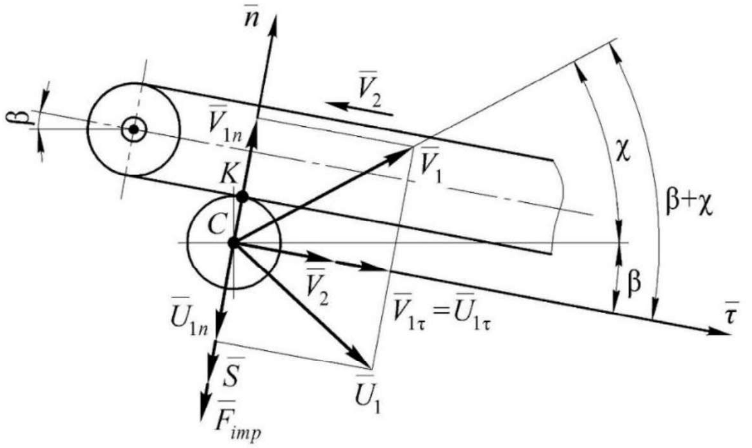

Figure 1. Equivalent schematic model of impact interaction between potato tuber and moving elastic surface of rebounding conveyor's lower flight.

The equivalent schematic model shows the rotating rebounding conveyor inclined at an angle of β to the horizon, with the working lower flight of which the potato tuber makes impact contact after taking off from the surface of the spiral separator and flying up along the flight path that intersects the conveyor's lower surface at the impact contact point *K*. In order to simplify the analytical calculations, the body of the potato tuber in the model is approximated by a spherical shape. It is obvious that the tuber in its translational movement along some flight path in the air can also perform, under the effect of the moment of friction and some other factors acting on the tuber at the moment of its taking off from the separating surface, rotary motion about some of its axes, but in the impact interaction the effect of the rotary motion on the amount of impact interaction will be insignificant. Thus, at a first approximation it is assumed that the tuber performs solely translational movement along its flight path. Moreover, taking into account the insignificant size and mass of the tuber compared to those of the conveyor, it can be regarded as a material point. Therefore, the forces acting on the tuber at the point *K* of its contact with the conveyor's surface during the impact are assumed to be applied to the tuber's centre of mass (point *C*), as is shown in Fig. 1.

In the spiral separator under consideration, the potato heap is fed for cleaning from beside the first spiral, and it is this spiral that repulses some tubers upwards. However, the distance between the cleaning surface of the whole spiral separator and the belt of the recovering and rebounding conveyor is small – it is equal to 0.45…0.50 m.

Therefore, the potato tuber rebounded from the translationally moving rubber belt of the rebounding conveyor will land now on the other spirals of the separator (the belt completely decelerates the tuber's flight): after the collision, the tuber will come down already at a small velocity (in effect tangentially) and, after travelling a very short distance, land now ahead, on the next spiral. But, this landing will not cause a significant impact effect, since almost the whole cleaning surface of the spiral separator will be completely covered with soil impurities and plant residues, hence, the 'return' of the potato tuber repulsed by the rebounding conveyor will be virtually shock-free. The tuber under consideration can sustain a repeated impact, if it hits another potato tuber. But that negative possibility can be eliminated by adjusting the inclination of the rebounding conveyor belt relative to the plane of the cleaning surface. Then the repeated impacts will certainly be oblique and have a small effect on the overall rate of damage sustained by the potato tuber bodies during their cleaning in the spiral separator.

Since the normal component of the impact impulse plays the decisive role in the process of the mentioned impact contact, it is reasonable, for the purpose of investigating the process of collision, to establish the natural system of coordinates $\bar{\tau}C\bar{n}$ with the origin set at the potato tuber's centre (point *C*), the axis $\bar{\tau}$ directed parallel to the rebounding conveyor's lower flight, the axis $\bar{n}$ – perpendicular to the said flight (i.e. along the line of action of the normal component of the impact impulse) (Fig. 1).

The following velocity vectors have to be shown in the equivalent schematic model:

$\bar{V}_1$ – potato tuber's velocity prior to collision;

$\bar{V}_2$ – velocity of rebounding conveyor's belt;

$\bar{U}_1$ – potato tuber's velocity after collision.

In this case, the velocity vector $\bar{V}_1$ is directed at an angle of χ to the horizon, the velocity vector $\bar{V}_2$ – at an angle of β to the horizon.

As a result, the angle between the vectors $\bar{V}_1$ and $\bar{V}_2$ is equal to $\beta + \chi$ (Fig. 1).

RESULTS AND DISCUSSION

On the basis of the aforesaid, the collision between a potato tuber with a mass of *m* and the rotating rebounding conveyor (its moving lower flight) with a mass of *M*, which moves with a velocity of $\bar{V}_2$, will be analysed. In comparison with the potato tuber's mass, it can be assumed that the rebounding conveyor's mass $M \to \infty$. Also, it is assumed that the impact is oblique and partially elastic (coefficient of restitution during the impact interaction $k < 1$) (Wriggers, 2006).

The velocities of the potato tuber and the rebounding conveyor after the impact can be determined following the general technique described in Petrov (2004), which is applicable for the most general case of the collision between two bodies, which have different masses and velocities. In accordance with the mentioned technique, first, the projections of the velocities on the coordinate axes $\bar{n}$ and $\bar{\tau}$ are determined for the potato tuber and the rebounding conveyor prior to the impact. According to Fig. 1, they will be:

$$V_{1n} = V_1 \sin(\beta + \chi), \tag{1}$$

$$V_{1\tau} = V_1 \cos(\beta + \chi); \quad V_{2n} = 0; \quad V_{2\tau} = V_2.$$

Further, in accordance with the same technique, the projection of the common velocity $\overline{U}$ of both bodies on the axis $\bar{n}$ at the end of the perfectly inelastic collision is determined. It will be:

$$U_n = \frac{mV_{1n} + MV_{2n}}{m+M} \quad (2)$$

Since $V_{2n} = 0$ and $M \to \infty$, the final result is $U_n = 0$.
Hence, the projections of the velocities of the potato tuber and the rebounding conveyor prior to the impact on the coordinate axes $\bar{n}$ and $\bar{\tau}$ will be determined by the following expressions:

$$\begin{aligned} U_{1\tau} &= V_{1\tau}, \\ U_{2\tau} &= V_{2\tau}, \\ U_{1n} &= U_n(k+1) - kV_{1n}, \\ U_{2n} &= U_n(k+1) - kV_{2n}. \end{aligned} \quad (3)$$

After substituting the found values of the projections of the velocities prior to the impact (1) and the value $U_n = 0$ into (3), the following is obtained:

$$\begin{aligned} U_{1\tau} &= V_1 \cos(\beta+\chi), \\ U_{2\tau} &= V_2, \\ U_{1n} &= -kV_1 \sin(\beta+\chi), \\ U_{2n} &= 0. \end{aligned} \quad (4)$$

Meanwhile, the magnitudes of the velocities of the potato tuber and the rebounding conveyor after the impact are equal to, respectively:

$$\begin{aligned} U_1 &= \sqrt{U_{1\tau}^2 + U_{1n}^2} = V_1\sqrt{\cos^2(\beta+\chi) + k^2\sin^2(\beta+\chi)}, \\ U_2 &= \sqrt{U_{2\tau}^2 + U_{2n}^2} = V_2. \end{aligned} \quad (5)$$

The directions of the velocities of the bodies after the impact make angles with the normal line, their tangents being equal to:

$$\begin{aligned} \tan\left(\bar{n},\hat{\overline{U}}_1\right) &= \frac{U_{1\tau}}{U_{1n}} = -\frac{\operatorname{ctg}(\beta+\chi)}{k}, \\ \tan\left(\bar{n},\hat{\overline{U}}_2\right) &= \frac{U_{2\tau}}{U_{2n}} = \infty. \end{aligned} \quad (6)$$

The next step is to find out the force of impact of the potato tuber on the moving flat surface of the rebounding conveyor.

In order to do that, the principle of momentum will be applied to the potato tuber during the collision; in the vector notation, it will appear as follows:

$$m\left(\overline{U}_1 - \overline{V}_1\right) = \overline{S}, \quad (7)$$

where m – mass of tuber; $M \to \infty$ – impact impulse.

The equation (7) of the tuber's impact on the moving flat surface of the rebounding conveyor can be broken down into its projections on the axes $\bar{n}$ and $\bar{\tau}$. That will produce:

$$\left.\begin{aligned} m\left(U_{1n}-V_{1n}\right)&=S_n\,, \\ m\left(U_{1\tau}-V_{1\tau}\right)&=S_\tau\,. \end{aligned}\right\} \qquad (8)$$

After substituting the values of the velocity projections U_{1n}, V_{1n}, $U_{1\tau}$, $V_{1\tau}$ that were obtained earlier into (8), the following values will be obtained for the projections of the impact impulse on the axes $\bar{n}$ and $\bar{\tau}$:

$$\left.\begin{aligned} S_n&=-mV_1\sin\left(\beta+\chi\right)\cdot\left(k+1\right), \\ S_\tau&=0. \end{aligned}\right\} \qquad (9)$$

Taking into consideration the fact that the total impulse S is determined by the following expression:

$$S=\sqrt{S_\tau^2+S_n^2}\,, \qquad (10)$$

it follows that $S=S_n$, i.e.:

$$S=-m\cdot\left(k+1\right)\cdot V_1\sin\left(\beta+\chi\right). \qquad (11)$$

After having found the impact impulse S, it becomes possible to determine at a certain approximation the force of impact F_{imp} of the potato tuber on the moving belt of the rebounding conveyor.

With that aim in view, the integral expression of the impact impulse in terms of the impact force (Dreizler & Lüdde, 2010) will be employed:

$$\bar{S}=\int_{t_0}^{t_0+\Delta t}\bar{F}_{imp}dt\,, \qquad (12)$$

where $\bar{F}_{imp}$ – impact force; Δt – duration of impact.

Subsequently, in accordance with the mean-value theorem from the integral calculus, the following can be written down:

$$S=F_{imp.av.}\Delta t\,, \qquad (13)$$

where $F_{imp.av.}$ – average impact force for the time of impact Δt.

It can be found from (13) that:

$$F_{imp.av.}=\frac{S}{\Delta t}. \qquad (14)$$

According to (Dreizler & Lüdde, 2010), the maximum impact force F_{imp} will approximately be equal to:

$$F_{imp}=2F_{imp.av.}, \qquad (15)$$

or, taking into account (14),

$$F_{imp}=\frac{2S}{\Delta t}. \qquad (16)$$

The substitution of the expression (11) into the expression (16) produces:

$$F_{imp}=-\frac{2m\left(k+1\right)V_1\sin\left(\beta+\chi\right)}{\Delta t}. \qquad (17)$$

The sign '$-$' in the expressions (11) and (17) indicates that the direction of the vectors $\bar{S}$ and $\bar{F}_{imp}$ is opposite to the direction of the axis $\bar{n}$. Nevertheless, in this case the magnitudes of these values are of primary importance, therefore, the sign '$-$' can be omitted in the following expressions.

Obviously, in order to prevent damage to the potato tuber, it is necessary to provide for the following condition being fulfilled:

$$F_{imp} \leq \left[F_{imp}\right], \tag{18}$$

where $[F_{imp}]$ – permissible force of impact of the potato tuber on the surface of the rebounding conveyor, at which the tuber remains intact.

Thus, taking into account the expression (17), the following inequation is arrived at:

$$\frac{2m(k+1)V_1 \sin(\beta+\chi)}{\Delta t} \leq \left[F_{imp}\right]. \tag{19}$$

It is possible to derive from the obtained inequation (19) the limit for the magnitude of the potato tuber's velocity V_1 prior to its collision with the surface of the rebounding conveyor, set by the requirement to prevent damage to the tuber. The said velocity limit actually represents the condition for the potato tuber's impact interaction without damaging it, and it will hold true in case of tubers colliding with any surface. The limit of the velocity magnitude is:

$$V_1 \leq \frac{\left[F_{imp}\right]\Delta t}{2m(k+1)\sin(\beta+\chi)}. \tag{20}$$

Thus, the dynamic condition has been obtained that ensures ruling out damage to the potato tuber during its collision with a moving or static surface, in this particular case – the surface of the rebounding belt conveyor.

Having calculated the permissible velocity V_1 of the potato tuber prior to the impact, it is possible to determine the design and kinematic parameters of the separating tool that will provide that velocity. At the same time, in the paper (Bulgakov et al., 2018) a formula was obtained for finding the potato tuber's velocity prior to the impact in case of the spiral separator, i.e. the velocity of the tuber's free flight:

$$V_1 = \sqrt{V_o^2 - 2gH}, \tag{21}$$

where H – height of trajectory of the potato tuber's flight from the separating surface to the point of impact contact; V_o – potato tuber's velocity at the moment of taking off from the separating surface.

Subsequently:

$$V_1^2 = V_o^2 - 2gH, \tag{22}$$

or

$$V_o^2 = V_1^2 + 2gH. \tag{23}$$

From the expression (23), it is possible to determine the value V_o, which will be equal to:

$$V_o = \sqrt{V_1^2 + 2gH}. \tag{24}$$

Since:

$$V_o = \omega \rho_i, \tag{25}$$

where ω – angular velocity of rotation of the cleaning spiral about its longitudinal axis, and

$$\rho = R + R_b, \tag{26}$$

where R – radius of the cleaning spiral; R_b – radius of the potato tuber, the following is obtained from the expression (24), taking into account the expressions (25) and (26):

$$\omega(R + R_b) = \sqrt{V_1^2 + 2gH}\,. \tag{27}$$

Finally, the permissible angular velocity of rotation ω of the cleaning spiral under the condition of not damaging the potato tuber will be:

$$\omega = \frac{\sqrt{V_1^2 + 2gH}}{R + R_b}. \tag{28}$$

Similarly, the radius R of the spiral at the specifi*ed* angular velocity ω of its rotation will be:

$$R = \frac{\sqrt{V_1^2 + 2gH}}{\omega} - R_b. \tag{29}$$

Hence, the value of the potato tuber's flight velocity V_1 determined in accordance with the expression (20), i.e. the limit set for the potato tuber's flight velocity by the condition of having an impact contact without damaging the tuber, can be substituted into the obtained expressions (28) and (29), which are based on the kinematic constraint of the potato tuber's flight velocity prior to the impact.

As a result of the mentioned substitution, the final expressions for ω and R are obtained, which can be used for numerical calculations on the PC.

They are:

$$\omega = \frac{\sqrt{\dfrac{\left[F_{imp}\right]^2 \Delta t^2}{4m^2 (k+1)^2 \sin^2(\beta + \chi)} + 2gH}}{R + R_b}, \tag{30}$$

and

$$R = \frac{\sqrt{\dfrac{\left[F_{imp}\right]^2 \Delta t^2}{4m^2 (k+1)^2 \sin^2(\beta + \chi)} + 2gH}}{\omega} - R_b. \tag{31}$$

In order to perform numerical calculations on the PC, it is necessary to specify the constant values (design and force parameters) of the spiral potato heap separator. According to the results of the design efforts, intralaboratory and field laboratory experimental studies performed by us, the above-said parameters have the following values (Table 1).

Table 1. Design and force parameters of spiral potato heap separator

Item no.	Description and designation of parameter	Unit of measurement	Value
1.	Mass of average size potato tuber, m	kg	0.074…0.453
2.	Radius of potato tuber, R_b	m	0.03…0.055
3.	Coefficient of restitution, k	–	0.80
4.	Tilt and β obliquity angles: χ	deg	15…35 25…65
5.	Height of potato tuber's flight path from separating surface to point of impact contact, H	m	0.30
6.	Radius of spiral, R	m	0.065
7.	Duration of impact, Δt	s	0.06
8.	Maximum permissible impact force, $[F_{imp}]$	N	52

Following the results of the numerical calculations performed on the PC with the use of a specially developed software programme, the curves presented in Figs 2–5 have been plotted.

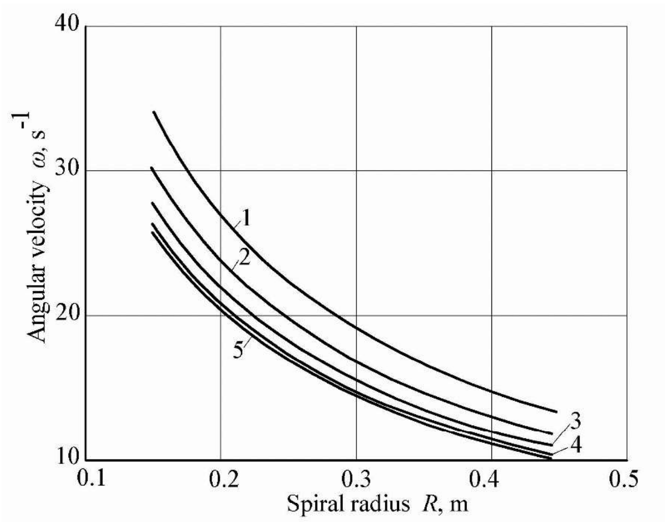

Figure 2. Relation between spiral's angular velocity ω and spiral's radius R at various values of angle χ: 1) $\chi = 25°$; 2) $\chi = 35°$; 3) $\chi = 45°$; 4) $\chi = 55°$; 5) $\chi = 65°$.

The analysis of the relations plotted in Fig. 2 has shown that the increase of the separator spiral's radius R results in the decrease of the permissible angular velocity ω of spiral under the condition of not damaging the tubers, and the increase of the value of the angle χ also implies lower values of the permissible angular velocity ω. The relations presented in Fig. 3 prove that increasing the rebounding conveyor installation height H makes it possible to operate the spiral springs at higher values of the angular velocity ω, which in the end contributes to improving the performance of the spiral potato heap separator.

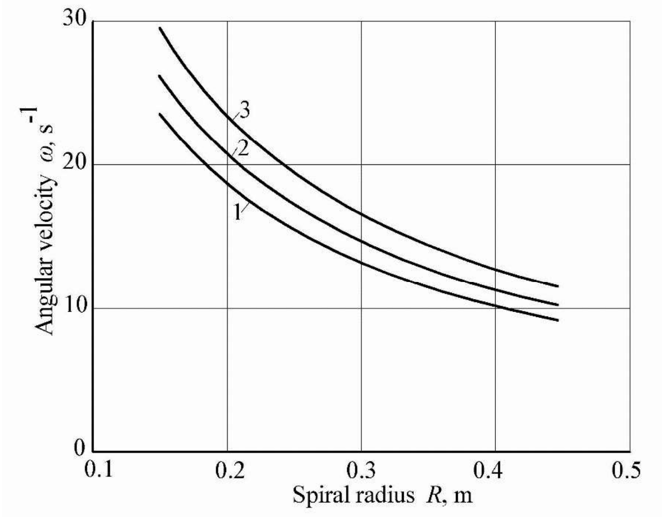

Figure 3. Relation between spiral's angular velocity ω and spiral's radius R at various values of tuber's flight height H: 1) H = 0.1 m; 2) H = 0.35 m; 3) H = 0.7 m.

The analysis of the relations represented by the curves in Fig. 4 has revealed the significant influence of the potato tuber's radius R_b and, accordingly, its mass m on the permissible angular velocity ω of the separator's spirals.

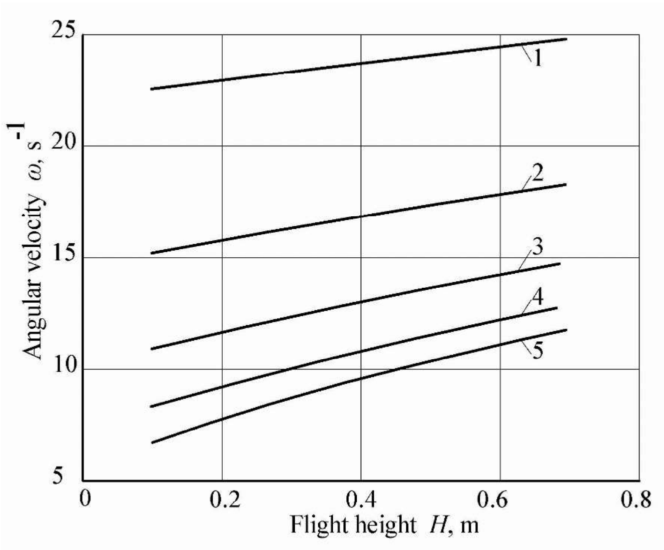

Figure 4. Relation between spiral's angular velocity ω and potato tuber's flight height H at various values of tuber's radius R_b: 1) R_b = 0.035 m; 2) R_b = 0.040 m; 3) R_b = 0.045 m; 4) R_b = 0.050 m; 5) R_b = 0.055 m.

The relations between the angular velocity ω and the rebounding conveyor's tilt angle β are presented in Fig. 5.

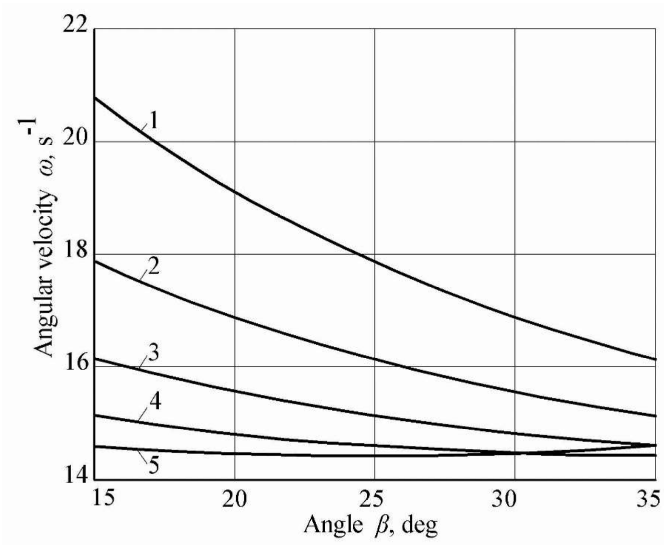

Figure 5. Relation between spiral's angular velocity ω and conveyor's tilt angle β at various values of angle χ: 1) χ = 25°; 2) χ = 35°; 3) χ = 45°; 4) χ = 55°; 5) χ = 65°.

As may be inferred from the presented curves, the mentioned relations are of significance only when the potato tuber's impact angle varies within a range of χ = 25–45°.

The undertaken experimental laboratory and field studies of the spiral separator (Bulgakov et al., 2017 and 2018) mounted on the test unit modelling a single-row potato-digger have shown the high efficiency of its operation.

CONCLUSIONS

1. A new analytical mathematical model of the impact interaction of the potato tuber during the potato heap separation has been developed.
2. Analytical expressions have been obtained, which allow calculating the impact impulse and impact force, in case of the tuber colliding with the elastic surface of the rebounding conveyor, as functions of the separator's kinematic parameters.
3. The dynamic constraints on the permissible velocity of the potato tuber prior to the impact interaction imposed by the condition of not damaging the tuber have been analytically determined.
4. The obtained relations and the results of the PC-assisted calculations provide for determining the rational parameters of the spiral potato heap separator as well as lead to the conclusion that the mounting height and tilt angle of the rebounding conveyor have to be adjusted depending on the average diameter of the potato tubers R_b. Thus, for an average tuber mass of m = 0.2 kg the rational parameters of the spiral separator are as follows: χ = 25–45°; tuber's flight height H = 0.15…0.35 m; rebounding conveyor tilt angle β = 15–25°; angular velocity of the cleaning spirals ω = 15–20 s^{-1}.

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