The theory of sifting the soil mass when cleaning potatoes on a spiral separator

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Abstract

The removal of soil and impurities is an important problem when harvesting potatoes. and the main reason for this problem is due to the modalities employed to carry out the potatoes mechanical harvesting. The equipments currently implemented on potato harvesters do not always allow to obtain high levels of soil and impurities separation, mainly due to the gluing of the moist soil to the surfaces of the separating organs. The authors have developed a spiral separator of soil clods from potatoes heaps, patented in Ukraine. The purpose of this paper has been to analyze the theory of sifting the soil mass when a spiral separator is used. A mathematical model of the motion of an elementary body along the spiral surface of a potato heap separator has been built. The numerical solution of the model has highlighted that the lowest angular speed (10 rad s^{-1}) of the cleaning rollers allows the greatest amount of sifted soil mass. Field tests carried out confirmed that the developed spiral separator is able to perform the task achieving meaningful values of the efficiency of separation and heap purity. Further field and laboratory tests will be executed in order to improve the set up mathematical model.

Keywords: soil sifting, potatoes, spiral separator, mathematical model

INTRODUCTION

An important problem when harvesting potatoes is the removal of soil and impurities (Petrov, 2004). Using the mechanical harvest, fertile soil together with potatoes, is removed from the field in a quantity equal to 3-5% of the total harvest (Bourget, 2004). In this regard, it is estimated that in the major potato-producing countries of the world, over the past three years over than 1.1×10^{10} kg of fertile soil were removed from the fields (FAOSTAT).

The main reason for this problem is due to the modalities employed to carry out the potatoes mechanical harvesting, as the harvesters dig a significant amount of soil that is lifted together with the tubers. Furthermore, its effective separation from potato tubers become a hard task, taking into account that at the time of harvesting, depending on the plantation conditions, the soil humidity is about 7-20% (FAOSTAT; Scott, 2001; Manetto et al., 2017). Consequently, the search for new technical solutions aimed at improving the cleaning of the heap of potatoes during the harvesting represents an important scientific and technological challenge.

The equipments currently implemented on potato harvesters do not always allow to obtain high levels of soil and impurities separation, mainly due to the gluing of the moist soil to the surfaces of the separating organs, which reduces their effectiveness (Keijbets, 2008; Ichiki et al., 2013). Potato heap separators have to ensure a reliable execution of the cleaning as well as to be able to constantly clean themselves during the process impurities (Zaltzman and Schmilovitch, 1985). The technical devices that produce strong impacts on the heap to obtain the soil and impurities removal lead to an increase in the damage to the tubers, whereas obviously the amount of damaged tubers should be as low as possible (Esehaghbeygi and Besharati, 2009).

Many researchers and manufacturers have worked to set up efficient and reliable

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separators of potato heaps during excavation operations, as well as on potato cleaners and calibrators machines working at fixed-point (Al-Mallahi et al., 2010; Bentini et al., 2006). In this regard, the authors have set up and developed a spiral separator of soil clods from potatoes heaps, patented in Ukraine (Bulgakov et al., 2017). This spiral separator of potato heap consists of several sequentially placed drive cleaning spiral rollers, so as to form a cleaning surface located on one side of a feeding conveyor and on the other side of the discharge conveyor. Each cleaning roller is formed by a spiral mounted on the hub with the drive shaft. Figure 1 shows a view of a spiral separator from the side and top.

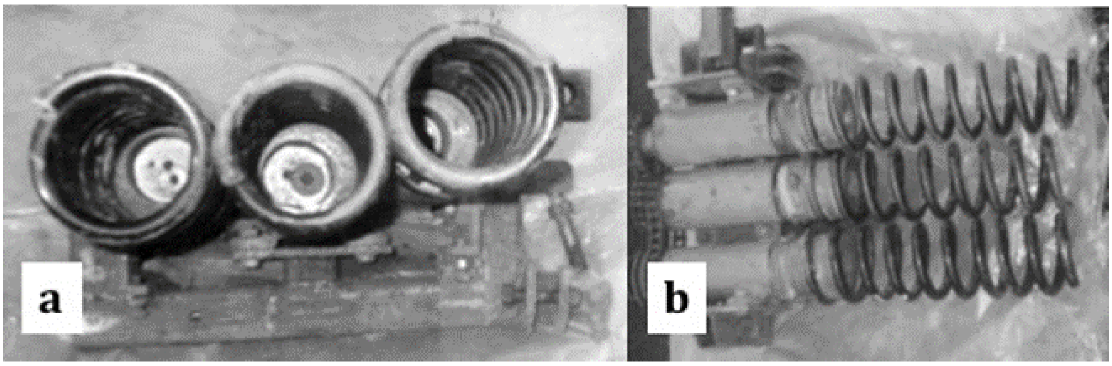

Figure 1. Spiral rollers for cleaning relevant to the potato heaps separator: a) side view; b) top view.

The cleaning surface of this potato heap separator is then fitted with significant gaps, which are formed by the spaces both among the coils of the spirals themselves and among the coils of the contiguous spirals To prevent sticking of soil on each separating roller or the complete sticking of wet soil inside the gaps among the spirals, the spirals of each roller are placed in such a way to go partially inside the spiral openings of the next roller. During the operation of the spiral separator, the mass of the heap falls on the cleaning surface formed by the spirals, which rotate in the same direction. The mass of the soil is transported in the direction of the coils, while small soil impurities immediately fall through the separation gaps between the spiral coils .

Taking in mind the aforesaid and considering that in the scientific literature there are not theoretical and experimental studies concerning the sifting the soil impurities and plant residues from the surface of cleaning of the separators, the purpose of this work is to analyze the sifting the soil mass when a spiral separator is used for cleaning potatoes. Therefore, a mathematical model of the motion of an elementary body along the spiral surface of a potato heap separator has been built, considering its design and operational parameters. Furthermore, results of field tests aimed at evaluating the performance of the developed spiral separator are reported.

MATERIALS AND METHODS

Preliminary theoretical aspects

The dynamics of the separation process has been evaluated considering the motion of a body of variable mass on the surface of the spiral working body, with the corresponding equivalent outline reported in Figure 2 (Bulgakov et al., 2018a). The separator is represented in the form of a cylinder (single coil) having the center at the point O, radius R, which rotates at the angular speed ω in the direction shown by the arrow (Figure 2). The elementary body M with mass m has been considered as the elementary volume of the soil on the outer surface of this cylinder. The center of the coil O has been connected with the point M and then E denotes the point of contact of the elementary body with the surface of the coil.

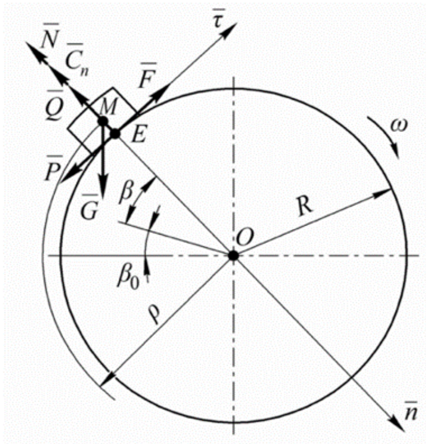

Figure 2. Equivalent outline of body motion of variable mass on the surface of the spiral working body.

A three dimensional coordinate system $E\tau n$ with origin in the point E is considered. Furthermore, the position of the elementary body of variable mass on the outer surface of the spiral is determined by the angle β, whereas its initial position is individualized through the angle β_0 (Figure 2) (Bulgakov et al., 2018b, Pascuzzi et al., 2017). The initial mass of the elementary body M is m_0; while its current value of the mass m, caused by its rotation on the spiral roller of an angle $\delta\beta$ is (Figure 2):

$$m = m_0 - \Delta m = m_0 - q' \; t \qquad (1)$$

where q' – intensity of soil separation; t – rotation time; Δm –change of mass.

The following forces are applied to the elementary body M of variable mass, at its point of contact E with the surface of the spiral:

- $\bar{N}$ – normal reaction of the surface of the spiral working body*;*
- $\bar{F} = f\bar{N}$ – friction force of the mass on the surface of the spiral separator which is directed in the same side of rotation of the spiral, in order to prevent sliding down of the body M, with f – coefficient of friction of the body M on the surface of the spiral;
- $\bar{P}$ – reactive force resulting from the weight loss of the body.

The following forces are applied to the elementary body M of variable mass, at its center of mass:

- $\bar{G}$ – force of the body weight of a variable mass, whose intensity is: $G = (m_0 - \Delta m) \cdot g$; where g – gravity acceleration;
- $\overline{C_n}$– centrifugal force, whose intensity is: $C_n = (m_0 - \Delta m)\dot{\beta}^2 \cdot \rho$, where: ρ – polar radius of the elementary body M of variable mass, relative to point O;
- $\bar{Q}$ – force due to the acceleration of the oscillating motion of the body, whose intensity is: $Q = (m_0 - \Delta m)\dot{\beta}^2 \cdot \rho \cdot A \cdot sin\left(\beta_0 + \varphi_F + \dot{\beta}t\right)$, where A – amplitude of the oscillations; φ_F – phase shift (Bulgakov et al., 2018b).

Experimental investigations

Experimental field investigations were carried out to assess some quality indicators of the developed spiral separator. An experimental equipment formed by a single-row semi-mounted potato digger Lidselmash manufacturer (Lida, Belarus) L-651 model, equipped with the spiral separator in question was set up. The main technical features of the aforesaid digger L-651 were: productivity 0.08-0.25 ha h^{-1}; operating speed 2.5 km h^{-1}; operating width 0.62 m; digging depth 0.22 m. Harvesting was executed from a one-row of potato plantation ('Lugovskaya'), whose yield inside the experimental plot was 25.3×10^3 kg ha^{-1}. Potatoes were planted with the ridge method with 0.7 m row spacing. At the moment of the harvest the field had the following main characteristics: black soil with humus medium content, average humidity 11% and hardness 0.4 MPa. According to the results of previous studies, the following field operative parameters were adopted during the test (Adamchuk et al., 2016): i) forward velocity of the experimental equipment in the range from 0.5 to 1.2 m s^{-1}; ii) angular velocity of the spiral rollers 10 rad s^{-1}. The considered quality indicators were (Bulgakov et al., 2017): i) the efficiency of separation q and ii) the heap purity. The efficiency of separation q was evaluated as percentage of the sifted soil, according to the following formula:

$$q = \frac{\Delta m_s}{m_s} \cdot 100 \tag{2}$$

where Δm_s – mass of sifted soil (kg); m_s – mass of soil, which enters the separator, kg. Conversely, the heap purity was assessed through a comparative evaluation with a current digger without a separator.

RESULTS AND DISCUSSION

Mathematical model of the motion of a body of variable mass inside the spiral separator

To compile the differential equation of motion of a body of variable mass, we apply the impulse-momentum theorem in differential form (Bulgakov et al., 2018c; Anifantis et al., 2018):

$$\frac{d}{dt}(m\bar{V}) = \sum_{i=1}^{n} \bar{F}_k \tag{3}$$

where $m\bar{V}$ – quantity of motion of the mass m; $\bar{V}$ – velocity of the mass; $\sum_{i=1}^{n} \bar{F}_k$ – geometric sum of forces acting on the body of variable mass m.

In this case, taking into account that $m = m_0 - \Delta m$ and the aforesaid system of forces, acting on the body of variable mass, Equation 3 can be written as follows:

$$\frac{d}{dt}[(m_0 - \Delta m)\bar{V}] = \bar{G} + \bar{N} + \overline{C_n} + \bar{Q} \tag{4}$$

After differentiation of Equation 4, with some transformation, you obtain:

$$(m_0 - \Delta m)\bar{a} = \bar{G} + \bar{N} + \overline{C_n} + \bar{Q} + \bar{P} \tag{5}$$

where $\bar{a}$ – acceleration of body of changing mass.

As known, the decomposition of the full acceleration $\bar{a}$ along the axes $\bar{\tau}$ and $\bar{n}$ of the coordinate system $E\tau n$, shown in Figure 2, has the form:

$$\bar{a} = \overline{a_\tau} + \overline{a_n} \tag{6}$$

Further, it is also known that:

$$a_\tau = \rho \cdot \ddot{\beta} \tag{7}$$

and

$$V = \rho \cdot \dot{\beta} \tag{8}$$

where $\dot{\beta}$ and $\ddot{\beta}$ are the angular speed and angular acceleration of the body.

Taking in mind Equations 6, 7 and 8, the projection of the Equation 5 along the axes $\bar{\tau}$ and $\bar{n}$, produces the following equations:

$$\begin{cases}(m_0 - \Delta m)\ddot{\beta} \cdot \rho = F \cdot cos\,\gamma - G\,cos\,(\beta_0 + \beta) - P \\ 0 = N + C_n - G \cdot sin\,(\beta_0 + \beta) + Q\end{cases} \quad (9)$$

where: γ – angle of lifting of the spiral line.

From Equations (9), after some transformations, you obtain the following nonlinear differential equation of second order for the motion of the body M of variable mass over the surface of the spiral (Figure 2):

$$(m_0 - \Delta m)\ddot{\beta} \cdot \rho = f(m_0 - \Delta m)cos\,\gamma\left[g \cdot sin\,(\beta_0 + \beta) - A \cdot \dot{\beta}^2 sin\,(\beta_0 + \psi_F + \dot{\beta} \cdot t) - \rho \cdot \dot{\beta}^2\right] - (m_0 - \Delta m)g \cdot cos\,(\beta_0 + \beta) - \frac{d(\Delta m)}{dt} \cdot \rho \cdot \dot{\beta} \quad (10)$$

The differential Equation 10 highlights that the sifting process on the spiral separator is influenced by the design parameters (radius of the spiral, spiral angle), friction properties, angular placement parameters (the angular parameter is a function of time) and the angular velocity of rotational motion of the spiral roller.

Practically, with sufficient accuracy, we assume that the body of variable mass does not slip relative to the spiral of the cleaning roller. Then we have $\dot{\beta} = \omega$, $\beta = \omega \cdot t$ and $\ddot{\beta} = 0$ and the differential Equation 10 after transformations takes the final form:

$$\frac{d(\Delta m)}{dt} = \{f \cdot cos\,\gamma[g \cdot sin\,(\beta_0 + \omega t) - A \cdot \omega^2 sin\,(\beta_0 + \psi_F + \omega t) - \rho \cdot \omega^2]\}\frac{(m_0 - \Delta m)}{\omega \cdot \rho} \quad (11)$$

The solution of the differential equation of the first order Equation 11 allows to evaluate the function $\Delta m(t)$ relative to the change in time of the mass of the body M produced by the sifting process on the cleaning spiral rollers of the separator.

A numerical integration of the differential Equation 11 has been carried out, considering the following values for the corresponding parameters: friction coefficient f=0.5; angle of lifting of the spiral line γ=20°; initial mass of the heap m_0=50 kg; spiral oscillation amplitude A=0.01 m; initial value of the angle β_0=45°; phase shift ψ_F=0°; radial mass position ρ=0.15 m; angular acceleration of the spiral $\ddot{\beta}$=0 rad s^{-2}; angular velocity of the spiral ω=10, 20, 30, 40, 50 rad s^{-1}. The results of this numerical integration are the graphs reported in the Figure 3, which show, for different angular velocities of the spiral rollers, the sifted soil mass by the spiral separator during the time range 0-0.25 s. Figure 3 shows that, by adopting the lowest angular speed (10 rad s^{-1}) of the cleaning rollers, the amount of sifted soil mass increases with the persistence time on their surface. On the contrary, angular speeds of the cleaning rollers greater than 10 rad s^{-1} produce in the time a reduction in the amount of sifted soil mass (Figure 3). This reduction becomes increasingly significant with the increase in angular speed of the spiral rollers.

Experimental investigations

The results of the experimental investigations aimed at evaluating the efficiency of separation and the heap purity are reported in Figure 4. The graphs of Figure 4 highlight that the increase of the forward velocity of the experimental equipment in the considered range did not affect in the same manner the quality indicators. In particular, the efficiency of separation q gradually increases with the speed up to 0.67 m s^{-1}, whereas for speeds in the range from 0.67 to 0.83 m s^{-1} slows down (graph 1 in Figure 4). Furthermore, further rises of velocities (up to 1.2 m s^{-1}) produce a meaningful reduction of efficiency of separation, which reaches 33.31% at a speed of 1.11 m s^{-1}. The trend of the parameter "purity of the heap" is strictly connected to the efficiency of separation of the equipment (graph 2 in Figure 4).

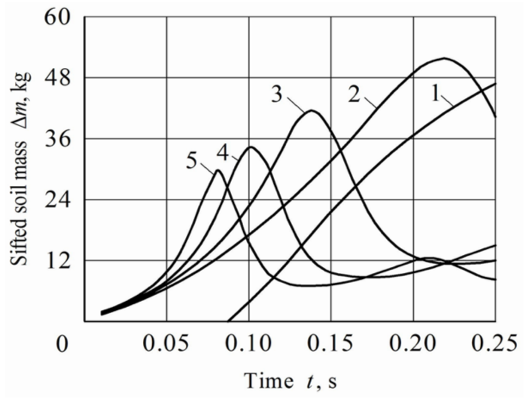

Figure 3. Sifted soil mass by the spiral separator during the time, with the following angular speed of the spiral rollers: 1) ω=10 rad s^{-1}; 2) ω=20 rad s^{-1}; 3) ω=30 rad s^{-1}; 4) ω=40 rad s^{-1}; 5) ω=50 rad s^{-1}.

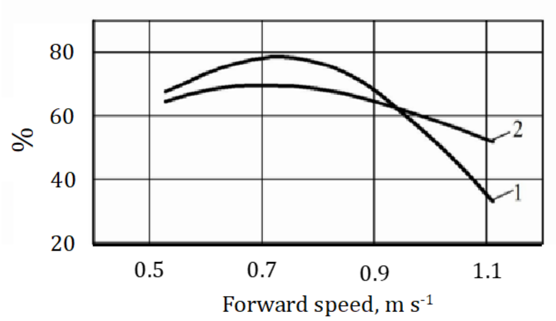

Figure 4. Evaluation of the quality indicators concerning the developed spiral separator as function of the forward speed of the experimental equipment: 1 – efficiency of separation; 2 – purity of the heap.

CONCLUSIONS

The following conclusions can be drawn from this study:

- According to the results of theoretical study, a mathematical model has built in order to assess the change in the time of the mass of the potato heaps due to the sifting process inside the developed spiral separator.
- A numerical solution of the mathematical model highlighted that angular speeds of the cleaning rollers up to 10 rad s^{-1} allow to obtain the highest amount of sifted soil mass in the time. Conversely, less quantity of sifted soil mass are obtained increasing the angular speeds of the rollers.
- A single-row semi-mounted potato digger was equipped with the developed spiral separator in order to experimentally assess the performance of the separator through some quality indicators. The field tests confirmed that the developed spiral separator is able to perform the task achieving meaningful values of the considered quality indicators.
- Further field and laboratory tests are planned to better verify the correspondence between the numerical results and the experimentally ones, in order to improve the set up mathematical model.

ACKNOWLEDGMENTS

The authors equally contributed to the present study.

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