

Acta Technologica Agriculturae 4
Nitra, Slovaca Universitas Agriculturae Nitriae, 2023, pp. 201–206

THEORY OF HEAP PARTICLE MOTION IN VIBRATION CLEANING OF POTATOES

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Theoretical research was conducted using the basic principles of higher mathematics and theoretical mechanics. Numerical calculations and graphical dependences are obtained using a PC based on developed and standard programs. The movement of the potato heap on the wing surface of the V-shaped heap distributor in the process of its distribution over the entire width of the separating conveyor was studied. An equivalent scheme of interaction of potato heap particle with the surface of the distributor wing is constructed, on the basis of which differential equations of its motion on the specified surface are made, taking into account the main constructive and kinematic parameters of the separating conveyor and V-shaped distributor. Based on the integration of the specified system of differential equations in quadratures, analytical expressions describing the laws of change of speed and movement of a particle of a potato heap in time at various values of constructive and kinematic parameters of the distributor and separating conveyor are received. Based on the obtained analytical expressions, calculations were performed and graphical dependences of heap velocity along the distributor wing on time at different values of the angle of distributor wings taking into account the oscillations of the separating conveyor blade were obtained. The allowable speed of movement of the heap along the wing of the distributor is determined from the condition of maintaining the equality of supply of the heap to the distributor and its ascent from the distributor. The specified speed is $1.62 \text{ m}\cdot\text{s}^{-1}$. The analysis of graphical dependences shows that the speed of the heap along the wing of the distributor decreases with increasing angle of the wing. If the speed is reduced to less than the allowable value, the heap will be unloaded on the wings of the distributor, which will lead to a disturbance of the technological process of the potato harvester. With the allowable time of movement of the heap along the distributor wing, the maximum allowable values of the deflection of the distributor wing are within 40–45°.

Keywords: potato heap; separating conveyor; distributor; differential equations; design and kinematic parameters

Potato harvesting is the most labour-intensive process in its production, which accounts for 45–60% of total labour costs. Experience in the operation of potato harvesters shows that they do not always provide quality harvesting of potatoes and have low reliability of the technological process, as the main separating body performs its function poorly. To obtain the tubers of required purity, harvesting units are used at reduced speeds and perform post-harvest cleaning at potato sorting points, which leads to increased costs for potato production and necessitates manual labour. Therefore, improving the quality of potato harvesters is an urgent scientific and technical problem, in particular the development of construction and scientific justification of the parameters of the combined digging and separating body.

It should be noted that the separation of the dug-up heap is the main operation of the technological process of harvesting potatoes because it depends primarily on the quality of potato harvesters. Many scientific works are devoted to the study of the process of potato separation (Bulgakov et al., 2022). Because of simple construction and high efficiency of potato transport, belt conveyors are

preferred for separation of potatoes from foreign matter. According to the results of research (Adamchuk et al., 2020; Beloev, 2021; Bulgakov et al., 2022; Byshov, 2000; Karaiev et al., 2021; Singh et al., 2021; Jamali et al., 2021), the values of the parameters of separating conveyors were substantiated – the speed of the conveyor, its length and width, and the angle of inclination to the horizon. Experimental studies have made it possible to establish the effect of the speed of the conveyor on the efficiency of sieving the soil, which is in a solid and plastic state (Astrakhan, 1989; Karaiev et al., 2021). Ogedengbe et al. (2022) studied the influence of cloth shakers, which are equipped with rod conveyors to increase the separation of potato heap. The use of shakers on bar conveyors can increase separation efficiency by 10–15%.

Betul et al. (2023) studied the mechanized harvesting of potatoes in difficult conditions, in particular on soils of high humidity. They proposed a device for increasing the separation of potato heap under these conditions. Trakhtenbroit (1983), Lapin (2018) and Bulgakov et al. (2020) proposed and investigated the separation intensifiers of different designs. The potato heap passes through the area of action of the leavening intensifier, which

improves soil separation due to the action of centrifugal forces on the soil while levelling and loosening the soil elements of the heap across the width of the conveyor. To increase the separation capacity, the working bodies use a connecting rod-eccentric mechanism (Braim et al., 1992; Correa et al., 2019; Jabro et al. 2016; Derevjanko et al., 2020). Various constructions of separating devices and their research are described by Nadykto et al. (2020), Rembalovich (2014) and Bulgakov et al. (2020). The main disadvantages of such devices are their complexity and low reliability, especially when working on heavy soils. The simplicity of construction and reliability in work is provided by our V-shaped distributor located with some backlash over the surface of the bar separating conveyor. This distributor divides the heap flow on the conveyor into two streams and, in combination with providing the conveyor web with necessary vertical vibrations, it provides an efficient distribution of the potato heap across the width of the conveyor.

Potato separation is only effective if the mix of potatoes and soil aggregates is evenly spread across the width of the conveyor. Separation efficiency is increased when the transporter intended for separation is vibrated.

The paper describes the aspects of the quality of potato separation depending on the working speed and the angle of inclination of the distribution wing designed and manufactured by the authors' research department.

Material and methods

The developed new design of the potato crop cleaner provides the regulation of speed of the crop through the cleaning rod conveyor and the working area of this conveyor, from which the separation (sifting soil particles down) of impurities is carried out.

This is achieved by using a V-shaped pile distributor, which is installed over the strip of rod cleaning conveyor on its longitudinal axis of symmetry.

For theoretical research and finding the analytically acceptable speed of movement of soil particles falling on one of the wings of the V-type

distributor, it is necessary to make differential equations of movement of soil particles along the working body. For this purpose, it is necessary to use the method of building calculation models of motion of material particles (in this case the potato crop particle) by working bodies of agricultural machines. The basis of this technique is first of all to develop the equivalent scheme of interaction of material particles on the surface of the working body. It is necessary to show the material particle in any position on an equivalent scheme, to attach all forces acting on it (active and the reactions of connections), and to show linear and angular sizes. Each of the forces applied to a material particle must be characterized from the physical point of view and the directions of vectors of these forces must be reasonably and precisely shown. After that, it is necessary to specify and show on the equivalent scheme the coordinate systems (if necessary, stationary and moving ones).

Further, according to the technique of construction of models of material particle motion, it is necessary to select the basic law of dynamics, which with a sufficient degree of accuracy will model the behaviour of the material particle on the surface of the working body. Using the accepted law further, it is necessary to make up a system (or one) of differential equations of motion of a material particle. Most often, such a system of differential equations is

compiled in projections to selected coordinate axes. If other processes (e.g., vibrational processes) are additionally imposed on the motion of a material particle, it is necessary to take them into account in the systems of differential equations.

After that, it is necessary to apply mathematical methods to the given system of differential equations, allowing to simplify it and prepare it for numerical solution. It is also necessary to specify the specific values of constant parameters included in these differential equations and to receive graphic dependences between the parameters of the investigated dynamic system.

Further analysis of the obtained dependencies will give the final solution of the problem.

Results and discussion

The analysis of the known designs of potato harvesters shows that the main separating body is a rod conveyor, which, especially in difficult conditions of potato harvesting, performs its function unsatisfactorily. It is possible to improve the process of separation of soil and plant elements of potato heap on separating working bodies and thus to improve the quality of potato harvesting machine by introducing intensifying working bodies into the machine construction, which will additionally interact with dug potato heap.

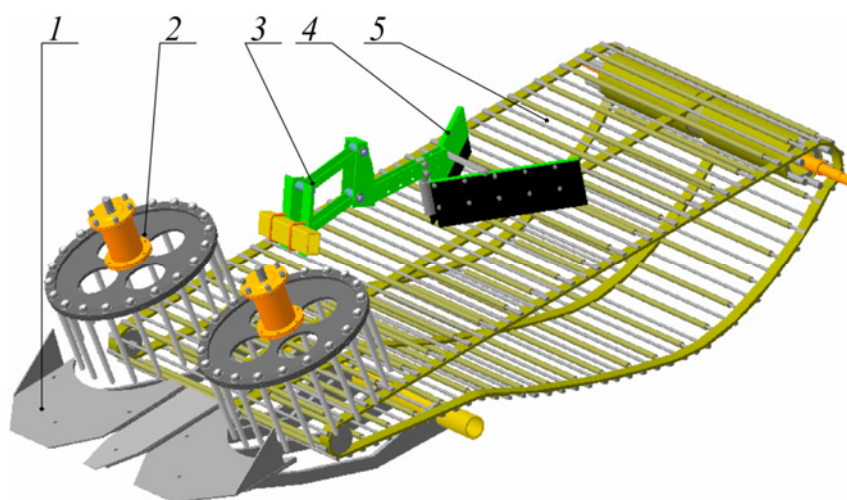


Fig. 1 General view of the digging and separating body of the potato harvester 1 – digging ploughshare; 2 – rod spreading drums; 3 – the mechanism of installation of the heap distributor; 4 – V-shaped distributor; 5 – feed bar separating conveyor

It should be noted that a significant disadvantage of potato heap separation on the separating conveyor is the uneven distribution of the heap on the width of the separating conveyor. The excavated layer of the heap is not distributed over the entire width of the conveyor belt, but moves in the form of a longitudinal roll, and the bulk of the heap is in the central part of the conveyor. During further movement, under the dynamic action of the shakers, the heap is partially levelled along the width of the conveyor belt, but not enough to ensure high-quality separation.

It is possible to intensify the separation process on the separating conveyor by evenly distributing the heap across the width of the conveyor. Since the excavated layer is well crushed by rod drums before feeding to the main conveyor, in this case, a passive working body is promising for uniform heap distribution (namely, a V-shaped distributor which divides the main heap flow into two streams). The general view of the new digging and separating body of the potato harvester developed by us is presented in Fig. 1.

For a high-quality technological process of heap distribution along the width of the conveyor, the distributor must have appropriate technological and constructional parameters. Its main parameter is the angle 2α of the wingspan, which is formed by the projections of the wings on the plane of the separating conveyor. The wrong choice of angle will either lead to unloading the heap in front of the distributor and, as a consequence, to disrupting the technological process of the machine, or to the fact that the heap will not be distributed across the width of the conveyor.

Therefore, to substantiate the value of the angle 2α of deflection of the distributor wings, the change in the angle of deflection of distribution wings 2α interacts with the separation efficiency of potatoes moving along the conveyor with the distribution wing.

We assume that fine soil structure when it is fed to the conveyor belt is preliminarily destroyed (crushed) by the rod drums and turns into a mass with broken structural bonds, in which

there is no adhesion between the particles.

To justify the rational value of the angle of disintegration of the distributor wings, it is necessary to make the differential equation of motion of the potato crop particle moved by separating conveyor during its interaction with the surface of the distributor wing. For this purpose, first of all, we build a spatial equivalent diagram of interaction of potato crop particle with the surface of the distributor (Fig. 2).

This equivalent diagram shows the following forces acting on the heap particle indicated by the letter M . Force $\bar{G}$ is applied at the point M – the weight of the heap particle, which is directed vertically downwards. Normal reaction $\bar{N}_1$ acts on the grain particle from the conveyor, and normal reaction $\bar{N}_2$ acts on the surface of the distributor wing. Also, the particle M of the heap is affected by the friction force $\bar{F}_1$ of the particle sliding on the conveyor surface, which is directed in the direction of conveyor movement and keeps the particle from shifting backwards, i.e. transports it.

At the point of contact of the particle M with the surface of the distributor, particle sliding friction

force $\bar{F}_2$ acts on the distribution surface, which is directed opposite to the velocity vector $\bar{V}$ of the particle on the surface of the distributor. Along the normal to the surface of the conveyor, the particle of the heap M is influenced by the force $\bar{P}$ of harmonic vibrations of the conveyor, which occur under the action of the shaking mechanism.

In addition to the above forces, the equivalent circuit shows the following design and construction parameters:

- α – the angle of inclination of the distributor wing relative to the longitudinal axis of the conveyor (deg.);
- β_{tr} – the angle of the conveyor belt to the horizon (deg.);
- $\bar{V}_{tr}$ the vector of translational velocity of the feed conveyor web ($\text{m}\cdot\text{s}^{-1}$);
- $\bar{V}$ the velocity vector of the heap particle along the spreader wing surface at any moment of time (in general, this vector is variable in both magnitude and direction) ($\text{m}\cdot\text{s}^{-1}$).

The equivalent scheme also shows the spatial Cartesian coordinate system $Oxyz$, in which the motion of the heap particle M is considered. In this case, the axis of this coordinate

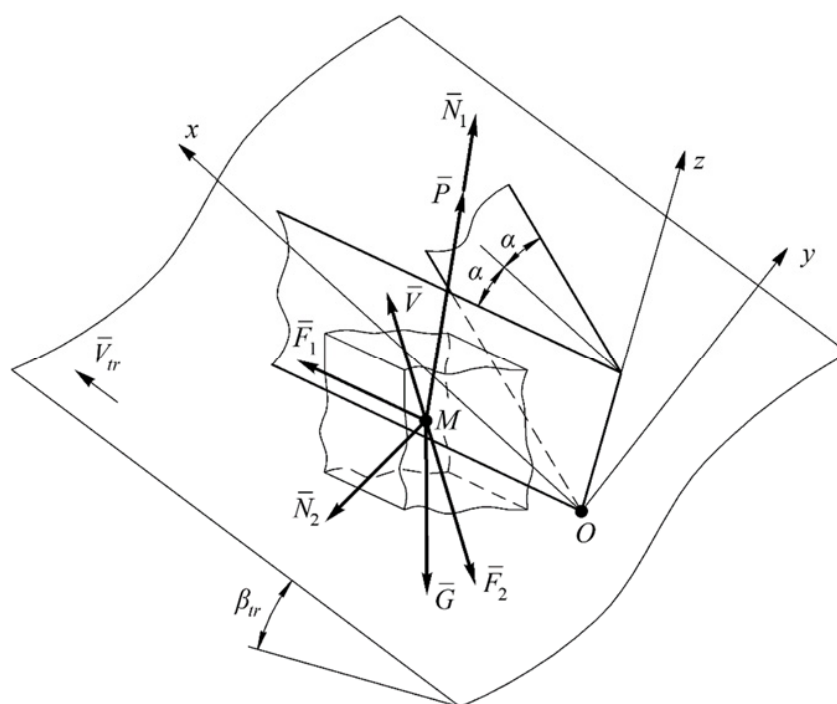


Fig. 2 Equivalent scheme of interaction of the potato heap particle with the surface of the distributor wing

system Ox is directed along the direction of motion of the feeding conveyor belt along its longitudinal axis. The axis Oy is perpendicular to the axis Ox to the right in the course of the feed conveyor.

The axes Ox and Oy are located in the plane of the infeed conveyor belt. The axis Oz is directed upwards, perpendicular to the plane of the conveyor belt, i.e., the plane xOy , and passes along the toe of the distributor.

First of all, the force of gravity $\bar{G}$ of the heap particle M will be equal to:

$$\bar{G} = mg \quad (1)$$

where: m – the mass of heap particles (kg); g – gravitational acceleration ($\text{m}\cdot\text{s}^{-2}$)

Normal reaction $\bar{N}_1$ and the force of sliding friction $\bar{F}_1$ from the feed conveyor can be found using the following analytical expressions:

$$\bar{N}_1 = mg \cdot \cos \beta_{tr} \quad (2)$$

$$\bar{F}_1 = f_1 \cdot N_1 = f_1 \cdot mg \cdot \cos \beta_{tr} \quad (3)$$

where: f_1 – the coefficient of friction of the heap sliding on the surface of the feed conveyor

The sliding friction force $\bar{F}_2$ of the heap particle on the surface of the distributor wing will be equal to:

$$\bar{F}_2 = f_2 N_2 \quad (4)$$

where: f_2 – the coefficient of friction of the heap sliding on the surface of the distributor wing

Force $\bar{P}$ from harmonic oscillations of the feed conveyor can be determined using the following expression:

$$\bar{P} = m \cdot \omega_{tr}^2 \cdot A_{tr} \cdot \sin(\psi_0 + \omega_{tr} t) \quad (5)$$

where: ω_{tr} – the circular frequency of conveyor oscillations ($\text{rad}\cdot\text{s}^{-1}$); A_{tr} – the amplitude of oscillations of the conveyor (m); ψ_0 – the initial position of the shaking mechanism crank (rad); t – current time (s)

To build the calculated mathematical model of motion of the heap particle M , it is necessary to make a differential equation of its motion according to the law of dynamics. The application of the basic law of dynamics of a material point is most suitable for this purpose.

The equation of motion of the heap particle M in its simultaneous contact, both with the surface of the conveyor and with the surface of the distributor wing, in a vector form according to the equivalent scheme will be:

$$m\bar{a} = \bar{G} + \bar{N}_1 + \bar{N}_2 + \bar{F}_1 + \bar{F}_2 + \bar{P} \quad (6)$$

where: $\bar{a}$ – the acceleration of the potato heap particle M ($\text{m}\cdot\text{s}^{-2}$)

After projecting further on the axes of the spatial Cartesian coordinate system the constituent vector equation

(6), we obtain the following system of differential equations of simultaneous motion of the potato crop particle M on the specified surfaces:

$$\left. \begin{aligned} m\ddot{x} &= -N_2 \sin \alpha + F_1 \cos \alpha - G \sin \beta_{tr} \cos \alpha - F_2 \frac{\dot{x}}{\sqrt{\dot{x}^2 + \dot{y}^2 + \dot{z}^2}} \\ m\ddot{y} &= -N_2 \cos \alpha - F_1 \sin \alpha - G \sin \beta_{tr} \sin \alpha - F_2 \frac{\dot{y}}{\sqrt{\dot{x}^2 + \dot{y}^2 + \dot{z}^2}} \\ m\ddot{z} &= N_1 + P - G \cos \beta_{tr} - F_2 \frac{\dot{z}}{\sqrt{\dot{x}^2 + \dot{y}^2 + \dot{z}^2}} \end{aligned} \right\} \quad (7)$$

Substituting the values of the forces included in the system of differential equations (7) according to Eq. (1)–(5), we obtain the following system of differential equations:

$$\left. \begin{aligned} m\ddot{x} &= -N_2 \sin \alpha + mg(f_1 \cos \beta_{tr} - \sin \beta_{tr}) \cdot \\ &\quad \cdot \cos \alpha - f_2 N_2 \frac{\dot{x}}{\sqrt{\dot{x}^2 + \dot{y}^2 + \dot{z}^2}} \\ m\ddot{y} &= -N_2 \cos \alpha - mg(f_1 \cos \beta_{tr} + \sin \beta_{tr}) \cdot \\ &\quad \cdot \sin \alpha - f_2 N_2 \frac{\dot{y}}{\sqrt{\dot{x}^2 + \dot{y}^2 + \dot{z}^2}} \\ m\ddot{z} &= m\omega_{tr}^2 A_{tr} \sin(\psi_0 + \omega_{tr} t) - f_2 N_2 \frac{\dot{z}}{\sqrt{\dot{x}^2 + \dot{y}^2 + \dot{z}^2}} \end{aligned} \right\} \quad (8)$$

In the system of differential equations (8), the value of normal reaction N_2 is unknown. However, as the heap moves along the axis Oy rather slowly, compared to moving along the axis Ox , with sufficient accuracy for practical calculations we can assume that $\ddot{y} = 0$ and $\dot{y} = 0$.

Then, the second equation of system (8) will turn into the equation of statics (equilibrium equation) of the following form:

$$-N_2 \cos \alpha - mg(f_1 \cos \beta_{tr} + \sin \beta_{tr}) \sin \alpha = 0 \quad (9)$$

From Eq. (9), normal reaction N_2 can be determined in the first approximation. It will be:

$$N_2 = -mg(f_1 \cos \beta_{tr} + \sin \beta_{tr}) \tan \alpha \quad (10)$$

Substituting Eq. (10) in the first and third equations of system (8), the following system of differential equations is obtained after transformation:

$$\left. \begin{aligned} \ddot{x} &= g(f_1 \cos \beta_{tr} + \sin \beta_{tr}) \tan \alpha \left(\sin \alpha + f_2 \frac{\dot{x}}{\sqrt{\dot{x}^2 + \dot{z}^2}} \right) + \\ &\quad + g(f_1 \cos \beta_{tr} - \sin \beta_{tr}) \cos \alpha \\ \ddot{z} &= \omega_{tr}^2 A_{tr} \sin(\psi_0 + \omega_{tr} t) + \\ &\quad + f_2 g(f_1 \cos \beta_{tr} + \sin \beta_{tr}) \tan \alpha \cdot \frac{\dot{z}}{\sqrt{\dot{x}^2 + \dot{z}^2}} \end{aligned} \right\} \quad (11)$$

Therefore, a system of second-order differential equations is obtained, which describes the motion of the heap particle M in the presence of a potato heap flow distributor on the separating conveyor.

If in the first approximation we assume that the vector $\bar{V}$ of average velocity of a particle M on the spreader wing surface is directed at some constant angle γ to the conveyor surface, then the system of differential equations (11) will be considerably simplified and will take the following form:

$$\left. \begin{aligned} \ddot{x} = & g(f_1 \cos \beta_{tr} + \sin \beta_{tr}) \tan \alpha (\sin \alpha + f_2 \cos \gamma \cos \alpha) + \\ & + g(f_1 \cos \beta_{tr} - \sin \beta_{tr}) \cos \alpha \\ \ddot{z} = & \omega_{tr}^2 A_{tr} \sin(\psi_0 + \omega_{tr} t) + \\ & + f_2 g(f_1 \cos \beta_{tr} + \sin \beta_{tr}) \tan \alpha \sin \gamma \end{aligned} \right\} \quad (12)$$

The system of differential equations (12) is linear and can be integrated in quadratures.

The projections of the velocity of the heap particle on the coordinate axis are determined by integrating the system of equations (12) under the following initial conditions: $t = 0$, $\dot{x}_0 = V_{mp} \cos \alpha$, $\dot{z}_0 = 0$.

As a result:

$$\left. \begin{aligned} V_x = \dot{x} = & \left[g(f_1 \cos \beta_{tr} + \sin \beta_{tr}) \tan \alpha (\sin \alpha + f_2 \cos \gamma \cos \alpha) + \right. \\ & \left. + g(f_1 \cos \beta_{tr} - \sin \beta_{tr}) \cos \alpha \right] \cdot t + V_{tr} \cos \alpha \\ V_z = \dot{z} = & -\omega_{tr} A_{tr} \cos(\psi_0 + \omega_{tr} t) + \\ & \left[f_2 g(f_1 \cos \beta_{tr} + \sin \beta_{tr}) \tan \alpha \sin \gamma \right] \cdot \\ & \cdot t + \omega_{tr} A_{tr} \cos \psi_0 \end{aligned} \right\} \quad (13)$$

The resulting velocity V of the heap particle M along the distributor wing is:

$$V = \sqrt{V_x^2 + V_z^2} \quad (14)$$

The law of motion of the heap particle along the distributor wing is found by integrating Eq. (13) under the initial conditions: $t = 0$, $x_0 = 0$, $z_0 = 0$.

As a result of integration, we receive:

$$\left. \begin{aligned} x = & \left[g(f_1 \cos \beta_{tr} + \sin \beta_{tr}) \tan \alpha (\sin \alpha + f_2 \cos \gamma \cos \alpha) + \right. \\ & \left. + g(f_1 \cos \beta_{tr} - \sin \beta_{tr}) \cos \alpha \right] \cdot \frac{t^2}{2} + V_{tr} \cos \alpha \cdot t \\ z = & -A_{tr} \sin(\psi_0 + \omega_{tr} t) + \\ & + \left[f_2 g(f_1 \cos \beta_{tr} + \sin \beta_{tr}) \tan \alpha \sin \gamma \right] \cdot \\ & \cdot \frac{t^2}{2} + \omega_{tr} A_{tr} \cos \psi_0 \cdot t + A_{tr} \sin \psi_0 \end{aligned} \right\} \quad (15)$$

With the use of Eqs (13)–(14) by means of the developed program of numerical calculations, the graphic dependences of the speed of movement of potato heap particles along the distributor wing on time t at different values of angles α of deviation of a wing are constructed, taking into account the fluctuations of the conveyor cloth. These graphical dependences are shown in Fig. 3.

The analysis of the obtained graphical dependences shows that the velocity of the heap V along the wing decreases with an increase in the angle α of wing tilt. When heap speed decreases less than the permissible value $[V]$, the heap will be discharged on the distributor wings, which will lead to a disturbance of the technological process of the potato harvester. Consequently, this obligatory condition must be met: $V \geq [V]$.

Taking into account the process of heap distribution across the conveyor belt width, the allowable speed of heap movement along the distributor wing can be found by ensuring the equality of heap supply to the distributor and its ascent from the distributor. This condition has the following analytical form:

$$\Delta \cdot b_{tr} \cdot [V] = A \cdot h_b \cdot V_{tr} \quad (16)$$

where: $[V]$ – the permissible speed of potato heap particles along the distributor wing ($\text{m} \cdot \text{s}^{-1}$); Δ – the gap between the distributor and conveyor (m); b_{tr} – conveyor width (m); A – the line between the rod drums (m); h_b – the height of the heap layer on the conveyor (m)

Therefore, according to Eq. (16), the speed of movement of heap particles along the distributor wing should not be less than the value:

$$[V] = \frac{A \cdot h_b \cdot V_{tr}}{\Delta b_{tr}} \quad (17)$$

According to the given construction parameters ($A = 0.35$ m, $h_b = 0.22$ m, $\Delta = 0.08$ m, $b_{tr} = 1.2$ m), allowable heap speed along the distributor wing is $[V] = 1.62$ $\text{m} \cdot \text{s}^{-1}$.

The analysis of the obtained dependences shown in Fig. 2 also indicates that for the allowable time of heap particle movement along the distributor wing, the maximum allowable values of the angle of inclination of the distributor

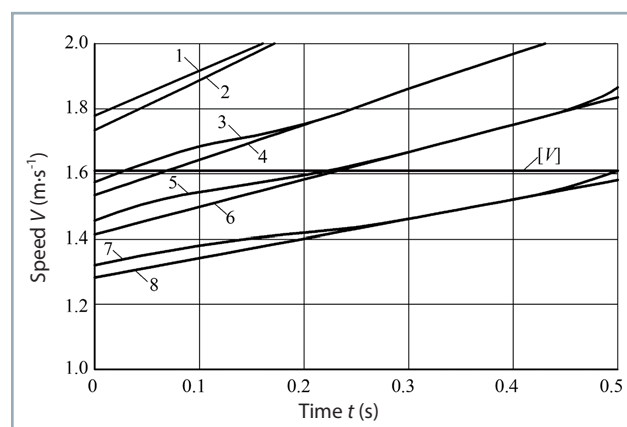


Fig. 3 Dependence of particle velocity along the spreader wing on time t at different values of the angle α of its wing tilt

($f_1 = f_2 = 0.55$, $V_{tr} = 2.0$ $\text{m} \cdot \text{s}^{-1}$, $\beta_{tr} = 22^\circ$): 1 – $\alpha = 30^\circ$, $\omega_{tr} = 4$ $\text{rad} \cdot \text{s}^{-1}$, $A_{tr} = 0.05$ m; 2 – $\alpha = 30^\circ$, $\omega_{tr} = 0$, $A_{tr} = 0$; 3 – $\alpha = 40^\circ$, $\omega_{tr} = 4$ $\text{rad} \cdot \text{s}^{-1}$, $A_{tr} = 0.05$ m; 4 – $\alpha = 40^\circ$, $\omega_{tr} = 0$, $A_{tr} = 0$; 5 – $\alpha = 45^\circ$, $\omega_{tr} = 4$ $\text{rad} \cdot \text{s}^{-1}$, $A_{tr} = 0.05$ m; 6 – $\alpha = 45^\circ$, $\omega_{tr} = 0$, $A_{tr} = 0$; 7 – $\alpha = 50^\circ$, $\omega_{tr} = 4$ $\text{rad} \cdot \text{s}^{-1}$, $A_{tr} = 0.05$ m; 8 – $\alpha = 50^\circ$, $\omega_{tr} = 0$, $A_{tr} = 0$

wing are within the range of $\alpha = 40\text{--}45^\circ$. Therefore, the construction and kinematic parameters of the V-shaped distributor of the potato heap for the new combined subsoil-separating working body of the potato harvester were analytically justified and found.

Conclusion

The permissible velocity of the potato crop along the distributor wing is determined under the condition of maintaining the equality of crop flow to the distributor and its descent from the distributor. The specified speed is $1.62\text{ m}\cdot\text{s}^{-1}$. The analysis of obtained graphic dependences indicates that heap speed along the distributor wing is miniaturized with an increase in the angle of inclination of its wing. At speed lower than the allowable value, there will be a heap piling up on the distributor wings, which will lead to a disturbance of the technological process of potato harvester work. With the allowable time of heap movement along the distributor wing, the maximum allowable values of distributor wing deflection are $40\text{--}45^\circ$.

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