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ANALYSIS OF THE PROCESS OF MATERIAL MOVEMENT IN A SCREW CONVEYOR

Viktor Baranovsky[1]; Ivan Karp[1]; Yaroslav Salo[2]; Bohdan Berezhenko[1]; Petro Marushchak[1]

[1]Ternopil Ivan Puluj National Technical University, Ternopil, Ukraine
[2]Lviv branch of the State Scientific Institution «Ukrainian Research Institute of Forecasting and Testing of Equipment and Technologies for Agricultural Production named after Leonid Pohorily», Mageriv, Ukraine

Abstract. *Screw conveyors, as a universal vehicle, are used for moving, grinding, mixing, dosing of various materials, including products of agricultural production – grain, root crops, fodder mixtures, etc. Increasing the technological efficiency of their use is achieved through constructive improvement and optimization of rational parameters and modes of operation, which is an actual scientific problem. The purpose of the work is to expand the functional capabilities of screw conveyors due to the combination of adjacent technological operations of grinding and moving root crops into one operation by developing a combined working body. The task of the research is to develop a mathematical model that describes the kinematic-dynamic processes of the movement of the flow of crushed root crops along the spiral turn of the auger along the axis of its rotation. In this aspect, two cases of movement of the body of crushed root crops by the working organs of the screw conveyor-shredder are considered: the body of crushed root crops moves along the working surface of the spiral coil without contact with the inner surface of the guide pipe – case I; the body of crushed roots moves simultaneously along the working surface of the spiral coil and the inner surface of the guide pipe – case II. The obtained analytical results of the movement of crushed root crops are a further step in the improvement of the methodology of optimizing the rational parameters of the combined screw mechanisms.*

Key words: *roots, screw conveyor, turn, model, displacement, parameters, force, angular velocity, equation of motion, unit normal, vector.*

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1. INTRODUCTION

According to the concept of Ukraine's transition to sustainable development, one of the strategic measures in the industrial sector is to increase the productivity and reduce the energy consumption of the screw conveyors, which are used in the processing lines of raw materials of the agro-industrial sector for the production of various national economic products.

The livestock sector of agriculture is the main consumer of fodder. Since no feed contains enough components (nutrients, vitamins, trace elements, etc.) that animals need, feeding certain types of feed causes animals to develop slowly. The return from them decreases, costs per unit of manufactured products increase, which leads to a decrease in the profitability of production of products in general [1, 2].

An important factor that ultimately determines the cost of produced feed is the indicators of the use of technical means of preliminary preparation and processing of components of agricultural products, which are used as part of the internal economic technological lines (feed shops) of the agricultural enterprise itself, which are intended for the production of feed [3].

The development of highly efficient technological processes of simultaneous grinding and movement of both single piece and bulk products of agar production requires an integrated scientific approach to the solution of the technical problem of increasing the technological indicators of work and expanding the technological capabilities of screw conveyors-shredders [4, 5].

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The assigned tasks are solved on the basis of the development of the methodology and the methodology of the substantiation of the technological process and the calculation of technological indicators and structural and kinematic parameters and modes of operation of screw conveyors.

Based on the analysis of the technological processes of the functioning of screw conveyors [6–10], it was established that the issue of simultaneous grinding and movement of root crops by screw mechanisms is insufficiently disclosed in scientific works. At the same time, there are significant technological capabilities and scientific prerequisites for the development of screw conveyors with a combined working body, which can ensure the effective performance of related functional operations of simultaneous grinding and moving of products.

Therefore, despite the considerable amount of methods and principles of developing analytical models that describe the processes of moving products by screw conveyors [11, 12], there are certain limitations regarding their application and the possibility of analytical justification of the main parameters of the working bodies of screw transport mechanisms.

2. EXPERIMENTAL METHODS

The efficient operation of the enterprise depends on the layout of the equipment of the technological lines, which should be carried out according to the block-modular principle, which allows to minimize auxiliary transmission (transport) operations and to ensure the possibility of changing the work modes of the workshop, to reduce the consumption of energy resources while guaranteeing the quality of products. These provisions can be implemented on the example of a possible structural scheme for the production (preparation) of multi-faceted feed by a farm in the process of processing agricultural sector products (Fig. 1).

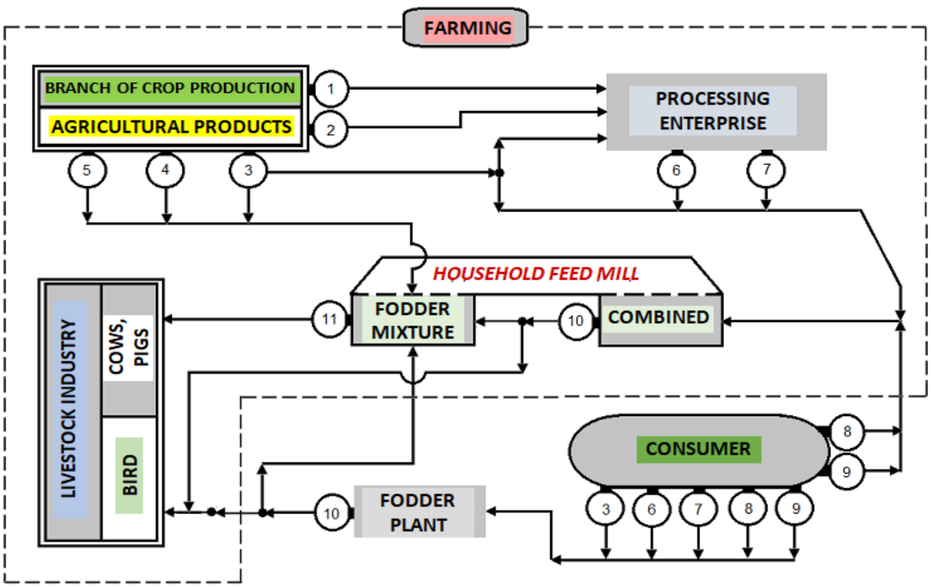

Figure 1. Structural scheme of variants of technology of obtaining full-fodder mixed fodders and feed mixtures in the household: 1 – green grass; 2 – seeds of oil crops; 3 – grain; 4 – rough feed; 5 – root crops; 6 – herbal flour; 7 – waste of processing of grain and oilseeds; 8 – protein-mineral supplements; 9 – premixes; 10 – full-fodder feed; 11 – full-fledged feed mixtures

In this context, providing animals with high-quality and full-fledged juicy feed obtained by processing root crops is one of the important tasks in the general task of increasing the physiological productivity of agricultural livestock.

The introduction of juicy fodder (products of processing fodder beet roots) into the diet of dairy cows increases milk productivity by 10.3%, assimilation of organic substances by 5...8%, nitrogen use by 3...5%. In general, root crops contribute to an increase in feed intake by animals by 8...11% [13, 14].

The purpose of the study is to increase (expand) the technological capabilities of screw conveyors by developing combined working bodies that ensure simultaneous grinding and movement of root crops in the process of their preparation and processing into juicy fodder. The main tasks of the research, which ensure the realization of the stated goal, are the substantiation of the parameters of the combined working body of the screw conveyor-shredder under the condition of reducing the energy consumption of the work process of the technical means used in the technological lines of processing root crops.

The existing technological processes and executive technical means for processing root crops into juicy fodder (Fig. 2) provide for preliminary preparatory operations of removing root crops from storage, their transportation to technical means that grind root crops, further operations of moving (transporting) crushed root crops to mixers-vaporizers, final operations of unloading fodder and its mechanized distribution to animals.

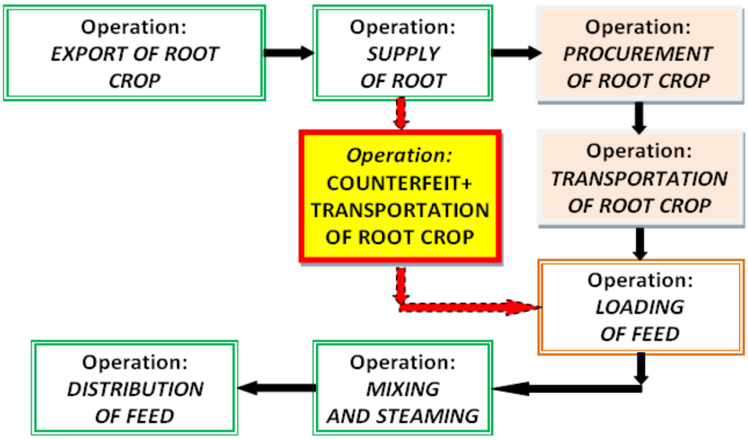

Figure 2. Generalized structural scheme of basic operations of root crop processing for feed

On the basis of the analysis of the existing generalized structural diagram of operations for the processing of root crops for animal feed (Fig. 1), we put forward a scientific hypothesis about the possibility of combining two adjacent technological operations, which are performed by separate mechanisms (shredding of root crops with a root cutter and transportation of crushed parts of root crops to mixers-vaporizers by a belt conveyor) into one continuous (combined) technological operation of simultaneous «shredding + transportation» (Fig. 2). This combined technological operation can be implemented by one screw technical means – a screw conveyor with a combined working body [15, 16].

The implementation of such a technical solution in production conditions will ensure an effective combination of related functional operations, both grinding and simultaneous transportation of root crops by one improved combined working body of the screw conveyor, which is mounted in a technological line intended for their processing and will significantly reduce the overall energy consumption of the process compared to the existing technology due to the elimination of an additional (intermediate) operational and technological means (root cutter), as a separate technical element, which has its own certain material capacity and certain energy consumption for the independent drive of working bodies.

3. RESULTS AND DISCUSSION

To develop an analytical mathematical model of the process of moving crushed parts of root crops through a spiral turn of a screw conveyor, we will consider a complex scheme of acting forces (Fig. 3).

We will analyze the process of movement of part 5 (Fig. 3) of crushed root crops, which is located at point *M*, which is located on the surface of the spiral coil 4, which is installed on the drum 3 of the screw conveyor 2 of the screw conveyor-shredder.

We assume that part 4 of chopped roots, or a body with mass m_n moves along the surface of the spiral coil during its rotation with an angular velocity ω_s without leaving the working surface of the coil. That is, the body, during a certain time of its movement along the working surface of the spiral coil, is connected to the screw conveyor coil and moves along the spiral coil.

In order to develop a mathematical model of the functioning of the screw conveyor of the conveyor-shredder, we introduce a fixed spatial coordinate system $Oxyz$, connected to the guide pipe, the reference point of which is located on the $O'O'$ axis of rotation of the screw conveyor shaft, and the Oz axis coincides with it. At the same time, the Ox axis is directed downward, and the Oy axis is horizontal.

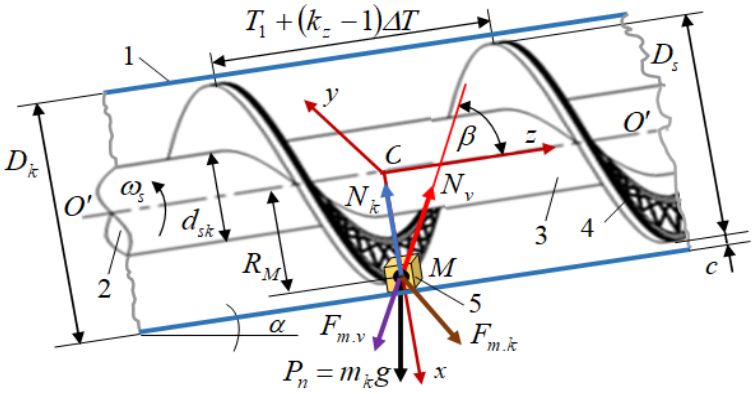

Figure 3. Scheme of forces acting on a part of shredded roots:
1 – guiding pipe; 2 – screw conveyor;3 – drum; 4 – spiral turn; 5 – part of shredded root crops

Let at the instant of time $t_0=0$ the initial angle of rotation of the turn of the screw conveyor is equal to $\varphi_0=const$, and the body of the crushed part of root crops is on the surface of the spiral turn at point M, the step of which, depending on the number of variable steps k_z, is equal to $T_1+(k_z-1)\Delta T$.

In a certain period of time t, the screw conveyor's turn will return to the angle $\varphi(t)=2\pi\omega_s t+\varphi_0$, where ω_s is the angular velocity of the screw conveyor, rad/s; φ_0 is the initial angle of rotation of the screw conveyor at the moment of time $t_0=0$, rad.

According to [17], along with the rotational movement, the screw conveyor carries out a plane-parallel movement in the xOy plane, which is perpendicular to the axis of rotation of the drum of the screw conveyor, i.e., the $O'O'$ axis, while according to [18], for the initial coordinates $x_0=0$, this plane-parallel movement can be specified by the canonical equation of motion of the center of rotation of the axis of rotation of the screw conveyor shaft

$$[x_0(t); y_0(t); z_0(t)] = [x_0(t); y_0(t); 0], t \geq 0. \quad (1)$$

The change of coordinates *x* and *y* during a certain period of time t according to the provisions of [19] can be presented in the form of functionals

$$x(t) = -f_x\left[\phi(t)\cos\phi(t)\right] + g\left[\phi(t)\sin\varphi(t)\right]; \quad y(t) = -f_y\left[\varphi(t)\sin\varphi(t)\right] - g\left[\varphi(t)\cos\varphi(t)\right]. \quad (2)$$

During the rotation of the screw conveyor, the following forces act on the body of crushed root crops, the volume of which is equal to V_m and which is located at point M :

- force of weight $P_n = m_n g = V_m \rho_k g$, N, where m_n, V_m – respectively, mass (kg) and body volume of crushed root crops, m^3; ρ_k – specific mass of root crops, kg/m^3;
- the reaction force of the spiral turn $N_v = R_v n_v$ of the screw conveyor, N, where R_v is the reaction of the working surface of the spiral turn, N; n_v is the unit normal to the working surface of the spiral turn;
- the reaction force of the working (inner) surface of the guide pipe of the screw conveyor-shredder $N_k = R_k n_k$, N, where R_k is the reaction force of the working surface of the guide pipe, N; n_k is a single normal to the working surface of the guide pipe of the screw conveyor-shredder;
- the force of friction of the body of crushed root crops sliding on the working surface of the spiral turn of the screw conveyor $F_{m.v} = N_v f_v$, N, where f_v is the coefficient of friction of the body of crushed root crops sliding on the surface of the spiral turn;
- the force of friction of the body of crushed root crops sliding along the working surface of the guide pipe of the screw conveyor-shredder $F_{m.k} = N_k f_k$, N, where f_k is the coefficient of friction of the body of crushed root crops along the surface of the guide pipe of the screw conveyor-shredder.

Let's consider two possible cases of movement of the body of crushed root crops by the working bodies of the screw conveyor-shredder:

- the body of crushed root crops moves along the working surface of the spiral coil without contact with the inner surface of the guide pipe – case I;
- the body of crushed roots moves simultaneously along the working surface of the spiral coil and the inner surface of the guide pipe –case II.

According to the classical laws of mechanics, let's write down the equation of motion of the body of chopped roots in a fixed $Oxyz$ coordinate system for cases I and II in vector form:

$$V_n \rho_k \frac{d^2 \vec{R}_M}{dt^2} = V_n \rho_k \vec{g} + \vec{R}_v \vec{n}_v (1 + f_v) + \vec{R}_k \vec{n}_k (1 + f_k); \; t > 0, \quad (3)$$

where $\vec{R}_M$ is the instantaneous radius vector of the position of the parts of root crops in the Oxy system at the moment of time t.

Let us denote the corresponding components of the vectors of equations (3) as follows:

- the instantaneous radius-vector of the position of the body of the crushed root crops in the Oxy system at the moment of time t through

$$\vec{R}_M(t) = [x_M(t); y_M(t); z_M(t)]; \quad (4)$$

- the force vector of the body weight of crushed root crops through

$$\vec{P}_n = \left(V_n \rho_k \vec{g}\cos\alpha; 0; -V_n \rho_k \vec{g}\sin\alpha\right) = \begin{pmatrix} \left(\iint\limits_{S_n} z(x,y)\,dxdy\right)\rho_k \vec{g}\cos\alpha; 0; \\ -\left(\iint\limits_{S_n} z(x,y)\,dxdy\right)\rho_k \vec{g}\sin\alpha \end{pmatrix}, \qquad (5)$$

where α is the angle of inclination of the screw conveyor-shredder to the horizontal plane, degrees;

- the vector of the frictional force of the body of crushed root crops sliding along the working surface of the spiral turn of the screw conveyor

$$\vec{F}_{m.v} = -\left|\vec{N}_v\right| f_v \left|\frac{d\vec{R}_ш}{dt} - \frac{d\vec{R}_M}{dt}\right| / \left|\frac{d\vec{R}_s}{dt} - \frac{d\vec{R}_s}{dt}\right| = -\frac{\left|\vec{R}_v \vec{n}_v\right| f_v \left|\frac{d\vec{R}_s}{dt} - \frac{d\left(2\pi\vec{\omega}_s t + \varphi_0\right)}{dt}\right|}{\left|\frac{d\vec{R}_s}{dt} - \frac{d\left(2\pi\vec{\omega}_s t + \varphi_0\right)}{dt}\right|}, \qquad (6)$$

while $\frac{d\vec{R}_M}{dt} = \frac{d\left(2\pi\vec{\omega}_s t + \varphi_0\right)}{dt} = \vec{\vartheta}_v$ is the velocity vector of the surface of the spiral turn of the screw conveyor at the point M and the moment of time t;

- the vector of the frictional force of the body of crushed root crops sliding along the working inner surface of the guide pipe of the screw conveyor-shredder

$$\vec{F}_{m.k} = -\left|\vec{N}_k\right| f_k \left|\frac{d\vec{R}_s}{dt}\right| / \left|\frac{d\vec{R}_s}{dt}\right| = -\left|\vec{R}_k \vec{n}_k\right| f_k \left|\frac{d\vec{R}_s}{dt}\right| / \left|\frac{d\vec{R}_s}{dt}\right|. \qquad (7)$$

To determine the bond reaction R_v of the working surface of the spiral coil and the bond reaction R_k of the working surface of the guide pipe of the screw conveyor-shredder, it is necessary to determine the unit normal vector $\vec{n}_v$ to the working surface of the spiral coil and the vector of the unit normal $\vec{n}_k$ to the working surface of the guide pipe of the screw conveyor-shredder.

To do this, we write down the equations of the surface of the screw and the surface of the guide pipe, which, according to [3, 4], can be given by the relations, respectively:

$$\hat{S}_s\left(0,5D_s;\varphi_s;z\right) = \left[z + 0,5T_1 + \left(k_z - 1\right)\Delta T\left(\varphi_s - 2\pi\left(d\varphi_s / dt\right)t - \varphi_0\right)\right] / \pi = 0; \qquad (8)$$

$$\hat{S}_k\left(x;y;z\right) = x^2 + y^2 - 0,25D_k^2 = x^2 + y^2 - \left(0,5D_s + 2\varepsilon\right)^2 = 0, \qquad (9)$$

where D_s is the diameter of the screw conveyor, m; D_k – inner diameter of the guide pipe of the screw conveyor-shredder, m; φ_s is the rotation angle of the screw conveyor, rad.

Then the unit normal vector $\vec{n}_v$ to the working surface of the spiral coil and the unit normal vector $\vec{n}_k$ to the working surface of the guide pipe of the screw conveyor-shredder can be written in the form:

$$\vec{n}_v = \begin{bmatrix} -\left[T_1 + \left(k_z - 1\right)\Delta T\right]\sin\varphi_s; \\ \left[T_1 + \left(k_z - 1\right)\Delta T\right]\cos\varphi_s; \\ 2\pi R_M \,/\, a\left(R_M\right) \end{bmatrix}; \tag{10}$$

$$\vec{n}_k = \begin{bmatrix} -\cos\left(\varphi_s - 2\pi\left(d\varphi_s / dt\right)t - \varphi_0\right); \\ -\sin\left(\varphi_s - 2\pi\left(d\varphi_s / dt\right)t - \varphi_0\right); 0 \end{bmatrix}, \tag{11}$$

where a is the angular parameter of the screw, according to [9] $a(R_M) = \sqrt{\left[T_1 + \left(k_z - 1\right)\right]^2 + 4\pi^2 R_M^2}$.

Also, taking into account the plane-parallel and translational movement of the screw conveyor, which is given by the canonical equation of motion $\left[x_0(t); y_0(t); z_0(t)\right] = \left[x_0(t); y_0(t); 0\right], t \geq 0$ of the center of rotation of the axis of the screw conveyor in the plane xOy, we determine the speed of movement of the working surface of the spiral turn of the screw conveyor

$$\vartheta_v = \left(\frac{d\left[\left(D_ш\right)\cos\left(2\pi \frac{d\phi_ш}{dt} t - \phi_0\right)\right]}{2dt}; \frac{d\left[\left(D_s + 2\varepsilon\right)\sin\left(2\pi\left(d\varphi_s / dt\right)t - \varphi_0\right)\right]}{2dt}; 0 \right) + \frac{d\left[x_0(t); y_0(t); 0\right]}{dt}, \tag{12}$$

or

$$\vartheta_v = \left(-2\pi \frac{d\varphi_ш}{dt} \cdot y + \frac{dx_0(t)}{dt}; \frac{dy_0(t)}{dt} + 2\pi \frac{d\varphi_ш}{dt} \cdot x; 0 \right). \tag{13}$$

In equations (3):

- we substitute: the values of the acting forces, which are determined according to (5)–(7); the value of the speed of movement (speed of movement) of the working surface of the spiral turn of the screw conveyor, which is determined according to (13).
- multiply by the scalar value of the unit normal $\vec{n}_v$ and $\vec{n}_k$, which are determined according to (10) and (11);

Then we will get the records of the equation for the 1st and 2nd cases of movement of the body of crushed parts of root crops, respectively: when the body of crushed parts of root crops moves along the working surface of the spiral coil without contact with the inner surface of the guide pipe; when the body of crushed parts of root crops moves simultaneously along the working surface of the spiral coil and the inner surface of the guide tub:

$$m_n \frac{d^2\left(0,5D_{ш}\right)}{dt^2} = \begin{pmatrix} \left(\iint\limits_{S_n} z(x,y)\,dxdy\right)\rho_k g\cos\alpha\cos\varphi_s;0; \\ -\left(\iint\limits_{S_n} z(x,y)\,dxdy\right)\rho_k g\sin\alpha\sin\varphi_s \end{pmatrix} + R_v\Theta +$$

$$+R_k\Omega - \left|R_v\Theta\right| \times \qquad ; \qquad (14)$$

$$\times f_v \frac{\left|\frac{d\left(0,5D_s\right)}{dt} - \left(-2\pi\left(d\varphi_s/dt\right)\cdot y + \frac{dx_0(t)}{dt}; \frac{dy_0(t)}{dt} + 2\pi\left(d\varphi_s/dt\right)\cdot x;0\right)\right|}{\left|\frac{d\left(0,5D_s\right)}{dt} - \left(-2\pi\left(d\varphi_s/dt\right)\cdot y + \frac{dx_0(t)}{dt}; \frac{dy_0(t)}{dt} + 2\pi\frac{d\varphi_s}{dt}\cdot x;0\right)\right|} - \left|R_k\Omega\right| f_k \frac{\left|\frac{d\left(0,5D_s\right)}{dt}\right|}{\left|\frac{d\left(0,5D_s\right)}{dt}\right|}$$

$$m_n \frac{d^2\left(0,5D_s\right)}{dt^2} = \begin{pmatrix} \left(\iint\limits_{S_n} z(x,y)\,dxdy\right)\rho_k g\cos\alpha\cos\phi_{ш};0; \\ -\left(\iint\limits_{S_n} z(x,y)\,dxdy\right)\rho_k g\sin\alpha\sin\varphi_s \end{pmatrix} + R_v\Theta + R_k\Omega - \left|R_v\Theta\right| \times \qquad , \qquad (15)$$

$$\times f_v \frac{\left|\frac{d\left(0,5D_s\right)}{dt} - \left(-2\pi\frac{d\varphi_s}{dt}\cdot y + \frac{dx_0(t)}{dt}; \frac{dy_0(t)}{dt} + 2\pi\frac{d\varphi_s}{dt}\cdot x;0\right)\right|}{\left|\frac{d\left(0,5D_s\right)}{dt} - \left(-2\pi\frac{d\varphi_s}{dt}\cdot y + \frac{dx_0(t)}{dt}; \frac{dy_0(t)}{dt} + 2\pi\frac{d\varphi_s}{dt}\cdot x;0\right)\right|} - \left|R_k\Omega\right| f_k \frac{\left|\frac{d\left(0,5D_s\right)}{dt}\right|}{\left|\frac{d\left(0,5D_s\right)}{dt}\right|}$$

where

$$\Theta = \begin{bmatrix} -\left[T_1 + \left(k_z - 1\right)\Delta T\right]\sin\varphi_s; \left[T_1 + \left(k_z - 1\right)\Delta T\right]\cos\varphi_s; \\ \frac{2\pi R_M}{\sqrt{\left[T_1 + \left(k_z - 1\right)\Delta T\right]^2 + 4\pi^2 R_M^2}} \end{bmatrix}; \quad \Omega = \begin{bmatrix} -\cos\left(\varphi_s - 2\pi\left(d\varphi_s/dt\right)t - \varphi_0\right); \\ -\sin\left(\varphi_s - 2\pi\left(d\varphi_s/dt\right)t - \varphi_0\right);0 \end{bmatrix}.$$

At the same time, according to equations (14) and (15), the entries of the equation for the 1st and 2nd cases of movement of the body of the crushed parts of root crops will have the following form:

$$\left(\iint\limits_{S_n} z(x,y)\,dxdy\right)\rho_k \frac{D_s}{2}\left(\frac{d\varphi_s}{dt}\right)^2 = \left[\begin{pmatrix} \left(\iint\limits_{S_n} z(x,y)\,dxdy\right)\rho_k g\cos\alpha\cos\varphi_s;0; \\ -\left(\iint\limits_{S_n} z(x,y)\,dxdy\right)\rho_k g\sin\alpha\sin\varphi_s \end{pmatrix}\right] +$$

$$+R_v\Theta\left(1 - f_v \frac{\left|\frac{d\left(0,5D_s\right)}{dt} - \begin{pmatrix} -2\pi\frac{d\kappa_s}{dt}\cdot y + \frac{dx_0(t)}{dt}; \\ \frac{dy_0(t)}{dt} + 2\pi\frac{d\varphi_s}{dt}\cdot x;0 \end{pmatrix}\right|}{\left|\frac{d\left(0,5D_s\right)}{dt} - \begin{pmatrix} -2\pi\frac{d\varphi_s}{dt}\cdot y + \frac{dx_0(t)}{dt}; \\ \frac{dy_0(t)}{dt} + 2\pi\frac{d\varphi_s}{dt}\cdot x;0 \end{pmatrix}\right|}\right) \qquad ; \qquad (16)$$

$$\left(\iint_{S_n} z(x,y)\,dxdy\right)\rho_k \frac{D_s}{2}\left(\frac{d\varphi_s}{dt}\right)^2 = \left[\begin{pmatrix}\left(\iint_{S_n} z(x,y)\,dxdy\right)\rho_k g\cos\alpha\sin\varphi_s;0;\\ -\left(\iint_{S_n} z(x,y)\,dxdy\right)\rho_k g\sin\alpha\sin\varphi_s\end{pmatrix}\right]+$$

$$+R_v\Theta\left(1-f_v\frac{\left|\dfrac{dD_ш}{2dt}-\begin{pmatrix}-2\pi\dfrac{d\varphi_s}{dt}\cdot y+\dfrac{dx_0(t)}{dt};\\ \dfrac{dy_0(t)}{dt}+2\pi\dfrac{d\varphi_s}{dt}\cdot x;0\end{pmatrix}\right|}{\left|\dfrac{0.5dD_s}{dt}-\begin{pmatrix}-2\pi\dfrac{d\varphi_s}{dt}\cdot y+\dfrac{dx_0(t)}{dt};\\ \dfrac{dy_0(t)}{dt}+2\pi\dfrac{d\varphi_s}{dt}\cdot x;0\end{pmatrix}\right|}\right)-R_k\Omega\left(1-f_k\frac{|dD_s/2dt|}{|dD_s/2dt|}\right). \tag{17}$$

From equations (16), (17) we find the reaction of the bond R_v of the working surface of the spiral turn and the reaction of the bond R_k of the working surface of the guide pipe of the screw conveyor-shredder:

$$R_v=\frac{\left(\iint_{S_n} z(x,y)\,dxdy\right)\rho_k R_M\left(\dfrac{d\varphi_s}{dt}\right)^2-\left[\begin{matrix}\left(\iint_{S_n} z(x,y)\,dxdy\right)\rho_k g\cos\alpha;\\ 0;-\left(\iint_{S_n} z(x,y)\,dxdy\right)\rho_k g\sin\alpha\end{matrix}\right]}{\Theta\left(1-f_v\dfrac{|(dR_s/dt)-(\Psi)|}{|(dR_s/dt)-(\Psi)|}\right)}; \tag{18}$$

$$R_k=\frac{\Omega\left(1-f_k\dfrac{|dD_s/2dt|}{|dD_s/2dt|}\right)}{\begin{matrix}\left(\iint_{S_n} z(x,y)\,dxdy\right)\rho_k\dfrac{D_s}{2}\left(\dfrac{d\varphi_s}{dt}\right)^2-\left[\begin{pmatrix}\left(\iint_{S_n} z(x,y)\,dxdy\right)\rho_k g\cos\alpha\sin\varphi_s;0;\\ -\left(\iint_{S_n} z(x,y)\,dxdy\right)\rho_k g\sin\alpha\sin\varphi_s\end{pmatrix}\right]+\\ +R_v\Theta\left(1-f_v\dfrac{|(dR_s/dt)-(\Psi)|}{|(dR_s/dt)-(\Psi)|}\right)\end{matrix}}, \tag{19}$$

where $\Psi=\begin{pmatrix}-2\pi(d\varphi_s/dt)\cdot y+\dfrac{dx_0(t)}{dt};\\ \dfrac{dy_0(t)}{dt}+2\pi(d\varphi_s/dt)\cdot x;0\end{pmatrix}$.

By substituting the values of the bond reaction R_v of the working surface of the spiral coil from equations (18) and the bond reaction R_k of the working surface of the guide pipe from equation (19) into the equations of motion (3), we obtain mathematical models of the dynamic process of the movement of the body of crushed root crops by the working bodies of the screw conveyor-shredder for cases I and II

$$m_k \frac{d^2\varphi_s}{dt^2} = m_k g \sin\alpha - \frac{\left[m_k R_M \left(\dot{\varphi}_s\right)^2 - \left(m_k g \cos\alpha; 0; -m_k g \sin\alpha\right)\right]\left(1+f_v\right)}{\left[-T_k \sin\varphi_s; T_k \cos\varphi_s; \frac{2\pi R_M}{\sqrt{T_k^2 + 4\pi^2 R_M^2}}\right] \times \left(1 - f_v \frac{\left|\dot{\varphi}_s - 2\pi\omega_s y + \dot{\varphi}_0\right|}{\left|\frac{dR_M}{2dt} - 2\pi\omega_s \cdot y + \frac{dx_0(t)}{dt}\right|}\right)}; \tag{20}$$

$$m_k \frac{d^2\varphi_s}{dt^2} = m_k g \sin\alpha - \frac{\left[m_k R_M \left(\dot{\varphi}_s\right)^2 - (\Gamma)\right]\left(1+f_v\right)}{[\Phi]\left(1 - f_v \frac{\left|\dot{\varphi}_s - 2\pi\omega_s y + \dot{\varphi}_0\right|}{\left|\frac{dR_M}{2dt} - 2\pi\omega_s \cdot y + \frac{dx_0(t)}{dt}\right|}\right)} - \frac{[\Omega]\left(1 - f_k \frac{\left|dD_s / 2dt\right|}{\left|dD_s / 2dt\right|}\right)\left(1+f_k\right)}{m_k \frac{D_s}{2}\left(\frac{d\varphi_s}{dt}\right)^2 - (\Gamma) + \frac{\left[m_k R_M \left(\dot{\varphi}_s\right)^2 - (\Gamma)\right]}{\left(1 - f_v \frac{\left|\dot{\varphi}_s - 2\pi\omega_s y + \dot{\varphi}_0\right|}{\left|\frac{dR_M}{2dt} - 2\pi\omega_s \cdot y + \frac{dx_0(t)}{dt}\right|}\right)}\left(1 - f_v \frac{\left|\dot{\varphi}_s - 2\pi\omega_s \left(d\varphi_s / dt\right)\cdot y + \frac{dx_0(t)}{dt}(\Psi)\right|}{\left|\frac{dD_s}{2dt} - (\Psi)\right|}\right)}, \tag{21}$$

where $\Phi = \left[-T_k \sin\varphi_s; T_k \cos\varphi_s; \frac{2\pi R_M}{\sqrt{T_k^2 + 4\pi^2 R_M^2}}\right]$; $\Gamma = \left(m_k g \cos\alpha \sin\varphi_s; 0; -m_k g \sin\alpha \sin\varphi_s\right)$.

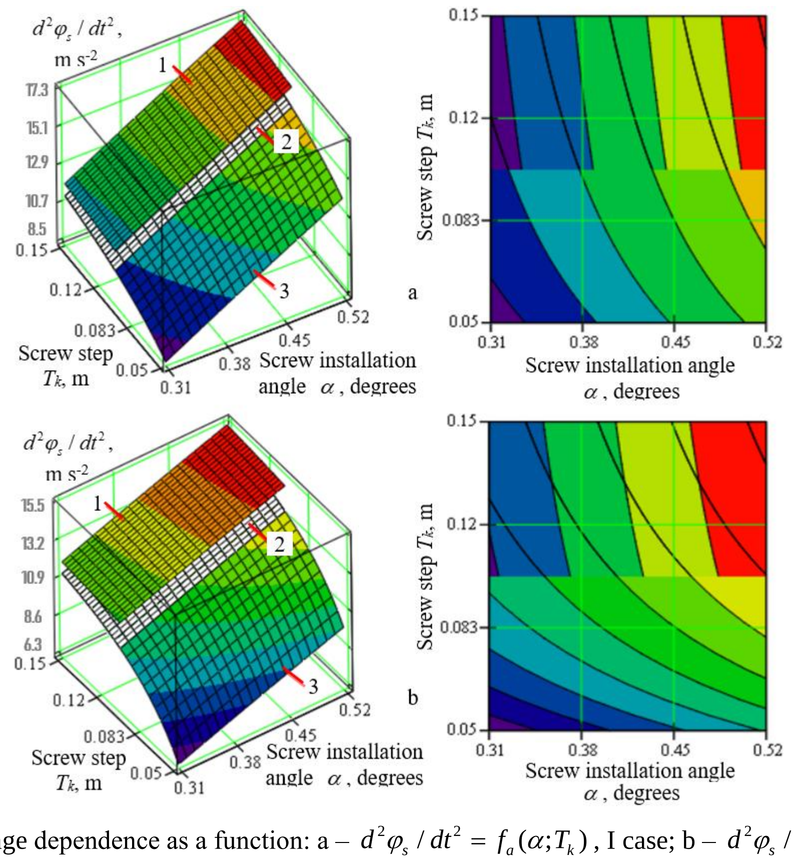

Figure 4. Change dependence as a function: a – $d^2\varphi_s / dt^2 = f_a(\alpha; T_k)$, I case; b – $d^2\varphi_s / dt^2 = f_a(\alpha; T_k)$, II case; 1, 2, 3 – $T_k = T_1 + 0.04$, m; $T_k = T_1 + 0.06$, m; $T_k = T_1 + 0.08$, m

Based on the analysis of graphical constructions (Fig. 4), it was established that the acceleration of the speed of movement of the crushed parts of root crops along the surface of the spiral turn at the screw pitch $T_k = T_1 + 0.08$ m varies within the range: from 8.5 to 12.9 m s^{-2} for the 1 case; from 6.3 to 13.2 m s^{-2} for the II case.

For changes in the pitch of the spiral turns $T_k = T_1 + 0.06$ m, the acceleration of the speed of movement of the crushed parts of root crops along the surface of the spiral turns varies within: from 9.6 to 15.1 m/s for the first case; from 8.9 to 13.2 m/s for the II case.

For changes in the pitch of the spiral turns $T_k = T_1 + 0.04$ m, the acceleration of the speed of movement of the crushed parts of root crops along the surface of the spiral turns varies within: from 10.7 to 17.3 m/s for the first case; from 11.1 to 15.5 m/s for the II case.

At the same time, at the step of the spiral coil in the range of 0.25 $\leq T_k \leq$ 0.05 m, with a step increment equal to 0.04 and 0.06 m, the crushed parts of root crops weighing more than 0.1 kg lose contact with the surface of the spiral coil at an angular velocity of less than 10 rad/s, surface 2 and 3.

4. CONCLUSIONS

1. Thus, the analytical values of the reaction of the bond R_v of the working surface of the spiral coil (18) and the reaction of the bond R_k of the working surface of the guide pipe of the screw conveyor (19) and the equations of motion of the body of crushed root crops (20) and (21) for I and II were obtained cases of movement of crushed parts of root crops, is the basis for further analytical calculations in order to substantiate and optimize the main structural and kinematic parameters and modes of operation of the working bodies of the conveyor-shredder.

2. For a full description of the process of the screw conveyor-shredder, the mathematical model of the dynamic process of the movement of crushed parts by the screw conveyor (18)–(21) must be supplemented with the initial conditions: $\varphi(0) = \varphi_ш$; $\frac{d\varphi(0)}{dt} = \varphi_0$.

3. It should also be noted that the mathematical model (18)-(21) is adequate only under the condition that R_v > 0 and R_k > 0. At the same time, in the case of R_v < 0 and R_k < 0, the body of the crushed roots loses contact with the surfaces and equation (3) no longer describe the process of motion (movement).

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АНАЛІЗ ПРОЦЕСУ РУХУ МАТЕРІАЛУ В ШНЕКОВОМУ КОНВЕЄРІ

Віктор Барановський[1]; Іван Карп[1]; Ярослав Сало[2]; Богдан Береженко[1]; Петро Марущак[1]

[1]Тернопільський національний технічний університет імені Івана Пулюя, Тернопіль, Україна
[2]Львівська філія Державної наукової установи «Український науково-дослідний інститут прогнозування та випробування техніки та технологій для сільськогосподарського виробництва імені Леоніда Погорілого», Магерів, Україна

Резюме. *Шнекові конвеєри, як універсальний транспортний засіб застосовуються для переміщення, подрібнення, змішування, дозування різних матеріалів, у тому числі й продуктів аграрного виробництва – зерна, коренеплодів, кормових сумішей тощо. Підвищення технологічної ефективності їх використання досягається шляхом конструктивного удосконалення та оптимізації раціональних параметрів і режимів роботи, що є актуальною науковою проблемою. Шнековий транспортер-подрібнювач реалізовано на основі поєднання транспортного шнека та встановлених різальних ножів-*

подрібнювачів на напрямній трубі шнекового конвеєра. Мета роботи – розширення функціональних спроможностей шнекових конвеєрів за рахунок поєднання суміжних технологічних операцій подрібнення та переміщення коренеплодів у одну операцію шляхом розроблення комбінованого робочого органа. Завдання дослідження – розроблення математичної моделі, яка описує кінематично-динамічні процеси руху потоку подрібнених коренеплодів по спіральному витку шнека взовж осьової лінії його обертання. У цьому аспекті розглянуто два випадки переміщення тіла подрібнених коренеплодів робочими органами шнекового транспортера-подрібнювача: тіло подрібнених коренеплодів рухається по робочій поверхні спірального витка без контакту з внутрішньою поверхнею напрямної труби – І випадок; тіло подрібнених коренеплодів рухається одночасно по робочій поверхні спірального витка та внутрішній поверхні напрямної труби – ІІ випадок. Отримані аналітичні значення реакції в'язі робочої поверхні спірального витка та реакції в'язі робочої поверхні напрямної труби шнекового конвеєра та рівняння руху тіла подрібнених коренеплодів для І та ІІ випадків переміщення подрібнених частин коренеплодів є основою для подальшого проведення аналітичних розрахунків з метою обгрунтування та оптимізації основних конструктивно-кінематичних параметрів і режимів роботи робочих органів транспортера-подрібнювача.

Ключові слова: *коренеплоди, шнековий конвеєр, виток, модель, переміщення, параметри, сила, кутова швидкість, рівняння руху, одинична нормаль, вектор.*

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