RESEARCH OF THE OF BULK MATERIAL MOVEMENT PROCESS IN THE INACTIVE ZONE BETWEEN SCREW SECTIONS
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ДОСЛІДЖЕННЯ ПРОЦЕСУ ПЕРЕМІЩЕННЯ СИПКОГО МАТЕРІАЛУ В НЕАКТИВНІЙ ЗОНІ МІЖ ГВИНТОВИМИ СЕКЦІЯМИ

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ABSTRACT
The article presents the results of theoretical and experimental studies of the process of moving bulk material in the inactive zone between hinged screw sections of a flexible screw conveyor. The influence of the gap between the edges of adjacent screw sections and the magnitude of their circular displacement on the process of continuous transportation of bulk material is presented. The results of theoretical and experimental studies are compared. This will allow choosing the optimal design, kinematic and technological parameters of the developed sectional screw working body when transporting bulk agricultural materials along curved paths, both in horizontal and inclined directions, as well as along curved paths.

РЕЗЮМЕ
В статті представлені результати теоретичних і експериментальних досліджень процесу переміщення сипкого матеріалу в неактивній зоні між шарнірно з'єднаними гвинтовими секціями гнучкого гвинтового конвеєра. Наведено вплив величини зазору між краями сусідніх гвинтових секцій та величини їх колового зміщення на процес неперервного транспортування сипкого матеріалу. Проведено порівняння результатів теоретичних і експериментальних досліджень. Це дозволить вибрати раціональні конструктивні, кінематичні та технологічні параметри розробленого секційного гвинтового робочого органу при транспортуванні сипких сільськогосподарських матеріалів по криволінійних трасах, як у горизонтальному та похилому напрямках, а також по криволінійних трасах.

INTRODUCTION
Screw conveyors are widely used in the movement of various bulk materials, mainly agricultural products, which include: grain, granular seeds, fodder flour, chaff, bran, compound feed, cereal, granules of fertilizers, etc. The results of studies on the contact interaction of such bulk materials with working surfaces of screw conveyors are described in *(Loveikin V. and Rogatynska L., 2011; Lyashuk O.L., et.al., 2015; Rogovskii I.L., et.al., 2019; Wang D.-X., 2012, Pylypaka S.F., et.al., 2019).*

Research on mechanical and technological properties of agricultural materials is given in the works (*Tsarenko O.M., et.al., 2003; Rogovskii I.L., et.al., 2019)*.

Mainly for transportation of such cargoes rigid auger conveyors installed at different angles to the horizon are used, as well as flexible screw conveyors, the determination of the parameters and modes of which are described in the works (*Hevko B.M., et.al., 2018; Haydl H.M., 1986; Mondal D., 2018; Owen Philip J.,2010, Qi J., et.al., 2017*, *Roberts Alan W., and Bulk Solids, 2015, Tian Y. et.al., 2018).*

Pneumatic conveyors, which can transport various loads of curved tracks, have been widely used. The main disadvantage of these types of conveyors is significant energy costs and price, which limits their use. The study of these types of conveyors, as well as screw feeders for feeding bulk materials are in the works of *(Baranovsky V.M., et.al.,2018, Hevko R.B., et.al., 2018; Lech M., 2001; Manjula E.V.P.J., et.al., 2017*; *Naveen T. et.al., 2015).*

The combination of technological operations, such as transportation and mixing of feed mixtures, is possible with the use of conveyor washers that can work on different routes, but only stationary.

The results of studies on such conveyors are given in (*Hevko R.B., et.al., 2017; Hevko R.B., et.al., 2018; Lyashuk O.L., et.al., 2018; Yao Y.P., et.al., 2014).*

The results of theoretical and experimental developments, which are presented in this article, are a continuation of previous studies and are aimed at improving the efficiency of the work of screw conveyors, the constructive schemes and the working bodies of which are given in the studies (*Hevko B.M., et.al., 2018; Hevko R.B., et.al., 2014, 2016, 2019*).

MATERIALS AND METHODS

In order to increase the reliability of the flexible screw conveyor functioning, it is proposed that its working body is made of separate screw sections that are hinged to each other. Fig.1a shows the location of the edges of adjacent sections, the screw ribs 1 and 2 which are located in the axial direction with a gap δ (inactive zone). The screw sections are interconnected using a hinge mechanism 3, made on the principle of a universal joint with spaced axes that are mutually perpendicular and located in an elastic casing 4. In the circumferential direction, the edges of adjacent helical ribs are offset from each other by an angle α. The idea of the design of such a working body is that when the bulk material ascends from the edge of the screw rib 1, the distance δ must fly through after some time t_1. At the same time, the edge of the screw rib 2 is the least (it is necessary to take into account the angle of the material flight) for a time t_2 and it must be rotated through an angle α in order to capture the transported material.

A general view of the sections of the working body located on the curvilinear region and its individual elements are presented in Fig.1b.

The purpose of these studies is to establish rational parameters and operating modes of the developed working body, which will ensure stable transportation of bulk materials on various technological routes.

Let's consider the movement of bulk cargo through a fixed casing using the screw sector of the screw spiral. Let us single out its elementary volume, which simultaneously contacts the fixed casing and the rotating section of the screw spiral. From the side of the casing, a reaction acts on it, perpendicular to its surface and the corresponding friction force. The reaction from the side of the gutter is determined by the vector sum of the gravity efforts of the selected elementary volume and centripetal force.

The elementary volume is also affected by the reaction from the surface of the screw rib directed perpendicular to the surface of the screw at the contact point and the corresponding friction force. Fig.1c shows the forces acting on the elementary volume of bulk material moving in the casing.

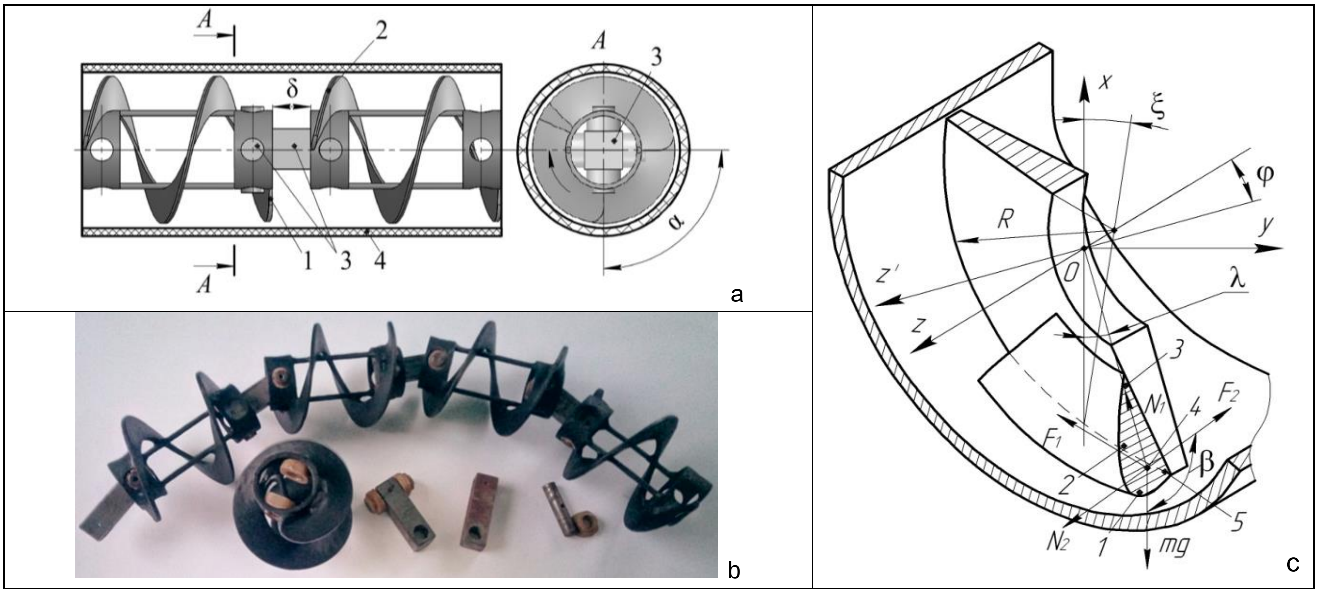


Fig. 1 - Design and calculation scheme of the screw working body, the sections of which are hinged

a - the image of two sections; b - is a general view of sections of a working body located on a curved section and its individual elements; c - scheme for determining the forces acting on the elementary volume of bulk material that moves inseparably in the casing

We will assume that the friction forces between the particles of the material (grains, maize, or other bulk material) significantly exceed their friction forces over the surface of the auger and casing.

This assumption makes it possible to consider the motion of particles as a whole with the same angular velocity. The actual movement of the material differs from the ideal, so points 1 and 2, which are at the edge of the cross-section of the bulk material flow are slightly behind points 3, 4 and 5, which are near the edges of the auger.

A significant lag will be observed only in the case of transport of material having a low coefficient of friction between individual particles (grains). However, for the transport of grain material, the intermixing of the individual particles is negligible, the particles almost stick together and move in a continuous stream, especially at high speeds. This statement is experimentally confirmed in the works (*Hevko R.B., et al.,* 2018, *Tsarenko O.M., et al., 2003*).

The speed of movement of point 1, which is at the edge of the stream cross section, is maximum due to the maximum distance from the centre of the casing.

The same will be the linear velocity of point 5. The velocity of points 2 and 4 decreases in proportion to the radius at which they move. The lowest speed is characteristic of point 3, which is closest to the centre of rotation.

The equation of motion of a single elementary volume of bulk material that is unrelated to the flow can be written as a system of two differential equations:

$$m(d^2z/dt^2) = N_1\cos\xi - F_1\sin\xi - F_2\sin\beta - mg\sin\varphi \tag{1}$$

$$mR(d^2\lambda/dt^2) = N_1\sin\xi + F_1\cos\xi - F_2\cos\beta - mg\sin\lambda\cos\varphi \tag{2}$$

where m is the mass of the material particle; R is the radius of the casing; N_1 - the reaction of the screw on the material; F_1 - friction force from reaction N_1; N_2 is the reaction of the casing to the material; F_2 - friction force from reaction N_2; ξ - is the angle of elevation of the screw surface; φ is the angle of inclination of the auger section axis to the horizon; β is the direction of the material particle motion relative to the casing; λ is the angular position of a material particle in its rotational motion; z is the longitudinal coordinate of the particle along the casing axis.

The N_2 reaction is determined by the condition:

$$N_2 = mg\cos\lambda\cos\varphi + mR\cdot(d\lambda/dt)^2 \tag{3}$$

The friction forces are determined accordingly:

$$F_1 = f_1N_1; \quad F_2 = f_2N_2 \tag{4}$$

where f_1 is the coefficient of friction of the material on the helical rib surface; f_2 is the coefficient of friction of the material on the casing surface.

Between the directions of motion of a material particle and the geometry of a helical edge, when rotating it at an angular velocity ω, it is possible to write such geometric dependences:

$$tg\beta = \dot{z}/R\dot{\lambda}; \quad tg\xi = \dot{z}/R(\omega - \dot{\lambda}) \tag{5}$$

If we consider the movement of the selected element of material in the stream, then from the equation (2) last addition can be excluded, because its weight is offset by the support of the bulk material below. The rest of the effort is still ongoing. Then equation (2) takes the form:

$$mR(d^2\lambda/dt^2) = N_1\sin\xi + F_1\cos\xi - F_2\cos\beta \tag{6}$$

To solve the system of equations (1) - (5), we apply the transformation to get rid of the unknown force N_1 and express the parameters through the magnitude of the angle λ. First, this system takes the form:

$$m\ddot{z} = N_1(\cos\xi - f_1\sin\xi) - f_2(mg\cos\lambda\cos\varphi + mR\dot{\lambda}^2)\sin\beta - mg\sin\varphi \tag{7}$$

$$mR\ddot{\lambda} = N_1(\sin\xi + f_1\cos\xi) - f_2(mg\cos\lambda\cos\varphi + mR\dot{\lambda}^2)\cos\beta - mg\sin\lambda\cos\varphi \tag{8}$$

In the final form, the differential equation of motion for the variable λ takes the form:

$$\ddot{\lambda} + \dot{\lambda}^2A + B_c\cos\lambda - B_s\sin\lambda - C = 0 \tag{9}$$

In this equation, the coefficients are determined by the following dependencies:

$$A = f_2[\cos(\beta+\xi) - f_1\sin(\beta+\xi)] \qquad B = (f_2g/R)\cdot[\cos(\beta+\xi) - f_1\sin(\beta+\xi)]\cos\varphi\cos\xi$$

$$B_s = (g/R)\cdot(\cos\xi - f_1\sin\xi)\cos\varphi\cos\xi; \qquad C = (g/R)\cdot(\sin\xi + f_1\cos\xi)\cos\varphi\cos\xi \tag{10}$$

In the case of flow movement, when applying formula (6), the coefficient B_s = 0.

During the flow, it is necessary that the centripetal force is greater than the force of gravity. Otherwise, the particles of bulk material will not be in continuous mode, which significantly distorts the picture of stream transportation. This is achieved under the condition $\dot{\lambda} > \sqrt{g/R}$ (*Hevko R.B.*, *et al., 2014*).

An important moment of movement is the separation of the flow particles from the spiral rib and their free flight inside the casing to a halt or until the next section comes into contact with the screw rib.

The free movement of cargo particles on the surface of the casing in case of separation from the blade is written in the form of two differential equations of the second order:

$$m(d^2z/dt^2) = -F_2 \sin\beta - mg\sin\varphi \tag{11}$$

$$mR(d^2\lambda/dt^2) = -F_2 \cos\beta - mg\sin\lambda\cos\varphi \tag{12}$$

After the conversion we get:

$$m\ddot{z} = -f_2(mg\cos\lambda\cos\varphi + mR\dot{\lambda}^2)\sin\beta - mg\sin\varphi \tag{13}$$

$$mR\ddot{\lambda} = -f_2(mg\cos\lambda\cos\varphi + mR\dot{\lambda}^2)\cos\beta - mg\sin\lambda\cos\varphi \tag{14}$$

The third stage of motion may be the free flight of the flow particles at separation from the casing surface if the calculated value of the pressure force on the chute is $N_2 < 0$. Then, the equation of particles' motion can be described by a system of three independent differential equations of motion on three mutually perpendicular axes, and x, y, z:

$$\ddot{x} = -g\cos\varphi; \qquad \ddot{y} = 0; \qquad \ddot{z} = -g\sin\varphi \tag{15}$$

Free-fall body movement will end if contact with the casing occurs, that is, inequality $x^2 + y^2 \geq R^2$. The relation between velocities in Cartesian and cylindrical coordinate systems when separating material particles from a helical edge will be written in the form:

$$\dot{x} = R\dot{\lambda}\sin\lambda \qquad \dot{y} = -R\dot{\lambda}\cos\lambda \tag{16}$$

When a material particle falls on the casing surface, the angular velocity of rotation is written as the sum of the projections of velocity vectors tangent to the circle at the point of contact:

$$\dot{\lambda} = (\dot{x}\sin\lambda - \dot{y}\cos\lambda)/R \tag{17}$$

Equation (9) is a second-order nonlinear differential equation, an analytical solution is impossible, and therefore we apply a numerical method for integrating such equations, the Runge-Kutta method.

Let's consider the flow of bulk material at different points in its cross section. The characteristic points of the flow cross-section are shown in Fig.1c.

The presence of different linear velocities for individual points of intersection of the material flow leads to different trajectories of their flight at separation from the auger edge. The linear velocity of separation of the particle:

$$v_i = R_i\dot{\lambda} \tag{18}$$

where R_i is the radius of rotation of the i particle.

The velocity v_i is directed tangential to the circle of the appropriate radius and directed along a vector that makes up the angle β_i with the circle in the XOY plane. It follows from (5) that:

$$tg\beta_i = \dot{z}/(R_i\dot{\lambda}) \tag{19}$$

Moreover, both the longitudinal (axial) $\dot{z}$ and angular velocities $\dot{\lambda}$ of all elements of the section, according to assumptions, are the same. An analysis of formula (19) shows that particles that are at smaller radii have a larger exit angle β_i, and accordingly, have a smaller component of the peripheral velocity in a plane perpendicular to the Z axis.

In order to determine the maximum possible distance of flight of particles from different points of the cross section, we consider the free motion of each of the particles in a circle of the corresponding radius. We assume that individual particles interact with each other during free motion, that is, there are friction forces between them, and each of them moves in a circle of a preliminary radius. This assumption is justified by the fact that the lower particles cannot rise up due to the presence of upper particles there. The lag or advance of the lower particles relative to the upper is practically absent because of the significant friction forces between them. Therefore, at small distances, the motion of particles can be considered as the motion of a connected mass.

The smaller the radius of rotation of the particle R_i, the smaller the centripetal acceleration is:

$$a_{ni} = R_i \dot{\lambda}^2 \quad (20)$$

In the case of a decrease in angular velocity due to braking, the centripetal acceleration will become smaller than the acceleration of gravity g and the particles begin to fall freely onto the lower surface of the casing. Fall begins with the lower layers, gradually spreading to the upper layers.

The maximum flight length should be considered such a distance along the z axis, when the particle moves over the surface of the casing in contact with it. Such a study must be carried out for an arbitrary moment of separation of the particle from the blade $(0 \le \lambda \le 2\pi)$ and from that to determine the shortest flight length. In this case, it is necessary to calculate the angular displacement of the particle in the direction of the angle λ in order to determine the coordinates of the point that the particle reaches at the maximum flight length. Knowing the corresponding final coordinate, we can calculate the axial distance between the ends of the adjacent helical ribs δ and the necessary angular displacement α between them.

The motion of each particle is determined from equations (13) and (14), in which it is necessary to set the corresponding radii R_i, angles β_i, and friction coefficients f_i. When solving systems of differential equations (9), (13) and (14) and (15), it is necessary that the final conditions at the previous stage automatically become the initial ones for the following. To analyse the motion of a particle in the flow and in the separation zone, a program in Delphi was created using the Runge-Kutta method which has the ability to graphically display the results.

The experimental research procedure is as follows. A transfer pipe was adopted as the basis, the structure description and operation principle of which are given in the work (*Hevko R.B., et al.,* 2016). As bulk material was selected grain mixed with granules of plastic material of different colours. Directly under the discharge pipe was a tray on which the material was unloaded and, using filming, the flight range of the bulk material was fixed, fixing the trajectory of multi-coloured granules. The angle of departure of the material was fixed at λ = 90°, 180°, 270°. According to theoretical studies at an angle λ = 270°, the flight length L of the material is minimal, therefore, to ensure continuous movement of material between adjacent screw sections, the most unfavourable option must be taken into account. The rotation frequency of the working body *n* and its angle of inclination to the horizon φ, according to the results of theoretical studies, were chosen at the following values *n* = 450, 600, 750 rev/min; φ = 10°, 20°, 30°.

RESULTS

Based on the results of the calculations, graphical dependences (Fig. 2) of the free flight length L of the material particles on the rotational speed n of the working body $L = f(n)$, (Fig. 2a) and the inclination angle φ of the screw section axis to the horizon $L = f(\varphi)$, (Fig. 2b) at different angular positions of the material particle at the moment of its separation from the helical rib λ are presented.

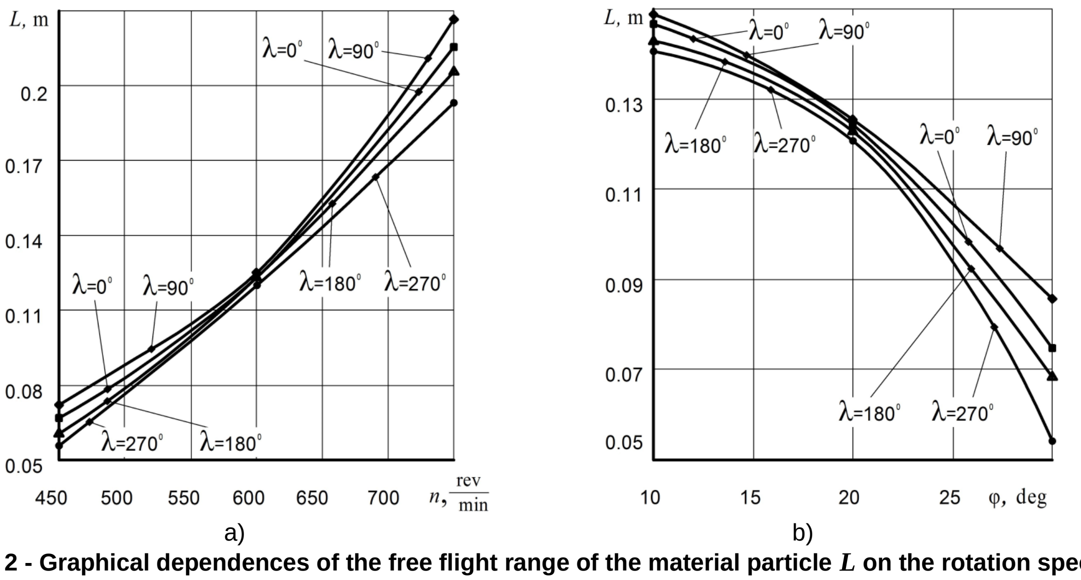


Fig. 2 - Graphical dependences of the free flight range of the material particle L on the rotation speed of the working body *n* (a) and the angle of inclination of the screw section axis to the horizon (b) at different angular positions λ of the particle at the time of separation from the screw edge to contact with the lower surface of the casing

When making calculations and studying the influence of one of the parameters on the value of L, the others were assumed constant and the value of their parameters was: ξ = 22.6°; φ = 20°; R = 50 mm; n = 600 rev/min.

From the analysis of the graphic dependences $L = f\,(n)$ we can conclude that the maximum value of L corresponds to the separation angle of the material particle from the helical rib λ = 90°, (λ = 0° corresponds to the lower horizontal point of the casing) and will be L = 0,228 m for n = 750 rev/min (Fig. 2a). The minimum value of L will be L = 0.193 m for λ = 270°.

At n = 450 rev/min the values of L for various values of λ are in the range L = 0.056...0.072 m, and at n = 600 rev/min the minimum range of variation is L = 0.119…0.125 m at various values of λ.

From the analysis of the graphical dependencies $L = f\,(\varphi)$, we can conclude that the maximum value of L corresponds to the minimum angle φ = 10° and will be L = 0.144…0.148 m (Fig. 2b) for various values of λ. With increasing angle φ, the value of L decreases, and at φ = 30° it is L = 0.054...0.086 m.

With an increase in the elevation angle ξ, the range of L values also increases for various angular positions λ at the moment of separation of the material particle from the helical rib.

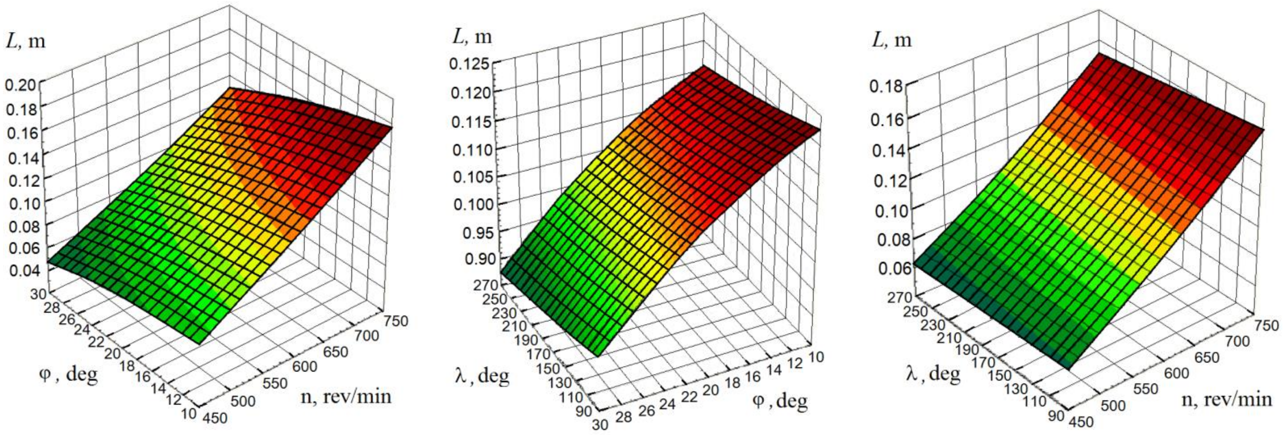
A multivariate experiment was also performed. The range of parameters changes had the following limits: 450 ≤ n ≤ 750 rev/min; 0 ≤ λ ≤ 270 deg; 10 ≤ φ ≤ 30 deg.

Based on the statistical processing of the regression equation to establish the change, L has the form:

$$L = -0.06384 + 0.304 \cdot 10^{-3} \cdot n + 0.1783 \cdot 10^{-2} \cdot \varphi - 0.1853 \cdot 10^{-4} \cdot \lambda + 0.715 \cdot 10^{-7} \cdot n^2 - \\ -0.377 \cdot 10^{-5} \cdot n \cdot \varphi - 0.86 \cdot 10^{-7} \cdot n \cdot \lambda - 0.455 \cdot 10^{-4} \cdot \varphi^2 + 0.194 \cdot 10^{-5} \cdot \varphi \cdot \lambda - 0.48 \cdot 10^{-7} \cdot \lambda^2 \quad (21)$$

When establishing the influence of two factors on the value of L, the third is assumed to be unchanged with its average value. The average values of the factors are as follows: n = 600 rev/min; λ ≤ 270 deg; 10 ≤ φ ≤ 30 deg.

The surface response range of flight of the wheat grain L with a bulk weight of 720 kg/m^3, is shown in Fig. 3.



a) b) c)

Fig. 3 – Response surfaces of the flight range of the material *L*: a - ***L* = *f* (*φ*; *n*)**; **b** - ***L* = *f* (*λ*; *φ*)**; c **= *L* = *f* (*λ*; *φ*)**

Based on the analysis of the regression equation and response surfaces, it was found that the maximum speed on the value of L has the rotation frequency of the working body n. So, for average values of λ and φ of growth of n from 450 to 750 rev/min, L increases by 0.092 m. The next in intensity of influence on the value of L is the angle of inclination of the screw section axis to the horizon φ. Its increase from 10° to 30° at average values of λ and n leads to a decrease in L by 0.028 m. The angle λ has a minimal effect on L, whose growth from 90° to 270° for average values of φ and n leads to a decrease in L by 0.009 m.

The data obtained must be taken into account when designing such a sectional screw working body. Based on the most unfavourable option in this range of parameters, the distance between the ends of adjacent screw ribs δ should not exceed 0.04 m.

Experimental studies to determine the power for the transportation of grain material also shown that for n = 600 rev/min with a gap of δ = 14 mm the power is about N = 1.2 kW; at δ = 28 mm - N = 1.7 kW; at δ = 42 mm - N = 3.2 kW. Therefore, it is rational to choose a gap value δ within 0.01...0.03 mm.

The maximum productivity of the flexible screw conveyor was within the speed of rotation of the working body 600… 700 rev/min respectively 6.5… 7.7 m^3/h.

A comparison of the results of theoretical and experimental studies showed that at n = 600 rev/min; φ = 20° and various λ values, the discrepancy between the obtained data is 3.8%...14.7%.

Therefore, theoretical studies that can be applied to a wider range of changes in the structural and kinematic parameters of the working body with articulated sections have been carried out.

CONCLUSIONS

The article presents the results of theoretical and experimental studies of the working body of a flexible screw conveyor made of separate sections, which are hinged to each other.

Based on the derived equations of a particle motion of material between adjacent screw sections was found the dependence of their flight distance L from the rotational speed of the working body n, its angle to the horizon φ and different angular positions of the particle λ on the helical rib which moves in the flow of grain material at the moment of its separation from the helical rib.

Based on the proposed methodology, experimental studies were carried out, the results of which show that for the factor field the parameter changes are $450 \leq n \leq 750$ rev/min; 0 ≤ λ ≤ 270 deg; 10 ≤ φ ≤ 30 deg, the value of L varies in the range from 0.042 to 0.188 mm.

Taking into consideration the sharp increase in power costs for the material transportation process at δ > 0.032, the gap value δ should be chosen within 0.01...0.03 mm.

Based on comparisons of the results of theoretical and experimental studies at n = 600 rev/min; φ = 20° and various values of λ, their divergence is 3.8%...14.7%.

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