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THE STUDY OF INTERACTION PARAMETERS OF THE ELASTIC BRUSH SCREW WORKING BODY FIBERS WITH THE SPHERICAL SURFACES OF THE GRAIN MATERIAL

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Summary. *The article presents the design of the elastic brush screw working body of the screw conveyor, which makes it possible to reduce mechanical damage to grain, reduce dangerous loads caused by forced rolling when grain material is chocked during transportation. The relationship between the design parameters of elastic brush screw working bodies fibers and force loads on grains with elements of spherical surfaces and the conditions of their chocking during transportation is established. The calculation scheme for determining the parameters of grain transportation by an elastic brush screw working body is presented. The equation for determination of the allowable external load on the grain in the perpendicular direction to the flights of the elastic brush screw working body during transportation in the conveyor is derived. The condition of grain chocking between the fibers and the inner surface of the screw conveyor housing is determined.*

Key words: *brush screw working body, grain material, elastic fiber, chocking, force parameters.*

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Statement of the problem. When interacting with the screw conveyors, the grain material is subjected to various mechanical influences, in particular compression, friction, impacts, which lead to its macro- and micro-damages.

Based on the analysis of literary sources, the mechanical impact on the grain during interaction with the working bodies could be divided into two groups: damage caused by impact during the interaction of the grain with the surface of the working bodies; damage caused by friction and pinching of the grain in the gap between the active surface of the screw working body and the stationary part of the casing.

The analysis of screw conveyor designs revealed several trends aimed at reducing grain damage during transportation. The most effective ones include the complete replacement of the steel flights of the auger with elastic ones, or the partial framing of their outer edge with an elastic material (polymers, rubber). The use of such elastic materials as rubber, polyethylene, kapron, nylon reduces damage only in those cases when the process of interaction between the grain and the working bodies has an impact character. However, for grain, more dangerous loads are caused by forced rolling during pinching or pulling, as is observed in screw conveyors. In the process of pinching or pulling, the shell is deformed, chipped and torn, which contributes to the destruction of the grain.

This drawback can be eliminated in screw working bodies, in which the spiral is replaced by an element in the form of a set of separate thin fibers. This allows reducing mechanical damage to the grain several times.

For the successful use of such brush-like screw working bodies, additional theoretical and experimental studies are required to substantiate their parameters and modes of operation.

A separate direction of improvement of screw conveyors is the use of rotating casings [11, 12] with additional oscillations of the screw [13], which increases the productivity of transportation and mixing of grain materials, but does not eliminate the problem of grain destruction.

It is important to study the deformations of the elements of the screw working body during the transportation of loose materials [14; 15], deformations of individual fibers of the brush-like screw working body [7] or elastic sections of the auger [5] under the action of loads arising during the transportation of loose materials. The developed new designs of screw conveyors with elastic brush-like screw working bodies [16] require additional studies of the influence of their design parameters on the power parameters of the grain materials transportation process.

The subject of the article is too find the relationship between the structural parameters of fibers of elastic brush-like screw working bodies with force loads on grains with elements of spherical surfaces and the conditions of their pinching during transportation.

Formulation of the problem. To determine the force parameters of the interaction of the fibers of the elastic brush-like screw working body (EBSWB) with the grain material, as well as the conditions of grain pinching in the conveyor, as an example, grain materials with elements of a spherical surface, which are part of such agricultural crops as corn [3], peas, were considered.

In order to form a mathematical model, several assumptions and idealization of the parameters of the interaction between grains and fibers of EBSWB were adopted. The shape of the grain is assumed to be ideal without taking into account micro protrusions on the surface; the cross-section of the fibers is circular; the length of all fibers is the same; the coefficients of friction between the grain, fibers and the conveyor casing are constant values; the movement of the fibers relative to the shaft is within the limits of small elastic deformations with constant stiffness coefficients; radial and angular grain displacement, load fluctuations and interaction with other grains are not taken into account.

The analytical scheme for determining the parameters of grain transportation by an elastic brush-like screw working body is presented in Fig. 1. The grain 5 with a spherical or ellipsoidal element is moved by the fibers 4 of the EBSWB 3 with the central shaft 1. In the casing 2 of the screw conveyor, the grain 5 is pinched between two fibers of the EBSWB and the inner surface of the casing. Grain can interact with more fibers. During further rotation of the shaft, deformation of the fibers occurs with movement of the grain in the opposite direction. Since the fibers are made of a material whose modulus of elasticity and hardness are orders of magnitude lower than these parameters of steel, when the fibers are deformed, forces arise that do not exceed the maximum permissible force acting on the grain, which leads to its damage. Therefore, the probability of grain damage in a screw conveyor with EBSWB is significantly reduced compared to a conventional screw conveyor with a metal screw working body.

EBSWB can be installed in the casing both with a gap and without a gap. There is also a gap between the fibers placed on the shaft. When the radius of the EBSWB increases, the distance between the fibers increases, and accordingly, the gap between them increases as well.

With a large gap, the productivity of the conveyor decreases, but an increase in the density of fibers leads to an increase in the consumed power of transportation due to an increase in power consumption for friction between the fibers and the casing. Therefore, substantiation of the distance between fibers is one of the necessary tasks of designing screw conveyors with EBSWB.

Research results. Based on the calculation scheme of Fig. 1, the equation of equilibrium of the grain at the initial moment of contact with the fibers of the elastic brush-like screw working body (EBSWB) in the projection on the axis y is deduced:

$$2N_1 \cos\alpha + 2F_{t1} \sin\alpha + F_{t2} - P = 0, \qquad (1)$$

if N_1 – normal force of interaction between grain surface and fiber of EBSWB;

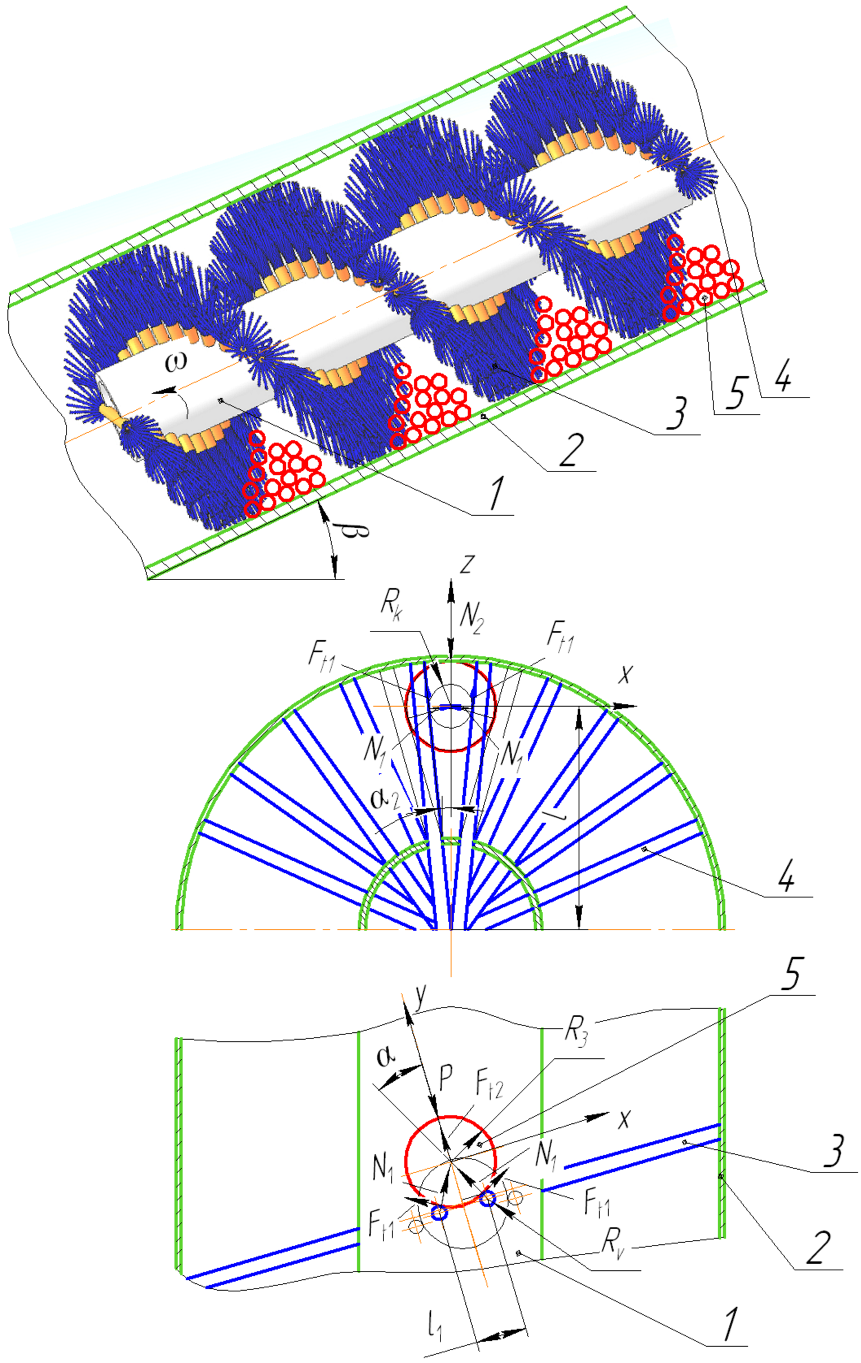

Figure 1. The calculation scheme for determination of the grain transportation parameters by an elastic brush screw working body: 1 – shaft; 2 – casing; 3 - elastic brush screw working body (EBSWB); 4 – fibers of EBSWB; 5 – grain

F_{t1} – friction force between grain and fiber of EBSWB;
F_{t2} – frictional force between the grain and the casing;
P – external load on the grain in the direction perpendicular to the flights of EBSWB when moving in the conveyor;
α – angle of contact between grain and fiber. It is defined as the angle between the normal to the grain surface at the point of contact with the fiber and the axis y.

The equation of grain equilibrium at the initial moment of contact with the fibers of the elastic brush-like screw working body (EBSWB) in the projection on the x and z-axes is respectively:

$$N_1 \sin \alpha - N_1 \sin \alpha + F_{t1} \cos \alpha - F_{t1} \cos \alpha = 0; \qquad (2)$$

$$2N_1 \sin \alpha_2 - N_2 + 2F_{t1} \cos \alpha_2 = 0, \qquad (3)$$

if N_2 – normal force of interaction of the surface of the grain with the inner surface of the casing; α_2 – contact angle between the grain and the EBSWB fiber in the vertical plane. It is defined as the angle between the grain tangent to the surface at the point of contact with the fiber and the axis *z*.

The friction forces between the grain and the EBSWB fiber and between the grain and the casing are determined by the following dependencies:

$$F_{t1} = \mu_1 N_1; \qquad (4)$$

$$F_{t2} = \mu_2 N_2, \qquad (5)$$

if μ_1 – coefficient of friction between grain surface and fiber surface EBSWB;
μ_2 – coefficient of friction between the surface of the grain and the inner surface of the casing.

Based on the analytical scheme of Fig. 1, the contact angle between the grain and the fiber of EBSWB is determined by the dependence:

$$\alpha = \arcsin\left(\frac{l_1}{2(R_3 + R_v)}\right), \qquad (6)$$

if l_1 – distance between the centers of fibers of circular cross-section interacting with the grain. It is within the limits: $2R_v \le l_1 \le 2(R_3 + R_v)$.
R_3 – grain radius;
R_v – radius of the circular cross-section of the fiber.

Based on the analytical scheme of Fig. 1, the contact angle between the grain and the EBSWB fiber in the vertical plane is deduced:

$$\alpha_2 = \arcsin\left(\frac{R_k}{R_2 - R_3}\right), \qquad (7)$$

if R_2 – casing inner radius;
R_k – contact radius between the grain and the EBSWB fiber is determined by the dependence:

$$R_k = R_3 \sin \alpha. \qquad (8)$$

Then:

$$\alpha_2 = \arcsin\left(\frac{R_3 \sin \alpha}{R_2 - R_3}\right); \qquad (9)$$

$$\alpha_2 = \arcsin\left(\frac{R_3 l_1}{2(R_3 + R_v)(R_2 - R_3)}\right). \qquad (10)$$

Based on equation (3), formula is derived:

$$N_2 = 2N_1\left(\sin\alpha_2 + \mu_1\cos\alpha_2\right). \tag{11}$$

Substituting equation (11) into equation (1), we obtain:

$$2N_1\left(\cos\alpha + \mu_1\sin\alpha + \mu_2\left(\sin\alpha_2 + \mu_1\cos\alpha_2\right)\right) = P. \tag{12}$$

$$P = 2N_1\left(\sqrt{1-\frac{l_1^2}{4\left(R_3+R_v\right)^2}} + \mu_1\frac{l_1}{2\left(R_3+R_v\right)} + \mu_2\left(\frac{R_3 l_1}{2\left(R_3+R_v\right)\left(R_2-R_3\right)} + \right.\right.$$
$$\left.\left. + \mu_1\sqrt{1-\frac{R_3^2 l_1^2}{4\left(R_3+R_v\right)^2\left(R_2-R_3\right)^2}}\right)\right). \tag{13}$$

During simultaneous interaction of grains with more than two fibers, equations (12) and (13) can be written:

$$P = \sum_{i=1}^{n} N_{1i}\left(\cos\alpha_i + \mu_1\sin\alpha_i + \mu_2\left(\sin\alpha_{2i} + \mu_1\cos\alpha_{2i}\right)\right). \tag{14}$$

$$P = \sum_{i=1}^{n} N_{1i}\left(\sqrt{1-\frac{l_{1i}^2}{4\left(R_3+R_v\right)^2}} + \mu_1\frac{l_{1i}}{2\left(R_3+R_v\right)} + \mu_2\left(\frac{R_3 l_{1i}}{2\left(R_3+R_v\right)\left(R_2-R_3\right)} + \right.\right.$$
$$\left.\left. + \mu_1\sqrt{1-\frac{R_3^2 l_{1i}^2}{4\left(R_3+R_v\right)^2\left(R_2-R_3\right)^2}}\right)\right). \tag{15}$$

if i – the number of fibers with which the grain interacts.

The value of the normal force N_1 of the interaction of the grain surface with the EBSWB fiber is determined by the formula [17]:

$$N_1 = \frac{3 f_1 E \pi d_v^4}{64 l^3} + F_{t3}, \tag{16}$$

if f_1 – the amount of fiber deflection;
E – modulus of elasticity of the fiber material;
F_{t3} – friction force between the fiber and the conveyor casing;
d_v – fiber diameter.

The value f_1 of the fiber deflection is determined applying the solution of the differential equation, which describes the curve of the centerline of the fiber.

The approximate value of the deflection of the fiber with sufficient accuracy for engineering calculations is determined as fallows.

If $\mu_1 > \operatorname{tg}\alpha$, $\mu_1 > \dfrac{l_1}{2\left(R_3+R_v\right)\sqrt{1-\dfrac{l_1^2}{4\left(R_3+R_v\right)^2}}}$ fiber deflection occurs in the opposite direction of the axis y. Therefore,

$$f_1 = \sqrt{l^2 - (l - 2R_3)^2}\,; \tag{17}$$

$$N_1 = \frac{3E\pi d_v^4 \sqrt{l^2 - (l - 2R_3)^2}}{64 l^3} + F_{t3}. \tag{18}$$

If $\mu_1 < \text{tg}\,\alpha$ fiber deflection occurs in the opposite direction of the axis x. Therefore,

$$f_1 = R_3 + R_v - \frac{l_1}{2}. \tag{19}$$

$$N_1 = \frac{3E\pi d_v^4 \left(R_3 + R_v - \frac{l_1}{2} \right)}{64 l^3} + F_{t3}. \tag{20}$$

When using EBSWB with several rows of fibers (for example, two, Fig. 2), which overlap for the first row of fibers, the force N_{11} of the interaction of the surface of the grain with the fiber is determined by the formula (20) with the deflection f_{11}, and for the fibers of the second row N_{12} – by the formula (18) (Fig. 2a).

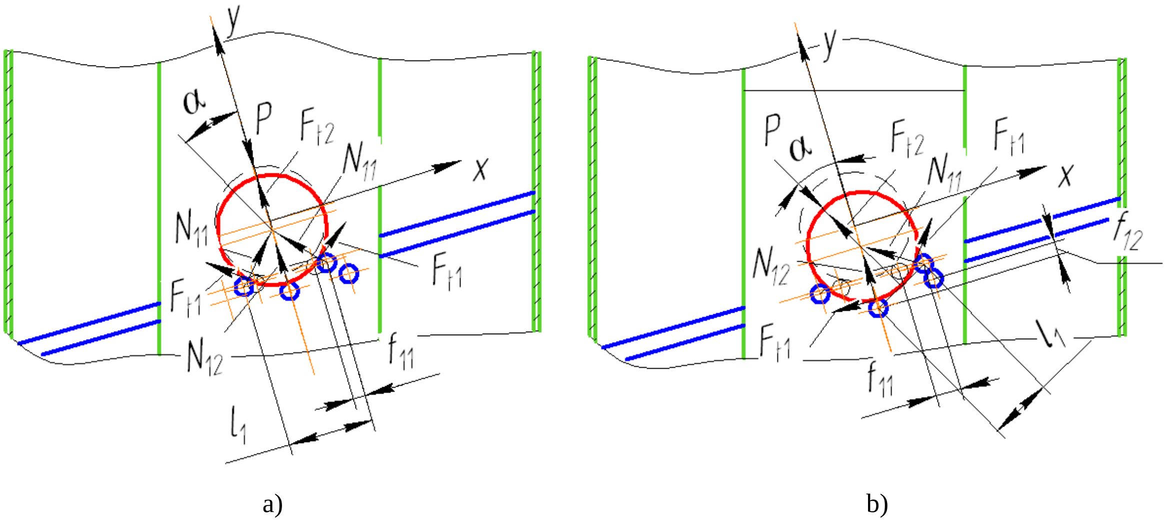

Figure 2. Interaction scheme of the grain with two rows of fibers a) deflection of the first row of fibers before the contact of the grain with the fiber of the second row b) further deflection of the fibers of the first and second rows

With further deflection of the fibers (Fig. 2b) by values of f_{11} for the first row and f_{12} for the second row, the grain moves into the gap between the fibers of the first and second rows. When the condition $\mu_1 < \text{tg}\,\alpha$ is reached with an increase in the gap between the fibers, the force N_{12} for the second row is also determined by the formula (20).

Based on equations (12) and (13), graphs of the dependence (Fig. 3 and Fig. 4) of the permissible external load P on the grain in the direction perpendicular to the flights of the EBSWB were developed on the contact angle α between the grain and the EBSWB fiber and the distance l_1 between the centers of the fibers of the circular transverse cross-section interacting with the grain during movement in the conveyor.

Based on equation (12), the condition of grain pinching between the fibers of EBSWB and the inner surface of the casing is determined:

$$\mu_1 > \frac{\cos\alpha + \mu_2 \sin\alpha_2}{\sin\alpha + \mu_2 \cos\alpha_2}. \qquad (21)$$

Substituting equation (9) into inequality (21), we obtain:

$$\mu_1 > \frac{\cos\alpha + \dfrac{\mu_2 R_3 \sin\alpha}{R_2 - R_3}}{\sin\alpha + \mu_2\sqrt{1 - \dfrac{R_3^2 \sin^2\alpha}{\left(R_2 - R_3\right)^2}}}. \qquad (22)$$

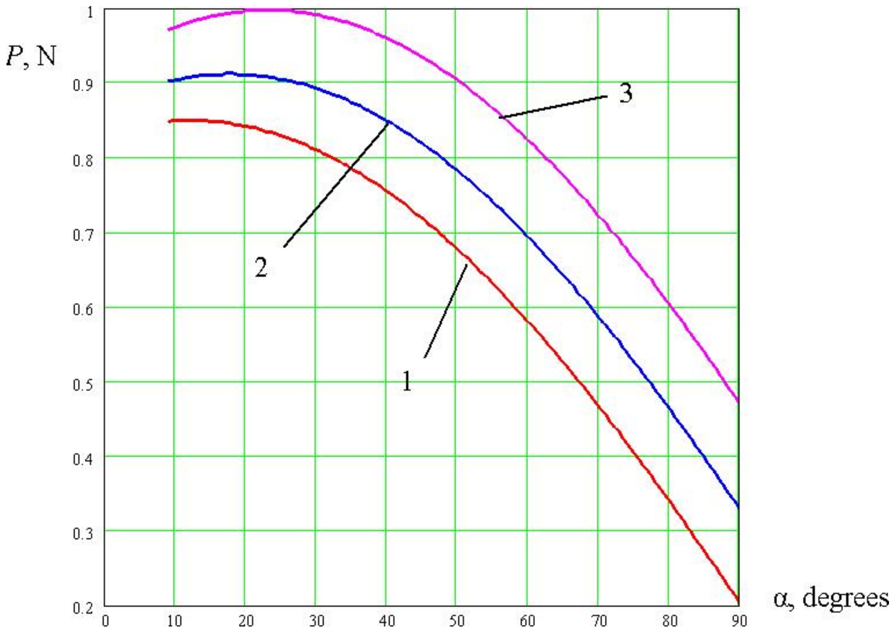

Figure 3. Graphs of the dependence of the allowable external load *P* on the grain in the perpendicular direction to the flights of the EBSWB from the contact angle α between the grain and the fiber of the EBSWB during transportation in the conveyor R_3=2mm: 1) μ_1=0.2; μ_2=0.2; 2) μ_1=0.3; μ_2=0.3; 3) μ_1=0.4; μ_2=0.4

Based on formula (22), the grain pinching condition is determined depending on the distance l_1 between the centers of fibers of round cross-section interacting with the grain:

$$\mu_1 > \frac{\sqrt{1 - \dfrac{l_1^2}{4\left(R_3 + R_v\right)^2}} + \dfrac{\mu_2 R_3 l_1}{2\left(R_3 + R_v\right)\left(R_2 - R_3\right)}}{\dfrac{l_1}{2\left(R_3 + R_v\right)} + \mu_2\sqrt{1 - \dfrac{R_3^2 l_1^2}{4\left(R_3 + R_v\right)^2\left(R_2 - R_3\right)^2}}}. \qquad (23)$$

Based on inequality (22), the critical contact angle α between the grain and the EBSWB fiber is determined, at which the grain pinching occurs, while for small values of the angle α_2 $\cos\alpha_2 \approx 1$ is accepted:

$$\alpha > \arcsin\left(\frac{R_3\mu_1\mu_2^2 - l\mu_1^2\mu_2 + l\sqrt{\left(\mu_1 l - R_3\mu_2\right)^2 + l^2\left(1-\mu_1^2\mu_2^2\right)}}{\left(\mu_1 l - R_3\mu_2\right)^2 + l^2}\right), \quad (24)$$

if $l = R_2 - R_3$.

In the case μ_2=0, in the absence of contact between the grain and the casing, inequality (24) is simplified to the formula

$$\alpha > \arcsin\left(\frac{\sqrt{\mu_1^2+1}}{\mu_1^2+1}\right). \quad (25)$$

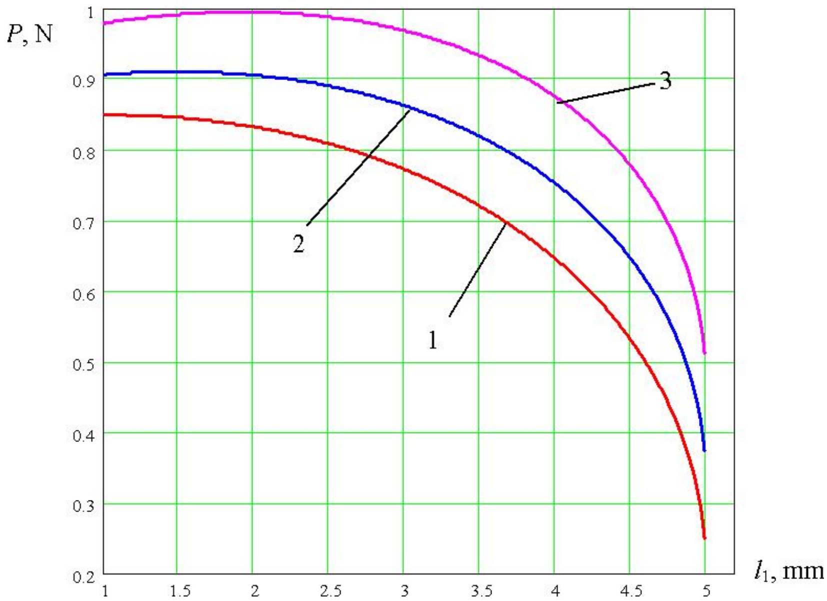

Figure 4. Graphs of the dependence of the allowable external load *P* on the grain in the perpendicular direction to the flights of the EBSWB from the distance l_1 between the centers of circular cross-section fibers interacting with the grain during transportation in the conveyor R_3=2mm, R_v=0.5 mm: 1) μ_1=0.2; μ_2=0.2; 2) μ_1=0.3; μ_2=0.3; 3) μ_1=0.4; μ_2=0.4

Based on inequality (24), the critical distance l_1 between the centers of the fibers of a circular cross-section, at which grain pinching occurs, is determined:

$$l_1 > 2\left(R_3 + R_v\right)\left(\frac{R_3\mu_1\mu_2^2 - l\mu_1^2\mu_2 + l\sqrt{\left(\mu_1 l - R_3\mu_2\right)^2 + l^2\left(1-\mu_1^2\mu_2^2\right)}}{\left(\mu_1 l - R_3\mu_2\right)^2 + l^2}\right). \quad (26)$$

In the case μ_2=0:

$$l_1 > 2\left(R_3 + R_v\right)\frac{\sqrt{\mu_1^2+1}}{\mu_1^2+1}. \quad (27)$$

Conclusions. The relationship between the structural parameters of fibers of elastic brush-like screw working bodies with force loads on grains with elements of spherical surfaces and the conditions of their pinching during transportation has been found.

Based on the derived equations and graphs, an increase in the contact angle α between grain and fiber is found to lead to a decrease in the value of the external load *P*. The maximum values of the external load *P* on the grain are reached at the angle $\alpha = \mathrm{arctg}(\mu_1)$. The starting points of the largest decline of the *P*(α) function depend on the value of the coefficients of friction μ_1 and μ_2. An increase in the coefficients of friction μ_1 and μ_2 leads to an increase in the load *P*. For example, for μ_1= μ_1=0.2, the inflection point is determined by the angle α=35 degrees, and for μ_1=μ_2=0.4, by the angle α=50 degrees. At an angle α=90 degrees, only frictional forces act on the grain. It was also found that an increase in the distance l_1 leads to a decrease in the *P* load, while an increase in the coefficients of friction μ_1 and μ_2 leads to an increase in the *P* load. A significant decrease in the *P* load is observed at l_1, which is equal to the grain diameter. With the help of the presented graphs and formulas, it is possible to select the distance between the fibers in order to ensure the movement of the grains at the set value of the external load. An increase in the angle α and the distance l_1 leads to an increase in the probability of grain pinching between EBSWB fibers with a coefficient of friction μ_1<0.5 for an angle α in the range from 50 degrees to 90 degrees and a distance l_1 from 4 mm to 5 mm with a grain radius of 2 mm. An increase in the coefficients of friction μ_1 and μ_2 leads to a decrease in the angle α, at which grain pinching is possible. When the coefficient of friction μ_1=0.5, the angle α is in the range from 52..64 degrees to 90 degrees for different values of the coefficient of friction μ_2. If there is no friction between the grain and the casing μ_2=0, it is also possible to pinch the grain between the fibers. The ratio of the gap between the fibers and the diameter of the grain, at which pinching of the grain is possible, is found. The greater is the coefficient of friction μ_1, the smaller is this ratio. For the coefficient of friction μ_1=0.5, pinching of the grain is possible when the ratio of the gap to the diameter of the grain is from 0.75, and for μ_1=0.3 – from 0.89.

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ДОСЛІДЖЕННЯ ПАРАМЕТРІВ ВЗАЄМОДІЇ ВОЛОКОН ЕЛАСТИЧНОГО ЩІТКОПОДІБНОГО ГВИНТОВОГО РОБОЧОГО ОРГАНА ЗІ СФЕРИЧНИМИ ПОВЕРХНЯМИ ЗЕРНОВОГО МАТЕРІАЛУ

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Резюме *Представлено конструкцію еластичного щіткоподібного гвинтового робочого органа гвинтового конвеєра, що дозволяє знизити механічні пошкодження зерна, зменшити небезпечні навантаження, викликані примусовим перекочуванням при защемленні або волочінні зернового матеріалу під час транспортування, як це спостерігається у гвинтових конвеєрах з металевими гвинтовими робочими органами. Встановлено взаємозв'язок конструктивних параметрів волокон еластичних щіткоподібних гвинтових робочих органів із силовими навантаженнями на зернини з елементами сферичних поверхонь та умовами їх защемлення при транспортуванні. Для формування математичної моделі прийнято кілька припущень та ідеалізацію параметрів взаємодії зернини з волокнами еластичного щіткоподібного гвинтового робочого органа. Представлено розрахункову схему для визначення параметрів транспортування зернини еластичним щіткоподібним гвинтовим робочим органом. Записано рівняння рівноваги зернини в початковий момент контакту з волокнами еластичного щіткоподібного гвинтового робочого органа. Визначено кути контакту між зерниною та волокнами еластичного щіткоподібного гвинтового робочого органа. Виведено рівняння для знаходження допустимого зовнішнього навантаження на зернину в напрямку, перпендикулярному виткам еластичного щіткоподібного гвинтового робочого органау при переміщенні у конвеєрі. Побудовано графіки залежності допустимого зовнішнього навантаження від кута контакту між зерниною та волокном і відстані між центрами волокон круглого поперечного перерізу, що взаємодіють із зерниною при переміщенні в конвеєрі. Визначено умову защемлення зернини між волокнами та внутрішньою поверхнею кожуха гвинтового конвеєра. Визначено критичний кут контакту між зерниною і волокном та критичну відстань між центрами волокон круглого поперечного перерізу, при яких відбувається защемлення зернини.*

Ключові слова: *щіткоподібний гвинтовий робочий орган, зерновий матеріал, еластичне волокно, защемлення, силові параметри.*

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