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Estimation of Eddy Currents and Power Losses in the Rotor of a Screw Electrothermomechanical Converter for Additive Manufacturing

Abstract. Screw conveyors are widely used in the movement of various loose and lump materials related to agricultural production, such as: seed granular materials, cereals, bran, chaff, turf, flakes, mixed feed, mineral fertiliser pellets, etc. However, the conventional flexible screw conveyor operating mechanisms do not fully meet the operational requirements for these types of conveyors. Screw operating mechanisms are characterised by the complexity of the design and manufacturing technology, high material consumption, which causes increased energy consumption, damage to the transported material and the inner surface of flexible sleeves. Therefore, the task of developing new designs of flexible sectional screw operating mechanisms with advanced technological capabilities is urgent. To increase the reliability of the flexible screw conveyor, it was proposed to make its operating mechanism from separate screw sections that are pivotally connected to each other. Therefore, the purpose of this study is to determine the rational parameters and operating modes of the developed operating mechanism, which would ensure stable transportation of loose and lump materials on various technological routes. The study was conducted using the methods of differential and integral calculus, the theory of mathematical and computer modelling, mathematical planning of the experiment. This paper shows the results of theoretical and experimental studies of the process of transporting loose or lump material in the inactive zone between the pivotally connected screw sections of a flexible screw conveyor. The results of comparison of the obtained results of theoretical and experimental studies are shown. This allows choosing rational design, kinematic and technological parameters of the developed sectional screw operating mechanism when moving loose or lump agricultural materials along curved routes, both in horizontal and inclined directions, and along curved routes

Keywords: hinged screw sections, inactive zone between sections, material flight length, straight and curved routes, material departure angle

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INTRODUCTION

Screw conveyors are widely used for moving a variety of loose and lump materials, mainly related to agricultural production, such as: seed granular materials, cereals, bran, chaff, turf, flakes, mixed feed, mineral fertiliser pellets, etc. The results of establishing the contact interaction of loose and lump materials with the working surfaces of screw conveyors are described in [1-3].

The study of the mechanical and technological properties of agricultural materials is given in [4]. As a rule, rigid screw operating mechanisms are used to transport bulk and lump materials, which can be placed at different angles. Flexible screw conveyors are also commonly used, the study of the parameters and operating modes of which is presented in [5-7].

Pneumatic conveyors that can transport various loads along curved routes are quite widely used. The main disadvantage of these types of conveyors is the significant energy consumption and price, which limits their use. Such types of conveyors and screw feeders for feeding loose materials are investigated in [8-10].

Combining technological operations, such as transportation and mixing of feed mixtures, is possible with the use of puck conveyors, which can operate on different routes, but only stationary ones. The results of studies of such conveyors are given in [11; 12].

However, existing screw flexible augers cannot fully meet the operational requirements that are put forward for these types of conveyors. The use of shaftless flexible spirals causes rapid destruction during the operation

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of the conveyor on curved tracks, due to the presence of alternating cyclic loads. The production of a screw in the form of a solid or sectional shaft, on which individual elements of screw blades are placed, causes a significant complication in the design of the screw, an increase in its material consumption, and this, in turn, leads to an increase in energy consumption and damage to moving materials.

Thus, the task of developing new designs and substantiating the parameters of screw flexible operating mechanisms of conveyors, the use of which would allow increasing the functional and operational indicators of the process of transporting loose and lump agricultural materials is relevant.

The purpose of this study is to improve the functional and operational characteristics of screw conveyors by developing and substantiating the parameters of flexible screw operating mechanisms, which are made on the basis of pivotally connected sections, for transporting loose agricultural materials.

The results of theoretical and experimental developments, which are described in this paper, are a continuation of previous studies [13-15] and are aimed at improving the efficiency of the process of operation of flexible screw conveyors, the operating mechanisms of which are made based on pivotally connected sections.

The paper presents the results of theoretical and experimental studies of the operating mechanism of a flexible screw conveyor made of separate sections that are pivotally connected to each other.

MATERIALS AND METHODS

In order to increase the reliability of the flexible screw conveyor, it was proposed to make its operating mechanism from separate screw sections that are pivotally connected to each other. The placement of the blades of adjacent sections is shown in Fig. 1a. In this case, screw blades 1 and 2 are placed in the axial direction with a gap δ (inactive zone). The hinge mechanism 3 connects screw sections to each other. It is made on the principle of a gimbal with separated axes placed mutually perpendicular. The edges of adjacent screw blades are offset by an angle α in the circular direction. The difference between the design of such a screw is that during the convergence of loose or lump material from the edge of the screw blade 1 to a distance δ it (particles of material) must fly by in a certain amount of time t_1. Moreover, the edge of the screw blade 2 is at least (the angle of departure of the material should also be considered) for the time t_2 it should turn a corner α, for the purpose of capturing the transported material.

Figure 1b provides a general view of the sections of the screw that is placed on the curved section and its individual sections.

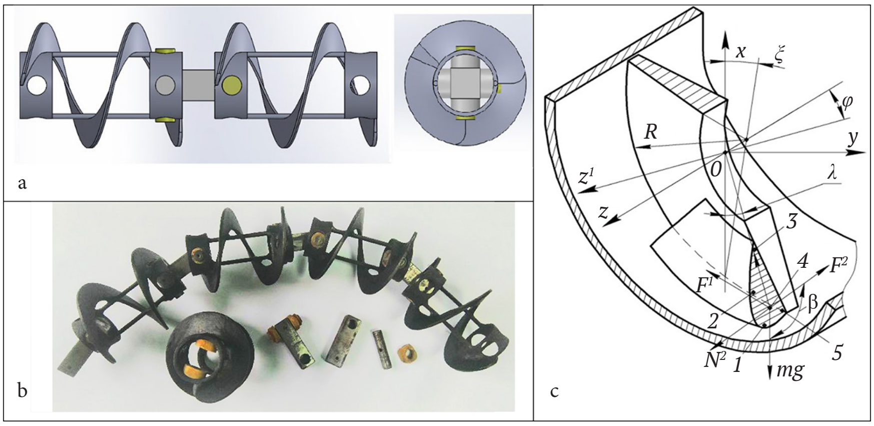

Figure 1. Design and calculation scheme of screw sections that are pivotally connected to each other: a – diagram of two sections; b – general view of the sections of the screw sectional mechanism, which is placed on the curved section and the view of individual elements of the sections; c – diagram for determining the forces acting on the elementary volume of loose material, which continuously moves in the casing

The study considers the movement of loose cargo along a fixed casing using the helical sector of the screw spiral. Its elementary volume is selected, which is simultaneously in contact with the fixed casing and the rotating section of the screw spiral. On the side of the casing, it is affected by a reaction directed perpendicular to the working surface and the friction force. The reaction from the chute side is equal to the vector sum of the forces that arise from the weight of the selected elementary volume and the centripetal force.

The elementary volume is also affected by the reaction from the surface of the screw blade, which is directed perpendicular at the point of contact to the surface of the operating mechanism, and the friction force also acts, respectively. Fig. 1b shows the forces acting on the elementary volume of loose material moving in the casing.

The equation of motion of a separate elementary volume of loose material that is not related to the flow has the form of a system of two differential equations

$$m(d^2z/dt^2)=N_1 cos\xi - F_1 sin\xi - F_2 sin\beta - mg\ sin\beta; \qquad (1)$$

$$mR(d^2\lambda/dt^2)=N_1 sin\xi - F_1 cos\xi - F_2 cos\beta - mg\ sin\lambda cos\varphi, \qquad (2)$$

where m – mass of the material particle; R – casing radius; N_1 – reaction that occurs in the screw to the material;

F_1 – friction force from the action of force N_1; N_2 – force generated in the screw from the material; F_2 – friction force from the reaction N_2; ξ – the angle of lifting of the screw helical line; φ – the angle of inclination of the axis of the screw section to the horizon; β – the angle of direction of movement of the material particle relative to the casing; λ – the angular position of the material particle in its rotational motion; z – longitudinal coordinate of the material particle along the casing axis.

Reaction N_2 is defined from the condition

$$N_2=mg\cos\lambda\cos\varphi+mR\cdot(d\lambda/dt)^2. \quad (3)$$

The friction forces are determined accordingly

$$F_1=f_1N_1 \qquad F_2=f_2N_2, \quad (4)$$

where f_1 – coefficient of friction of the material on the surface of the screw blade; f_2 – coefficient of friction of the material on the surface of the casing.

Considering the directions of movement of the material particle and the geometry of the helical blade, when it rotates at an angular velocity ω, the following geometric dependencies can be set:

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

Considering the movement of the selected material element in the flow, then the last term can be excluded from equation (2), since its weight force is compensated by the support of the loose material located below. The rest of the effort works as before. Then equation (2) will take the form

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

To solve the system of equations (1)-(5), transformations are used to reduce the unknown force from the equalities N_1 and output the parameters in terms of the angle value λ. Preliminary, this system will take the form:

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

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

$$-mg\sin\lambda\cos\phi \quad (8)$$

Therefore, the differential equation of motion for the variable λ will have the form:

$$\ddot{\lambda}+\dot{\lambda}A+B_c\cos\lambda-B_s\sin\lambda-C=0. \quad (9)$$

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

$$A=f_2[\cos(\beta+\xi)-f_1\sin(\beta+\xi)];$$
$$B=(f_2g/R)\cdot[\cos(\beta+\xi)-f_1\sin(\beta+\xi)]\cos\phi\cos\xi;$$
$$B_s=(g/R)\cdot[\cos\xi-f_1\sin\xi)\cos\phi\cos\xi;$$
$$C=(g/R)\cdot(\sin\xi+f_1\cos\xi)\cos\phi\cos\xi. \quad (10)$$

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

When there is a movement of the material flow, it is necessary that the centripetal force is greater than the weight force. Otherwise, particles of loose or lump material will not be able to stay in continuous mode, which significantly distorts the picture of flow transportation. This can be achieved if $\dot{\lambda} > \sqrt{g/R}$.

An important moment of particle movement occurs when the flow particles separate from the spiral fin and their free flight inside the casing until they stop or until they come into contact with the screw blade of the next section.

The free movement of load particles along the surface of the casing during the occurrence of separation from the edge of the screw spiral is recorded using two second-order differential equations

$$m(d^2z/dt^2)=-F_2\sin\beta-mg\sin\phi; \quad (11)$$

$$mR(d^2\lambda/dt^2)=-F_2\cos\beta-mg\sin\lambda\cos\phi. \quad (12)$$

After the conversion,

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

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

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

$$\ddot{x}=-g\cos\phi \qquad \ddot{y}=0 \qquad \ddot{z}=-g\sin\phi. \quad (15)$$

The movement of the body in free fall will be completed if there is contact with the casing, that is, an unevenness is performed $x^2+y^2\geqslant R^2$. The relationship of velocities in Cartesian and cylindrical coordinate systems when material particles are separated from the screw blade is written as

$$\dot{x}=R\dot{\lambda}\sin\lambda \qquad \dot{y}=-R\dot{\lambda}\cos\lambda. \quad (16)$$

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

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

Equation (9) is a second-order nonlinear differential equation. Its analytical solution is impossible. In this case, the numerical method of integrating these equations is used – that is, the Runge-Kutta method.

Consider the flow movement of loose material at different points of its cross-section. The characteristic points of the cross-section of the flow are shown in Fig. 1b.

It is assumed that the friction forces between material particles (grains, corn, or other loose material) significantly exceed the friction forces on the surface of the screw and casing. This assumption makes allows considering the motion of particles as a whole with the same angular velocity. The actual movement of the material differs from the ideal one, so points 1 and 2, which are located at the edge of the loose material flow section, are slightly behind points 3, 4, and 5, which are located near the screw blade.

A significant lag will be observed only in the case of transportation of a material that has a low coefficient of friction between individual particles (grains). However, for the transport of grain material, the mutual mixing of individual particles is insignificant, the particles almost stick together and move in a continuous stream, especially at high speeds. This statement was experimentally confirmed in [2; 16; 17].

The speed of movement of point 1, which is located at the edge of the flow section, is maximum due to the maximum distance from the centre of the casing. The linear velocity of point 5 will also be similar. The velocity of points 2 and 4 decreases in proportion to the radius along which they move. The lowest speed is typical for point 3, which is located closest to the centre of rotation.

The presence of different linear velocities for individual points of cross-section of the material flow leads to different trajectories of their flight when separated from the screw blade. Linear particle separation rate

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

where R_i – rotation radius of i-th particle.

Speed v_i is directed tangentially to a circle of the corresponding radius and is directed along the vector that makes up the angle β_i with a circle in the *XOY* plane. It follows from (5) that:

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

Moreover, as a longitudinal (axial) $\dot{z}$, and angular velocity $\dot{\lambda}$ all elements of the cross-section are assumed to be the same. Analysis of equation (19) shows that particles at smaller radii have a larger departure angle β_i, and, accordingly, have a lower component of the circular velocity in the plane perpendicular to the axis *Z*.

In order to determine the maximum possible flight distance of particles from different cross-section points, the free movement of each of the particles is considered along a circle of the corresponding radius. It is assumed that individual particles interact with each other during free motion, that is, there are friction forces between them, and the movement of each of them occurs along a circle of the previous radius. This assumption is substantiated by the fact that the lower particles cannot rise up due to the presence of upper particles there. There is practically no lag or advance of the lower particles relative to the upper ones due to significant friction forces between them. Therefore, at short distances, the motion of particles can be considered as the motion of a connected mass.

The smaller the particle's rotation radius R_i, the lower the centripetal acceleration:

$$a_{ni} = R_i \dot{\lambda}^2. \tag{20}$$

If the angular velocity decreases due to braking, the centripetal acceleration will be less than the acceleration of gravity g and the particles begin to fall freely to the lower surface of the casing. The decline begins with the lower layers, gradually spreading to the upper layers.

The maximum flight length is considered to be this distance along the *Z* axis when the particle moves over the surface of the casing before it comes into contact with it. Such a study should be carried out for an arbitrary moment of separation of the particle from the edge ($0 \leq \lambda \leq 2\pi$) and from them, 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 to determine the coordinates of the point that the particle will reach at the maximum flight length. Knowing the corresponding final coordinate, it is possible to calculate the axial distance between the ends of adjacent screw blades δ and the required angular displacement α between them.

The motion of each particle is determined from equations (13) and (14), in which it is necessary to put the corresponding radii R_i, angles β_i, and coefficients of friction f_i.

When solving systems of differential equations (9), (13), (14), and (15), it is necessary that the final conditions in the previous step automatically become initial for the next one.

To analyse the motion of a particle in the flow and in the breakaway zone, a programme was created in the Delphi software environment using the Runge-Kutta method and the ability to graphically display the results.

The method of conducting experimental studies is as follows: the reloading pipe was adopted as the basis, the description of the structure and principle of operation of which is given in [18-20]. Grain with admixtures of plastic material granules of different colours was chosen as the loose material. Directly under the discharge pipe was a tray on which the material was unloaded and the range of flight of the loose material was set by means of filming, fixing the trajectory of multi-coloured pellets. The angle of departure of the material was fixed at the values of λ=90°, 180°, 270°. According to theoretical studies at an angle λ=270° length L of the flight of the material is minimal, and therefore, to ensure continuous movement of the material between adjacent screw sections, it is necessary to consider the most unfavourable option. Speed of rotation of the operating mechanism n and the angle of its inclination to the horizon φ, according to the results of theoretical studies, is chosen at the following values: n=450, 600, 750 rpm; φ=10°, 20°, 30°.

RESULTS AND DISCUSSION

The results of the calculations performed allowed constructing graphical dependencies (Fig. 2) of free flight lengths *L* of material particles from the rotation speed value n of screw operating mechanism $L=f(n)$, (Fig. 2a) and the angle of inclination φ of the axis of the screw section to the horizon $L=f(\varphi)$, (Fig. 2b) for different angular positions of the material particle at the moment of its separation from the screw blade λ.

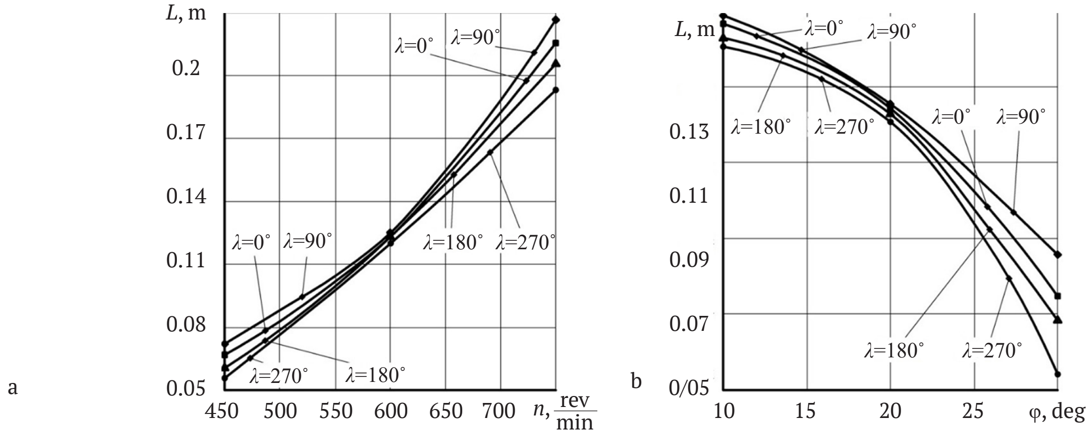

Figure 2. Graphical dependences of the free flight range of a material particle *L* on the speed of rotation of the screw operating mechanism *n*(a) and the angle of inclination φ of the axis of the screw section to the horizon (b) for different angular positions λ of the particle at the moment of separation from the screw blade to contact with the lower surface of the casing

When performing calculations and determining the effect of one of the parameters on the value L, others were taken as constants and the values of their parameters were: ξ=22.5°; ξ=20°; *R*= 52 mm; *n*=600 rpm.

From the analysis of graphical dependencies $L=f(n)$ it is established that the maximum value L corresponds to the angle of separation of the material particle from the helical fin λ=90°, (λ=0° corresponds to the lower horizontal point of the casing) and will be *L*=0.226 m for *n*=750 rpm (Fig. 2a). Minimum value *L* will be *L*=0.191 m for λ=270°.

At *n*=450 rpm, the values of L for different values λ are within *L*=0.055...0.073 M, and at *n*=600 rpm, the minimum range of change of *L*=0.118 0 0.124 m for different values of λ is observed.

From the analysis of graphical dependencies $L=f(\varphi)$ it is established that the maximum value L corresponds to the minimum angle φ=10° and will be *L*=0.144..0.148 m (Fig. 2b) at different values of λ. With increasing angle φ value *L* decreases, and at φ=30° is *L*=0.055...0.085 m.

As the lifting angle ξ increases, the range of values L also increases for different angular positions of λ at the moment of separation of the material particle from the screw blade.

A multi-factor experiment was also conducted. The factor field had the following range of parameter changes: $450 \le n \le 750$ rpm; $0 \le \lambda \le 270°$ deg; $10° \le \varphi \le 30°$.

Based on the statistical processing, the regression equation to determine the change in *L* has the form

$$L=-0.06384+0.304\cdot10^{-3}\cdot n+0.1783\cdot10^{-2}\cdot\phi-0.1853\cdot \cdot10^{-4})\cdot\lambda+0.715\cdot10^{-7}\cdot n^2-0.377\cdot10^{-5}\cdot n\cdot\phi-0.86\cdot10^{-7}\cdot n\cdot\lambda- -0.455\cdot10^{-4}\cdot\phi^2+0.194\cdot10^{-5}\cdot\phi\cdot\lambda-0.48\cdot10^{-7}\cdot\lambda^2. \quad (21)$$

When determining the influence of two factors on the value *L* , the third one is assumed to be unchanged with its average value. The average values of the factors are as follows: *n*=600 rpm; $\lambda \le 270°$; $10° \le \varphi \le 30°$.

Response surfaces range of grain material particles *L* are shown in Figure 3.

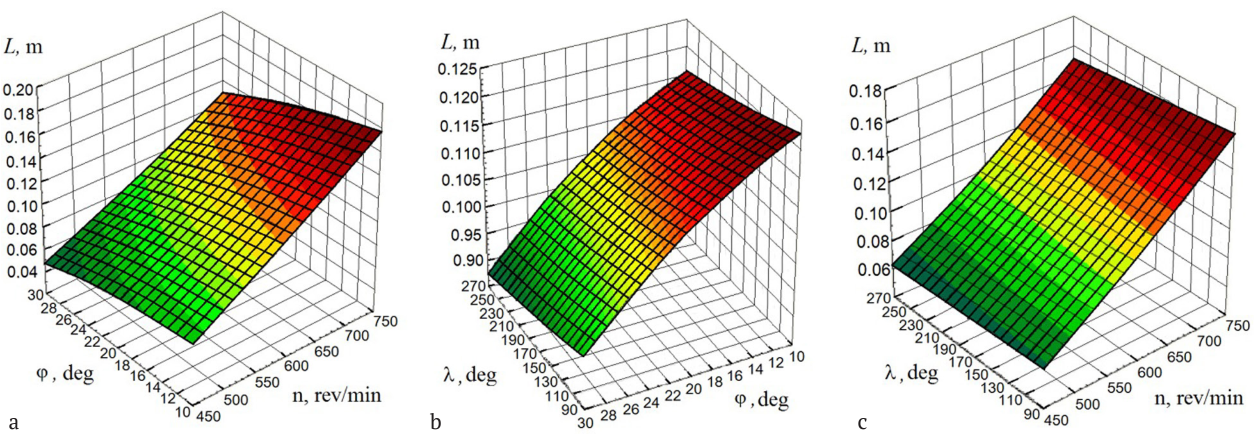

Figure 3. Response surfaces of the material's flight range *L*: a – $L=f(\varphi; n)$; b – $L=f(\lambda; \varphi)$; c – $L=f(\lambda; \varphi)$

Based on the analysis of the regression equation and response surfaces, it is established that the maximum effect on the value of *L* has a speed of rotation of the operating mechanism *n*. Thus, for the average values of λ and φ growth n from 450 to 750 rpm causes an increase in the value *L* by 0.092 m. The next most intense effect on the value *L* is an angle of inclination of the axis of the screw section to the horizon φ. Its increase from 10° to 30° at the average values of λ and n causes a decrease in the value *L* by 0.028 m. Minimal impact on the value *L* has an angle λ, the growth of which is from 90° to 270° at the average values of φ and n leads to a decrease in the value *L* by 0.009 m.

The obtained data must be considered when designing such a sectional screw operating mechanism. Based on the most unfavourable option in this range of parameter changes, the distance between the ends of adjacent screw blades δ the distance should not exceed 0.04 m.

In addition, experimental studies on determining the capacity for the process of transporting grain material have shown that for *n*=600 rpm with clearance 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 the gap value δ within 0.01...0.03 mm.

Comparison of the obtained results in theoretical and experimental studies, showed that for *n*=600 rpm; φ=20° and different values λ the difference between the obtained data is 3.7%...14.8%.

Therefore, the conducted theoretical studies can be applied to a wider range of changes in the design and kinematic parameters of the operating mechanism with a hinged connection of sections.

From the analysis of theoretical studies for the operating mechanisms of flexible screw conveyors [3; 6; 9], it can be concluded that the authors overwhelmingly deduced analytical dependencies to establish the functional, operational and design parameters of flexible screw operating mechanisms. At the same time, the issues of substantiating the parameters of screws that ensure their high functional and operational parameters with the minimum permissible weight of the operating mechanism are not resolved. This would significantly reduce energy costs for the movement process and the degree of damage to loose and lump agricultural material.

The results of experimental studies presented in this paper relate to screw spirals without the use of a flexible shaft. However, as practical studies have shown, during the transportation of material along a curved route (especially at small radii of curvature), due to the occurrence of cyclic alternating deformations, screw spirals are quickly destroyed, which sharply limits the use of such operating mechanisms due to non-compliance with operational requirements. In order to increase the reliability of the technological process, when developing and investigating operating mechanisms, it is necessary to use: a sectional method for manufacturing operating mechanisms (to eliminate alternating cyclic loads); increase the contact area between the torque transmission units, which would reduce internal stresses and forces in friction pairs by increasing the torque transmission arm.

CONCLUSIONS

The paper presents the results of theoretical and experimental studies of the operating mechanism of a flexible screw conveyor made of separate sections that are pivotally connected to each other.

Based on the derived equations of motion of loose material between separate adjacent helical sections, the dependences of the flight range of material particles L are established from the speed of rotation of the screw operating mechanism n, the angle of its inclination to the horizon φ, and the various angular positions of the particle λ, which moves in the material flow at the moment of its separation from the screw blade.

Based on the proposed method, experimental studies were conducted, according to the results of which it can be concluded that for the factor field of parameter changes: 450≤*n*≤750 rpm; 0°≤λ≤270°; 10°≤φ≤30° value L varies in the range from 0.042 to 0.188 mm.

Given the sharp increase in power costs for the material transportation process for δ>0.032, clearance value δ should be taken in the range of 0.01...0.03 mm.

Based on comparisons of the obtained results of theoretical and experimental studies at n=600 rpm; φ=20°, and different values of λ, their discrepancy is 3.7%...14.8%.

Based on a complex of theoretical and experimental studies, a competitive sectional screw operating mechanism has been created, which allows improving the functional and operational characteristics of screw conveyors for transporting loose and lump agricultural materials.

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Дослідження процесу переміщення сипкого матеріалу за допомогою гнучкого гвинтового конвеєра

Анотація. Гвинтові конвеєри знайшли широке використання під час переміщення різноманітних сипких та кускових матеріалів, які належать до сільськогосподарського виробництва, наприклад такі як: насіннєві гранульовані матеріали, зернові, висівки, полова, дерть, пластівці, комбікорми, гранули мінеральних добрив та ін. Але, загальновідомі гнучкі гвинтові робочі органи транспортерів не в повній мірі відповідають експлуатаційним вимогам, що висуваються до даних видів конвеєрів. Шнековим робочим органам характерна складність конструкції і технологія їх виготовлення, висока матеріаломісткість, що викликає підвищені енерговитрати, пошкодження транспортованого матеріалу та внутрішньої поверхні гнучких рукавів. Тому, актуальним є завдання розроблення нових конструкцій гнучких секційних гвинтових робочих органів із розширеними технологічними можливостями. Для підвищення надійності функціонування гвинтового гнучкого транспортера було запропоновано його робочий орган виконувати із окремих гвинтових секцій, що шарнірно з'єднані між собою. Отже, метою цих досліджень являється визначення раціональних параметрів та режимів роботи розробленого робочого органу, що дозволить забезпечити стабільне транспортування сипких та кускових матеріалів на різних технологічних трасах. Дослідження проведено із використанням методів диференціального та інтегрального числення, теорії математичного та комп'ютерного моделювання. методу математичного планування експерименту. У даній статті показані результати теоретичних та експериментальних досліджень процесу транспортування сипкого чи кускового матеріалу у неактивній зоні між шарнірно з'єднаними гвинтовими секціями гнучкого гвинтового конвеєра. Показано результати порівняння отриманих результатів теоретичних та експериментальних досліджень. Це дає змогу вибрати раціональні конструктивні, кінематичні та технологічні параметри розробленого секційного гвинтового робочого органу під час переміщення сипких чи кускових сільськогосподарських матеріалів по криволінійних трасах, як в горизонтальному та похилому напрямках, так і по криволінійних трасах

Ключові слова: шарнірно з'єднані гвинтові секції, неактивна зона між секціями, довжина польоту матеріалу, прямі та криволінійні траси, кут вильоту матеріалу