STUDY OF FIBER DEFORMATION OF ELASTIC BRUSH-LIKE SCREWS DURING GRAIN MATERIAL TRANSPORTATION

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ДОСЛІДЖЕННЯ ДЕФОРМАЦІЇ ВОЛОКОН ЕЛАСТИЧНИХ ЩІТКОПОДІБНИХ ШНЕКІВ ПРИ ТРАНСПОРТУВАННІ ЗЕРНОВОГО МАТЕРІАЛУ

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ABSTRACT

A new design of an elastic brush-like screw for grain material transportation and mixing by screw conveyors with a lower degree of damage to some particles of the material has been presented in the paper under discussion. The theoretical calculation of the fiber displacement value of an elastic brush-like screw has been carried out on the basis of the deformation analysis of an idealized system with elastic elements. A differential equation of the mean line of deformation of several fibers of an elastic brush-like screw located in the same plane perpendicular to the distributed loading during grain material transportation has been derived. The solution of the differential equation was obtained by the numeric method and on its basis the curves of the middle line of deformed fibers of an elastic brush-like screw for different values of its structural parameters. The results of the experimental study of the maximum deformation value of the elastic fibers of a brush-like screw have been presented.

РЕЗЮМЕ

У статті представлено нову конструкцію еластичного щіткоподібного шнека для транспортування та змішування зернових матеріалів гвинтовими конвеєрами із зниженим ступенем пошкодження окремих частинок матеріалу. Проведено теоретичний розрахунок величини переміщення волокон еластичного щіткоподібного гвинтового шнека на основі аналізу деформацій ідеалізованої системи з пружними елементами. Виведено диференціальне рівняння середньої лінії деформації декількох волокон еластичного щіткоподібного шнека, розміщених в одній площині перпендикулярній розподіленому навантаженню при транспортуванні зернового матеріалу. Розв'язок диференціального рівняння проведено чисельним методом, на основі чого побудовані графіки середньої лінії деформованих волокон еластичного щіткоподібного шнека при різних значеннях його конструктивних параметрів. Представлено результати експериментальних досліджень величини максимальної деформації волокон еластичного щіткоподібного шнека.

INTRODUCTION

Screw conveyors with different types of working bodies have been widely used in technological processes of agricultural and industrial production, namely in the transportation of grain, seed materials, granular mineral fertilizers, and others. Such materials can be badly damaged during transportation in closed casings, both rigid and elastic ones, and this can't meet the agrotechnical requirements. The main reasons for grain material damage involve particles' falling into a gap between the rotating screw surface and the fixed internal surface of the casing.

To avoid this damage, the screw surface is quite often made of elastic section materials *(Hevko R.B. et.al., 2015; Loveikin V. and Rogatynska L., 2011; Zalutskyi S.Z. et.al., 2018;)* or as an elastic brush-like screw *(Tian Y. et.al., 2018; Zaica A. et.al., 2016; Zaica A. et.al., 2020)*. The latter was proposed to use in grain material coating.

Another direction of the screw conveyor improvement is rotating casings use *(Rohatynskyi R. et.al., 2019)* with some extra screw oscillations *(Hevko B.M. et.al., 2015)*, enabling an increase in the grain material transportation and mixing efficiency, though it cannot solve the problem of grain damage completely.

Some papers consider the operation mode of an inclined screw conveyor which has a screw operating element with constant parameters incorporated in it (*Mondal, 2018, Lyashuk et.al, 2019*). The kinematics of grain loading has been investigated based on the motion equations in a screw conveyor. The analysis of loading movement at constant high-speed mode has been analyzed.

Polymer coatings of screws facilitate the operation resource increase of the mechanisms, though they do not provide any essential reduction of grain material damage. These papers (*Prisyazhnaya et.al.,2020; Prisyazhnaya et.al.,2021; Soldatenko et.al.,2021;*) conclude that the bio based composites constitute a promising field in polymeric composites that increase awareness for applications in various fields ranges to avoid pinching and damage during transportation.

It is very important to study screw deformations during bulk material transportation and to determine the values of screw oscillations *(Rohatynskyi R.M. et.al., 2015; Hevko I.B. et.al., 2015; Zaica A. et.al., 2019; Hou Junming et.al., 2023)*, deformations of separate fibers of a brush-like screw *(Hevko R.B. et.al., 2016; Tian Y. et.al., 2018)* or elastic sections of the screw *(Hevko R.B. et.al., 2019; Trokhaniak et.al., 2020),* under loading action conditions taking place during bulk material transportation. The developed new design of screw conveyors with elastic brush-like screws requires some further study of the impact of their design and kinematic parameters on the value of elastic fibers deformation on brush-like screw enabling us to predict the resistance to loading of the transported material to provide the fiber deformation within the boundaries of the maximum allowable value without reverse motion of the bulk material separate elements.

MATERIALS AND METHODS

One of the directions providing the reduction of grain and seed material damage is using the brush-like elastic elements on the screw spiral peripheral surface, as shown in fig. 1. The developed design of a screw conveyor with a brush-like elastic screw consists of guiding casing *1*, a shaft *2* where cylindrical tubes *3* are fixed with bunches of brush-like elastic elements *5*. The edges *4* of the tubes overhanging above the external surface of shaft *2* are being changed into an elliptical shape to fix the elastic brushes.

In case when some particles of grain material are caught between the internal surface of the guiding casing and the peripheral surface of the elastic brush, the latter sags and lets the material through without any damage.

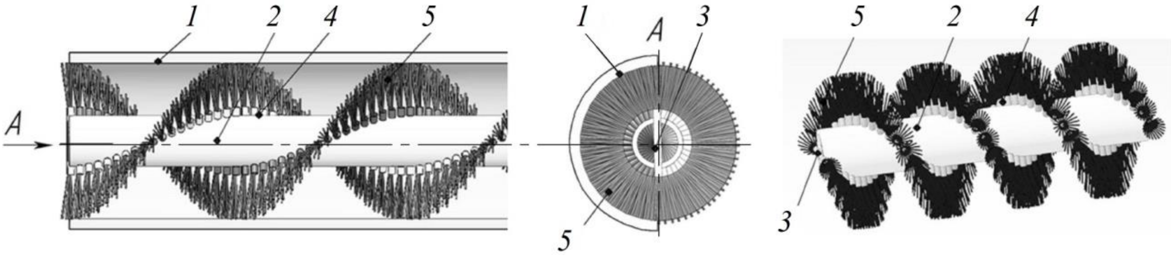


Fig. 1 - Design of a screw conveyor with an elastic brush-like screw

In another version, shown in fig. 2, a combined elastic screw conveyor consists of a bunker *1*, joined with a guiding casing *2*, where a screw *3* is located with an unloading nozzle *4*.

In the material loading zone, a step T_1 of the screw is the smallest one, and the stiffness C_1 of its surface is maximal. In the area of the bunker transition to the casing, the screw step T_2 and stiffness C_2 of its peripheral surface is average. In the material transportation zone, the step T_3 of the screw is the largest one, though its surface stiffness C_3 is minimal.

The above-mentioned design of the screw conveyor provides the guaranteed flow of the material towards the guiding casing, which will enable to provide the material distribution on the casing surface caused by the action of the centrifugal force within the process of its transportation.

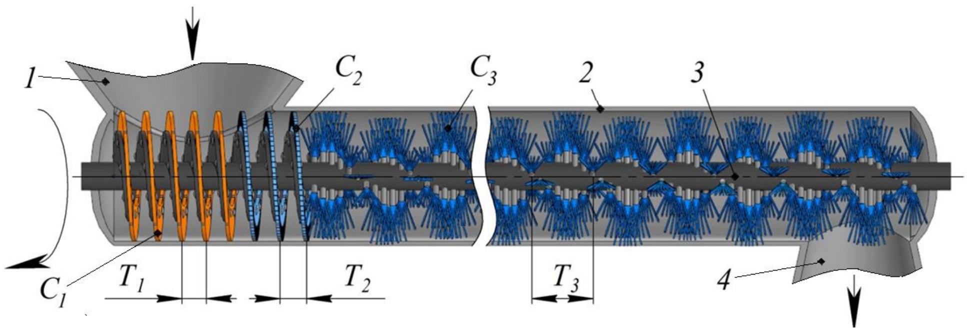
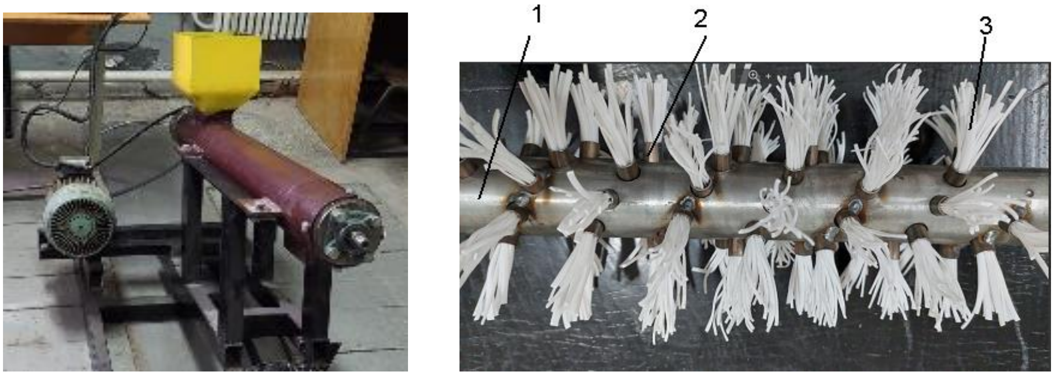


Fig. 2 - Design of a combined elastic screw conveyor

Based on the design shown in fig. 1, an experimental equipment is made to study the screw conveyor with an elastic brush-like screw. A picture of this equipment is given in figure 3.

An elastic brush-like screw, shown in fig. 3 *b* consists of a hollow shaft *1*, where some holes are made along the screw line perpendicular to its central axis, where some hollow cylindrical tubes *2* are fixed, overhanging above the external surface of the hollow shaft on which the bunches of brush-like elastic fibers *3* are fixed. The diameter of the fibers cross-section is from 1.8 mm to 2.6 mm, the length is from 28 mm to 36 mm and they are made from nylon. The external diameter of the brush-like screw is from 96 mm to 106 mm. The operating speed is from 180 to 250 rpm. The inclination angle of the casing is up to 45 degrees.



a) b)

Fig. 3 - Picture of a screw conveyor a) with an elastic brush-like screw b)

During the process of calculations, it was found, that the shaft and the casing rigidity is much greater than the rigidity of elastic brush-like screws, so the deformation of these elements was not taken into account in modeling. The displacement of the fibers of an elastic brush-like screw (fig. 4 *a*) has been determined from the analysis of deformations of an idealized system with elastic elements shown in fig. 4 *c*. A brush-like screw while being installed into the casing without any gap is subjected to the initial radial and axial deformation to reduce the damage of grain material and rests on the casing surface (fig. 4 *b*), in this case, the fibers are rigidly fixed on the shaft. Under the conveyor performance and loading increase conditions, the fibers of an elastic brush-like screw are bent in the negative direction of the axis *y*, and in this case, the bulk material transportation is provided (fig. 4 *c*). When the maximum allowable value of the load on the elastic brush-like screw is exceeded (fig. 4 *d*), the fibers are bent to create a gap between the casing and an elastic brush-like screw, whose value is sufficient enough to transport the grain material in the opposite direction. As the stiffness of the fibers of an elastic brush-like screw is lower than the rigidity of separate elements of grain material, the latter cannot be damaged.

Let's carry out the study of fibers static deformations on brush-like screw. The distributed loading $q(x)$ in the screw axial direction during grain material transportation to the fibers of brush-like screw is uneven along the length of the fibers and depends on the load factor q_1, the casing angle of inclination β, and the screw conveyor speed operation mode. In this case, the maximum value of such loading takes place on the screw external diameter, and the minimum one – on its external diameter.

The distributed load on the fibers of the elastic brush-like screw during bulk material transportation at a small load factor of a horizontal and hollow inclined screw conveyor with a small speed operation mode has been approximated by the dependence:

$$q(x) = \frac{(q_{\max} - q_{\min})x}{l} + q_{\min} \tag{1}$$

where l – the length of the working part of the elastic fibers of brush-like screw; $q_{\max}$ - maximum distributed load on the fibers (takes place on the brush-like screw external diameter); $q_{\min}$– minimal distributed load on the fibers.

The equation of the middle line of deformation of several fibers located in the same plane with the distributed load $q(x)$ will look as follows:

$$nEI\frac{d^2y}{dx^2} = M(x) - N_1\sin\gamma\cdot y + F_i\cdot y + G\cdot y\cdot\cos\beta\cos\theta \tag{2}$$

where n – the number of fibers located in the same plane with the distributed load $q(x)$; E – modulus of elasticity of the fibers material of the elastic brush-like screw; $M(x)$ - the bending moment of a fiber of the elastic brush-like screw; N_1 – the force of initial deformation of the elastic fibers of brush-like screw at its fixing in the casing; y – inclination angle of the elastic fibers of brush-like screw after initial deformation; N_i– centrifugal force acting on the fibers during the elastic brush-like screw rotation; G – weight force acting on the fibers; $G=mg$; I – the moment of inertia of the fiber cross-section of the elastic brush-like screw; β - inclination angle of the casing; θ – the angle of rotation of the elastic brush-like screw; m– fiber mass; g – free-fall acceleration.

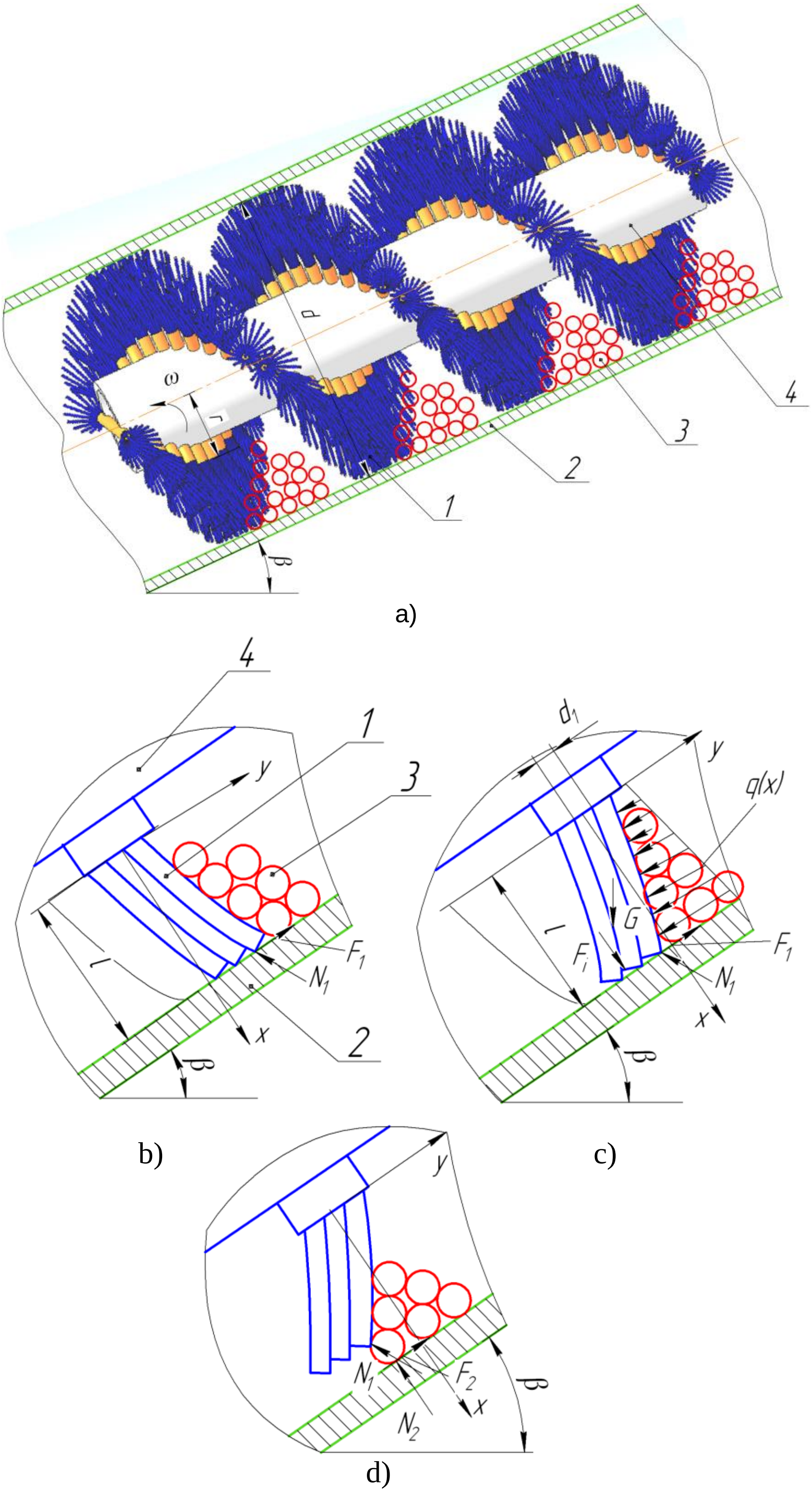


Fig. 4 - Calculation scheme to determine the deformation of an elastic brush-like screw during grain material transportation:

1 – elastic brush-like screw; 2 – casing; 3 - bulk material; 4 – shaft

The bending moment of a fiber of the elastic brush-like screw is found by the formula *(Pysarenko H.S., et.al., 1988)*:

$$M(x) = \int_x^l Q(x)dx + M(0) \tag{3}$$

where $Q(x)$ - the shear force in the fibers of the elastic brush-like screw; $M(0) = 0$ – the bending moment of a fiber cross-section of the elastic brush-like screw.

The shear force in the fibers of the elastic brush-like screw is calculated in the following way:

$$Q(x) = F_1 + N_1 \cos\gamma - \int_x^l q(x)dx - G \cdot \sin\beta \tag{4}$$

where F_1 – friction force between the fibers of elastic brush-like screw and the casing.

The force of initial deformation of the fibers of elastic brush-like screw at the moment of its installation in the casing has been found for the case when the fibers are considered as a cantilevered beam *(Pysarenko H.S., et.al., 1988)*:

$$N_1 = \frac{3nfEI}{l^3} \tag{5}$$

where f – is the value of the initial deformation of the elastic fibers of brush-like screw at the moment of its installation in the casing.

The value of initial deformation of the elastic fibers of brush-like screw at the moment of its installation in the casing has been found by the formula:

$$f = \sqrt{l^2 - (l-k)^2} \tag{6}$$

where k – length of the fiber part that is used to remove the gap between the elastic brush-like screw and the casing.

This length has been found on the basis of the conveyor structural parameters:

$$k = \frac{D-d}{4} \tag{7}$$

where D – is the external diameter of the elastic brush-like screw prior to its installation in the casing; d– the casing internal diameter.

The moment of inertia of the fiber round-shaped cross-section:

$$I = \frac{\pi d_1^4}{64} \tag{8}$$

where d_1 – is the diameter of the fiber cross-section.

The angle of inclination of fibers of the elastic brush-like screw after initial deformation:

$$\gamma = \arcsin \frac{\sqrt{l^2 - \left(l - \frac{D-d}{4}\right)^2}}{l} \tag{9}$$

After substituting the formulae Eq. 6, Eq. 7, Eq. 8 in equation Eq. 5, it has been obtained:

$$N_1 = \frac{3n\sqrt{l^2 - \left(l - \frac{D-d}{4}\right)^2} E\pi d_1^4}{64l^3} \tag{10}$$

Centrifugal force acting on the fibers during the elastic brush-like screw rotation:

$$F_i = m\omega^2 (r+l) \tag{11}$$

where ω – angular rotation frequency of the elastic brush-like screw; r – radius of the central shaft.

The friction force between the elastic fibers of brush-like screw and the casing:

$$F_1 = N_1\mu_1 \tag{12}$$

where μ_1 – is the friction coefficient between the elastic fibers of brush-like screw and the casing.

RESULTS AND DISCUSSION

After substituting the Eq. 3, Eq. 4, Eq. 11, Eq. 12 in equation Eq. 2, the equations of the middle line of several fibers' deformation of the elastic brush-like screw have been obtained:

$$nEI\frac{d^2y}{dx^2}=\int_x^l N_1\left(\cos\gamma+\mu_1\right)dx-\int_x^l\int_x^l\left(\frac{\left(q_{\max}-q_{\min}\right)x}{l}+q_{\min}\right)dxdx-\int_x^l mg\sin\beta dx- \\ -N_1\sin\gamma\cdot y+m\cdot y\left(\omega^2\left(r+l\right)+g\cos\beta\cos\theta\right) \quad (13)$$

In case when there is a gap between the elastic fibers of brush-like screw and the casing, equation Eq. 13 is written in the simplified form:

$$nEI\frac{d^2y}{dx^2}=-\int_x^l\int_x^l q(x)dxdx-\int_x^l mg\sin\beta dx+m\cdot y\left(\omega^2\left(r+l\right)+g\cos\beta\cos\theta\right) \quad (14)$$

After the integration of the Eq. 13 we have obtained:

$$nEI\frac{d^2y}{dx^2}=N_1\left(\cos\gamma+\mu_1\right)\left(l-x\right)-\frac{1}{2}\left(q_{\max}\left(l^2-x^2\right)+q_{\min}\left(l-x\right)^2\right)\left(1-\frac{x}{l}\right)- \\ -mg\sin\beta\left(l-x\right)-N_1\sin\gamma\cdot y+m\cdot y\left(\omega^2\left(r+l\right)+g\cos\beta\cos\theta\right) \quad (15)$$

Taking into account equation Eq. 10, it has been obtained:

$$\frac{nE\pi d_1^4}{64}\frac{d^2y}{dx^2}=\frac{3n_1\sqrt{l^2-\left(l-\frac{D-d}{4}\right)^2}E\pi d_1^4}{64l^3}\left(\left(\cos\gamma+\mu_1\right)\left(l-x\right)-\sin\gamma\cdot y\right)- \\ -\frac{1}{2}\left(q_{\max}\left(l^2-x^2\right)+q_{\min}\left(l-x\right)^2\right)\left(1-\frac{x}{l}\right)-mg\sin\beta\left(l-x\right)+m\cdot y\left(\omega^2\left(r+l\right)+g\cos\beta\cos\theta\right) \quad (16)$$

The differential equation Eq. 16 can be used to determine the deformation of the elastic fibers of brush-like screw under static load conditions.

The general solution of the differential equation Eq. 16 looks like this:

$$y=A_1\sin(k_1x)+A_2\cos(k_1x)+y^* \quad (17)$$

where A_1 and A_2 – are the coefficients that can be determined from the boundary conditions, mm; y^* - partial solution of the equation; k_1 – frequency characteristics.

The initial conditions for the solution of equation Eq. 16 are as follows: when $x=0$, $y=0$, $dy/dx=0$.

The solution of Eq. 16 has been found using the numerical method and is presented as curves in fig. 5 - 8 for different variable parameters. The view of the mean line of deformed fibers of an elastic brush-like screw at different values of external distributed load on the fibers from the side of the transported material is presented by the curves in fig. 5. The view of the mean line of deformed fibers of an elastic brush-like screw at different values of diameter d_1 of the fiber cross-section is presented by the curves in fig. 6. The view of the mean line of deformed fibers of an elastic brush-like screw at different values of length *k* of the fiber part used to remove the gap between the elastic brush-like screw and the casing is presented by the curves in fig. 7. The view of the mean line of deformed fibers of an elastic brush-like screw at different values of length *l* of the working part of the fibers of elastic brush-like screw is presented by the curves in fig. 8.

To check the adequacy of the differential equation Eq. 16 and its solution by the numerical method, some experimental study was conducted on the maximum deformation value Δy of nylon fibers of the elastic brush-like screw using the technique described in the article (*Hevko R.B. et.al, 2016*). The loading on the elastic fibers of brush-like screw from the side touching the casing was performed by means of some measured cargo in the form of balls, here the angle of inclination of the casing β was equal to 90 degrees. The deformation Δy was measured by a caliper. During the above-mentioned experiments, three main factors have been varied: diameter of the fiber cross-section d_1, length *l* of the working part of the elastic fibers of brush-like screw, and load *P* of the measured cargo.

To find the dependence $\Delta y = f(d_1, l, P)$, the full factorial experiment was used. Taking into account, that the dispersions in each point of the factorial space are homogeneous, it has been decided to apply the system of the experiment implementation scheme with duplication in one point (in the center of the plan) four times. After processing the experimental research results, the regression equation was derived to predict the value of deformation Δy :

$$\Delta y = 3.397 - 9.34d_1 + 0.425l + 3.04P - 0.432d_1l - 2.696d_1P + 0.148lP + 5.05d_1^2 + 0.0086l^2 + 0.012P^2 \quad (18)$$

Empirical dependence Eq. 18 adequately shows the parameter under study on the intervals of variable factors: 1.8 mm< d_1 <2.6 mm, 28 mm< l <36 mm, 1.4 N < P <2.6 N .

On the basis of Eq. 18 the response surfaces of the maximum deformation value Δy as a functional are drawn, as shown in fig. 9.

Fig. 5 - Curves of mean line of deformation of four nylon fibers of an elastic brush-like screw located in the same plane with distributed load l =30 mm, k =0.1 mm, d_1 = 0.1 mm, β = 45 degrees:

1) deformation at the initial installation of an elastic brush-like screw in the screw conveyor casing q_{max} =0 N/mm; $q_{\min}$ = 0 N/mm; 2) q_{max} =0.05 N/mm; $q_{\min}$ = 0.02 N/mm; 3) q_{max} =0.1 N/mm; $q_{\min}$ = 0.06 N/mm

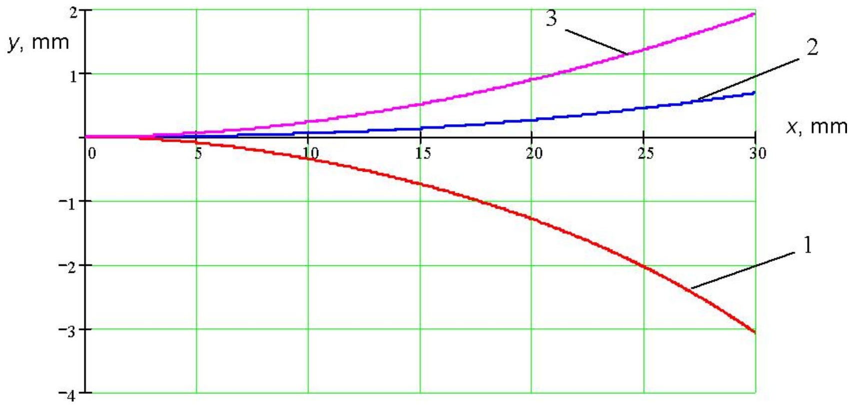


Fig. 6 - Curves of mean line of deformation of four nylon fibers of an elastic brush-like screw located in the same plane with distributed load l =30 mm, k =0.1 mm, β = 45 degrees:

q_{max} =0.05 N/mm; $q_{\min}$ = 0.02 N/mm; d_1 = 1.7 mm; 2) d_1 = 2 mm; 3) d_3 = 2.3 mm

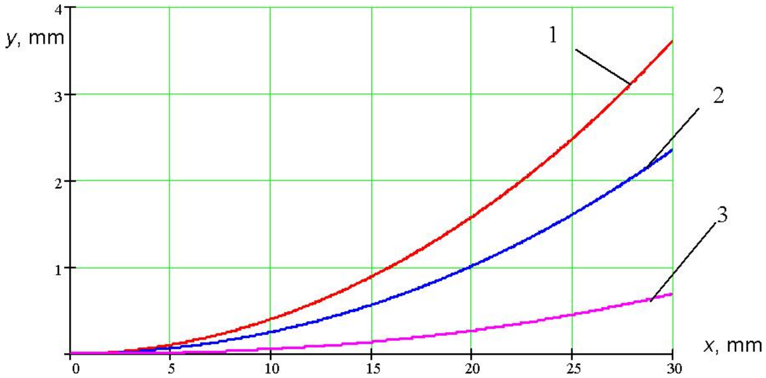


Fig. 7 - Curves of mean line of deformation of four nylon fibers of an elastic brush-like screw located in the same plane with distributed load l =30 mm, d_1 = 2 mm, q_{max} =0.05 N/mm; $q_{\min}$ = 0.02 N/mm; β = 45 degrees:

1) k =0.3 mm, 2) k =0.2 mm, 3) k =0.1 mm

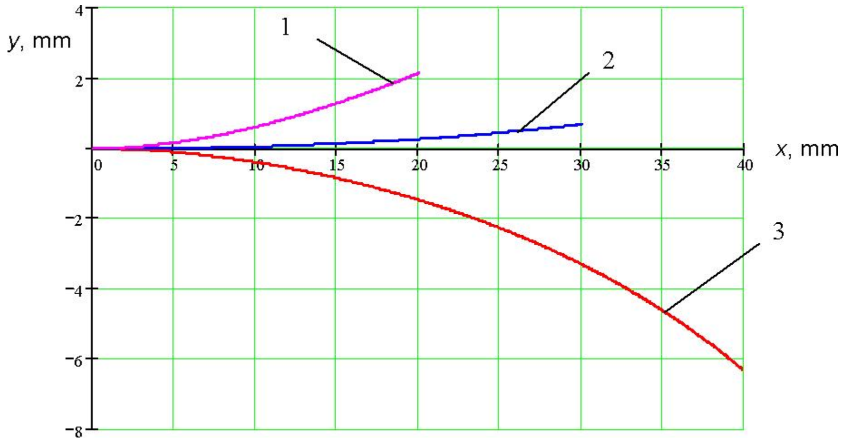


Fig. 8 - Curves of mean line of deformation of four nylon fibers of an elastic brush-like screw located in the same plane with distributed load k =0.1 mm, d_1 = 2 mm, q_{max} =0.05 N/mm; q_{min} = 0.02 N/mm; β = 45 degrees: *1)* l =20 mm; *2)* l =30 mm; *3)* l =40 mm

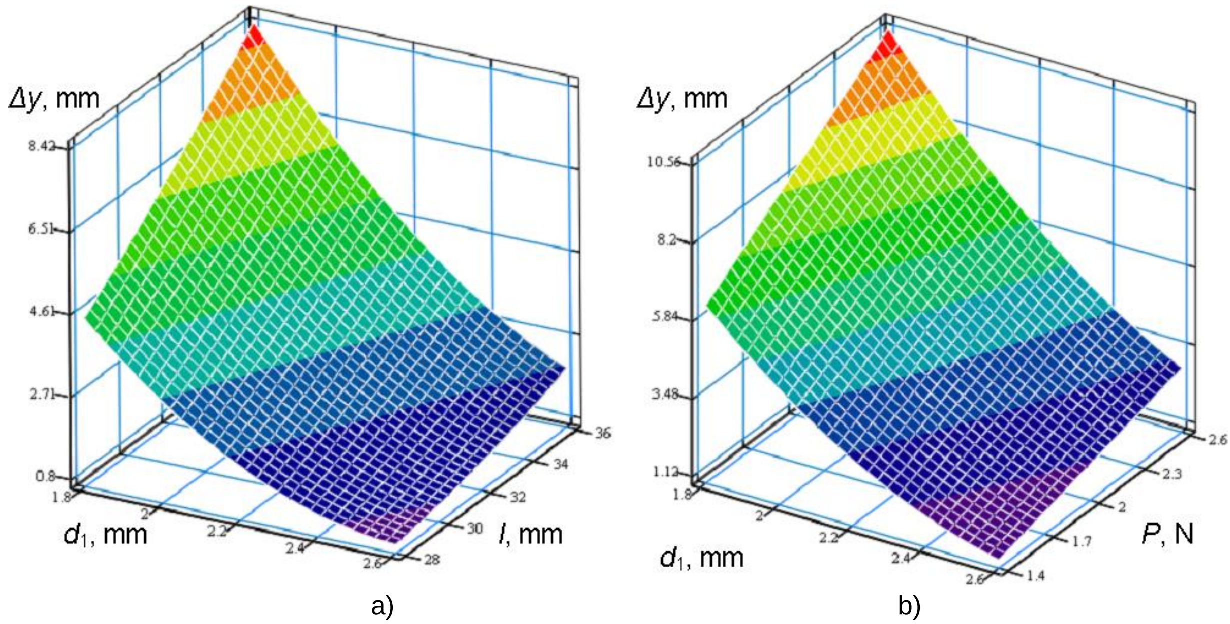


Fig. 9 - Response surfaces of the maximum deformation value Δy as a functional

a) $\Delta y = f(d_1;l)$ *at* $P = 2$ *N; b)* $\Delta y = f(d_1;P)$ *at* $l = 36$ *mm*

CONCLUSIONS

Curve 1 in fig. 5 corresponds to fig. 4*b*, for the case when the brush-like screw at the moment of its installation in the casing is initially deformed up to 2.5 mm and rests on the casing surface, here there isn't any external distributed load from the side of the transported material. When the increase of external load q_{min} and q_{max} is up to 0.06 N/mm and 0.1 N/mm respectively the deformation of the fibers of elastic brush-like screw is up to 1.5 mm (curve 3), which corresponds to fig. 4*c,* and the total bending of the fiber is 5 mm.

When the fiber diameter is reduced (fig. 6) from 2.3 mm (curve 3) to 1.7 mm (curve 1) for the same external loads, the fiber deformation takes place in the negative direction of the axis *y* from 2 mm to 3 mm and the total bending of the fiber is 5 mm.

When the value k (fig. 7) increases from 0.1 mm to 0.3 mm, the previous deformation of the fiber also increases (fig. 4 b) from 0.7 mm to 3.5 mm, providing the increase in uploading capacity of the elastic brush-like screw, though the material transportation capacity also gets higher due to the greater force of friction between the fibers of the elastic brush-like screw and the conveyor casing.

When the fiber working part *l* increases (fig. 8) from 20 mm (curve 1) to 40 mm (curve 3), for the same external loads the fiber deformation takes place in the negative direction of the axis *y* from 2.2 mm to 6.4 mm, and the total bending of the fiber is 8.6 mm. Thus, the use of fibers of greater length *l* of the working part can reduce the loading capacity of the elastic brush-like screw, though the transported material damage value is lower.

The real value of the deformation quantity of the fibers of elastic brush-like screw during the bulk material transportation process is higher due to the dynamic load that occurred. As the probability of resonance is inconsiderable, the real value of the deformation quantity of the fibers of elastic brush-like screw during the bulk material transportation process can be determined by the product of the fiber deformation value at static calculations by the dynamism factor: $y_r = y \cdot k_d$.

On the basis of the analysis of the regression Eq.18 and the constructed curves (fig. 9), it has been found, that the smaller diameter of the fiber cross-section d_1 and the bigger length of the working part of the elastic fibers of brush-like screw l is, and the greater load P is, the value of deformation Δy of nylon fibers of the elastic brush-like screw is higher. The maximum value of deformation Δy is 10.5 mm, and the minimum one is 0.7 mm. The increase of the parameter d_1 from 1.8 mm to 2.6 mm results in a 4.4 times reduction of the deformation Δy. The increase of the parameter l from 28 mm to 36 mm causes a 2.4 times increase in deformation Δy and, in this case, the increase of load P from 1.4 H to 2.6 H results in 2.36 times increase in deformation Δy. The deviation of the theoretical results of the study from the experimental ones is not more than 17%.

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