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INVESTIGATION OF THE SECTIONAL WORKING BODY DEFORMATION OF A FLEXIBLE SCREW CONVEYOR

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Abstract. Flexible screw conveyors are used in various sectors of the national economy for the transfer of food and agricultural products, building materials, etc. In the process of transportation of goods with the help of flexible screw conveyors there is an overload often, resulting in significant deformations and breakdowns of elements of their working bodies. At the same time, high requirements relate to the reliability and durability of these mechanisms, along with the provision of high technical and economic indicators and low maintenance and repair costs. Therefore, when using flexible screw conveyors with sectional working bodies, it is important to determine the permissible loads and bending radii to avoid critical deformations. Taking advantage of the proposed model makes possible to develop new designs of the screw conveyor intake devices and to interpret their efficient parameters.

Keywords: service cooperatives, parameters, modeling, efficiency, indicators, technological system.

INTRODUCTION

The purpose of the work is to study the deformation of the sectional working body of the flexible screw conveyor, provided that its operational and technological parameters are maintained. Many works consider the basic principles of designing and modeling screw

conveyors (Owen *et al.* 2009; Liu, 2010) and others devoted to theoretical substantiation of the processes of flexible screw reloading mechanisms, methods of calculating their basic parameters, the development of progressive structures of these means of mechanized transportation of powder materials along curvilinear tracks.

Thus, it is necessary to improve and develop new designs and determine optimal design and kinematic parameters of hinged sectional operating elements of screw conveyers, which can provide the improvement of functional and operating characteristics of the process of transporting loose materials (Hevko *et al.* 2018; Dzyura *et al.* 2018).

The analysis of the basic provisions related to the design of flexible screw conveyors (FSC), indicates the lack of unambiguous view of various authors on the nature of the phenomena observed during the operation of such means of mechanization. In certain studies, particular attention is paid to those literary sources that cover the selection of parameters of working bodies and processes of transportation of powder goods, including grains and their damage and injury.

MATERIALS AND METHODS

For transportation of bulk materials on curvilinear trajectories the construction of a section of a flexible screw conveyor is

proposed, the calculation scheme of which is shown in figure 1.

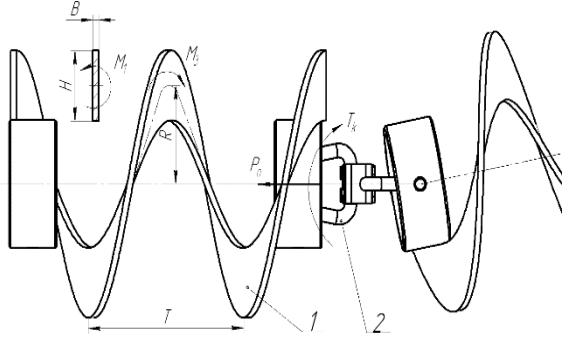


Figure. 1. Scheme of the section of the flexible screw conveyor: 1 - screw element; 2 connecting-transmitting link

The sections of the flexible screw conveyor are non-rigid parts, therefore, in order to ensure their efficient operation, it is necessary to calculate their rigidity when moving different materials under appropriate external loads: torque and axial force. Particularly important is the change in the outer radius and the step of the auger of the screw conveyor during the transport of the load, as these parameters affect the efficiency of this process.

Equation of the middle line of the screw element of the section of the conveyor in a parametric form Gevko, R. B., Vitrovyi, A. O., & Pik, A. I. 2012, Gevko, I. B., Leshchuk, R.Y. & Novasad, I. Ya. 2005.

$$\begin{aligned} x &= R \cos t \\ y &= R \sin t \\ z &= \frac{T}{2\pi} t \end{aligned} \quad (1)$$

where R - radius of the middle line of the screw element, mm; T - step of the screw element, mm.

We will perform the replacement of the parameter t in the equation (1) with the length of the arc of the middle line of the screw element of the conveyor section:

$$l = \int_0^t \sqrt{\dot{x}^2 + \dot{y}^2 + \dot{z}^2} dt \quad (2)$$

$$l = t \sqrt{R^2 + \frac{T^2}{4\pi^2}} \quad (3)$$

$$t = \frac{l}{\sqrt{R^2 + \frac{T^2}{4\pi^2}}} \quad (4)$$

Substituting the equation (4) into the system of equations (1), we obtain:

$$\begin{aligned} x &= R \cos \frac{l}{\sqrt{R^2 + \frac{T^2}{4\pi^2}}} \\ y &= R \sin \frac{l}{\sqrt{R^2 + \frac{T^2}{4\pi^2}}} \\ z &= \frac{T}{2\pi} \frac{l}{\sqrt{R^2 + \frac{T^2}{4\pi^2}}} \end{aligned} \quad (5)$$

We find the curvature of the arc of the middle line of the screw element of the conveyor section:

$$K = \sqrt{\left(\frac{d^2x}{dl^2}\right)^2 + \left(\frac{d^2y}{dl^2}\right)^2 + \left(\frac{d^2z}{dl^2}\right)^2} \quad (6)$$

Substituting the equation (5) into the equation (6), after transformations and reductions we get:

$$K = \frac{R}{R^2 + \frac{T^2}{4\pi^2}} \quad (7)$$

We find the torsion of the arc of the middle line of the screw element of the conveyor section:

$$\Omega = \left(\frac{R^2 + \frac{T^2}{4\pi^2}}{R} \right)^2 \frac{\begin{vmatrix} -R \sin t & R \cos t & \frac{T}{2\pi} \\ -R \cos t & -R \sin t & 0 \\ R \sin t & -R \cos t & 0 \end{vmatrix}}{\left[(-R \sin t)^2 + (R \cos t)^2 + \frac{T^2}{4\pi^2} \right]} \quad (8)$$

After the transformations and reductions of equation (8), we obtain:

$$\Omega = \frac{T}{2\pi R^2 + \frac{T^2}{2\pi}} \quad (9)$$

The arc of the middle line of the screw element of the conveyor section is determined by the basic parameters R and T , which are related to the initial parameters R_0 and T_0 by the following relationships:

$$R = R_0 + \Delta R; \quad (10)$$

$$T = T_0 + \Delta T, \quad (11)$$

where ΔR - is the magnitude of the change in the radius of the middle line of the section screw element of the conveyor section during the load, mm; ΔT - is a value of step change of the middle line of the screw element of the conveyor section during the load, mm.

The values ΔR and ΔT are functions of the external load on the conveyor section and the initial dimensions of the middle line of the screw element, and also depend on the elastic properties of the material of the screw element.

We establish the relationship between ΔR , ΔT and the change in the curvature ΔK and torsion $\Delta \Omega$ of the middle line of the section screw element of the conveyor. By differentiating the relations (7) and (9), we obtain an equation for changing the curvature and torsion of the middle line of the screw element of the conveyor section:

$$\Delta K = \frac{\left(-R^2 + \frac{T^2}{4\pi^2}\right)\Delta R - R\frac{T}{2\pi^2}\Delta T}{\left(R^2 + \frac{T^2}{4\pi^2}\right)^2}; \quad (12)$$

$$\Delta \Omega = \frac{-4T\pi R\Delta R + \left(2\pi R^2 - \frac{T^2}{4\pi^2}\right)\Delta T}{\left(2\pi R^2 + \frac{T^2}{4\pi^2}\right)^2}. \quad (13)$$

From equation (12) we find:

$$\Delta R = \frac{\Delta K \left(R^2 + \frac{T^2}{4\pi^2}\right)^2 + R\Delta T \frac{T}{2\pi^2}}{-R^2 + \frac{T^2}{4\pi^2}}. \quad (14)$$

Also, from equation (13) we find:

$$\Delta R = \frac{\Delta \Omega \left(2\pi R^2 + \frac{T^2}{4\pi^2}\right)^2 - \left(2\pi R^2 - \frac{T^2}{4\pi^2}\right)\Delta T}{-4T\pi R} \quad (15)$$

Assimilating equations (14) and (15), after transformations we obtain:

$$\Delta T = \frac{\Delta \Omega (256\pi^8 R^6 - 64\pi^6 R^4 T^2 + 64\pi^5 R^4 T^2 + 4T^4 R^2 \pi^2 - T^6) + \dots + \Delta K (-256\pi^7 T R^5 - 128\pi^5 T^3 R^3 - 16\pi^3 T^5 R)}{4\pi^2 (32\pi^5 R^4 + 24\pi^3 R^2 T^2 - 4R^2 \pi^2 T^2 + T^4)} \dots \quad (16)$$

The change in the torsion and curvature of the middle line of the screw element of the conveyor section is due to the appearance of the axial force P_0 and the torque T_k at the ends of the screw element during the transport of the goods.

According to Gevko, R. B., Vitrovyi, A. O., & Pik, A. I. 2012, for the change of curvature and torsion in the case of linear deformation, the following relations can be written:

$$\Delta \Omega = \frac{M_1}{GJ_p}; \quad (17)$$

$$\Delta K = \frac{M_3}{EJ_x}. \quad (18)$$

where M_1 - the torque applied to the rotation in a plane perpendicular to the axial line of the rotation, H · mm; M_3 - bending moment, that bends the turn in the

plane, where the curvature K , H mm; $J_p = HB^3\xi$ - moment of inertia of torsion section, mm⁴; $J_x = \frac{HB^3}{12}$ - the moment of inertia of the bending section, mm⁴; E and G - respectively, the modulus of elasticity of the material of the tensile and shear screw element, H / mm²; H - height of the cross section of the tape of the screw element, mm; B - width of the cross-section of the tape of the screw element, mm; ξ - coefficient, which depends on the ratio of H to B .

The torque applied to the rotation in a plane perpendicular to the axial line of the spiral is determined by the formula Gevko, R. B., Vitrovyi, A. O., & Pik, A. I. 2012, Gevko, B.M., & Rohatynskyi, R.M. 1989.

$$M_1 = T_k \sin \alpha + P_0 R \cos \alpha, \quad (19)$$

where α is the angle of recovery of the middle line of the screw element of the conveyor section.

The angle of recovery of the middle line of the screw element of the section of the conveyor is determined by the known formula:

$$\alpha = \arctg\left(\frac{T}{2\pi R}\right). \quad (20)$$

The bending moment bending the turn in the plane, where the curvature K is measured, is based on the formula Gevko, B.M., & Rohatynskyi, R.M. 1989.

$$M_3 = T_k \cos \alpha - P_0 R \sin \alpha. \quad (21)$$

Substituting equations (17), (18), (19), (21) into the equation (16), we obtain the value of changing the step of the middle line of the screw element of the conveyor section during loading:

$$\Delta T = \frac{\frac{T_k \sin \alpha + P_0 R \cos \alpha}{GHB^3\xi} (256\pi^8 R^6 - 64\pi^6 R^4 T^2 + 64\pi^5 R^4 T^2 + 4T^4 R^2 \pi^2 - T^6) + \frac{12(T_k \cos \alpha - P_0 R \sin \alpha)}{EHB^2} (-256\pi^7 TR^5 - 128\pi^5 T^3 R^3 - 16\pi^3 T^5 R)}{4\pi^2 (32\pi^5 R^4 + 24\pi^3 R^2 T^2 - 4R^2 \pi^2 T^2 + T^4)} \quad (22)$$

On the basis of equations (14) and (22), the graphic dependences of the

change in the radius and the step of the middle line of the screw element of the conveyor section on the geometric parameters of the turns during loading are constructed (Figs 2, 3, 4).

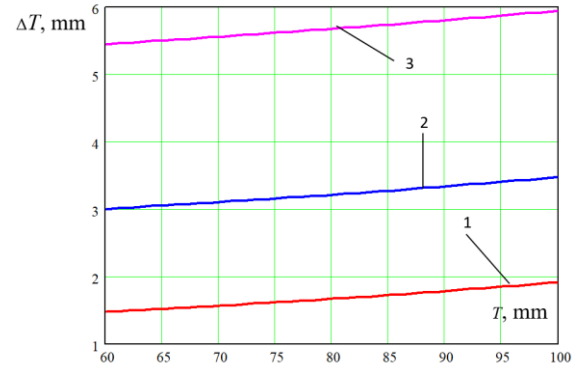


Figure. 2. Diagram of the dependence of the value of the change of the step of the middle line of the screw element of the conveyor section from the step of the turns $P_0 = 50H$, $T_k = 1000 \text{ N} \cdot \text{mm}$, $H = 20 \text{ mm}$, $B = 2,5 \text{ mm}$: 1) $R = 30 \text{ mm}$; 2) $R = 40 \text{ mm}$; 3) $R = 50 \text{ mm}$.

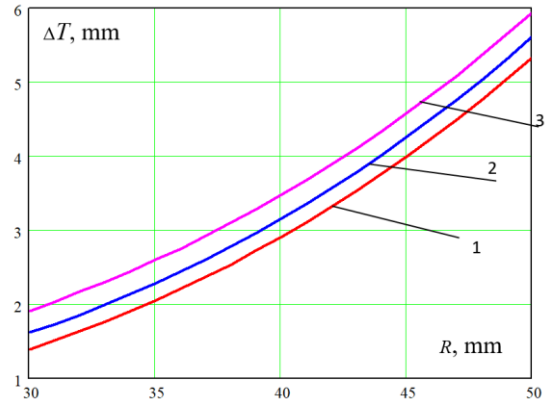


Figure. 3. Diagram of the dependence of the value of the change of the step of the middle line of the screw element of the conveyor section from the average radius of the turns $P_0 = 50H$, $T_k = 1000 \text{ N} \cdot \text{mm}$, $H = 20 \text{ mm}$, $B = 2,5 \text{ mm}$: 1) $T = 50 \text{ mm}$; 2) $T = 75 \text{ mm}$; 3) $T = 100 \text{ mm}$.

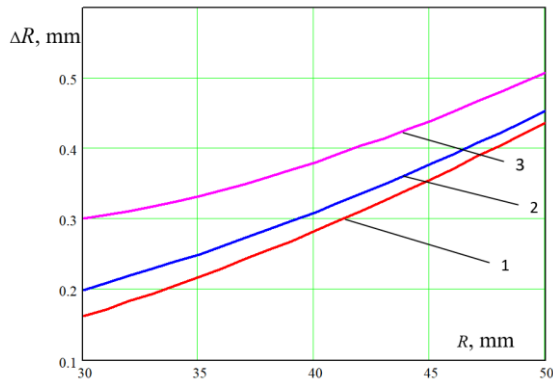
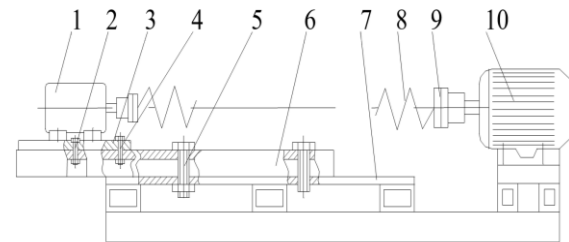


Figure. 4. Diagram of the dependence of the magnitude of the middle line of the screw element section of the conveyor change in the radius from the average radius of the turns $P_0 = 50H$, $T_k = 1000N \cdot mm$, $H = 20mm$, $B = 2,5 mm$: 1) $T = 50mm$; 2) $T = 75mm$; 3) $T = 100 mm$

As can be seen from the formulas (14) and (22) and the graphs, the deformation of the screw element of the conveyor section completely depends on the geometry of the turns (the lifting angle of the middle line of the screw element of the conveyor section, the radius of the middle line of the screw element, the step of the turns of the screw element, the cross section of the screw element ribbon) and external load. It is also established that with increasing the radius of the middle line of the screw element and the step of the spiral sheath, there is an increase in the change in the radius and the step of the middle line of the screw element of the conveyor section at the same external loads, which affects the performance of the transportation process.

Special bench equipment was used to study the deformation-force characteristics of sectional screw working bodies (Gevko *et al.* 2016). The stand (Fig. 5, 6) consists of a frame 7, on which a generator (DC motor 4PF112LVB04) 1 mounted on a rotary plate 3 which, with the help of a pair of bolted joints 2 and 4, is fixed to the guide channel 6. The latter is fixed to the frame 7, and its fixation in the given position is provided by bolted

connection 5. Also, the stand contains a three-phase asynchronous electric motor (AIR90L4UZ) 10, which is fixed on a mobile plate. The investigated screw working element 8, using either the flange connections, or the flange connection and the safety coupling 9, is installed on the output shafts of the electric motors 1 and 10.



a)



b)

Figure. 5. Stand for the study of strain-force characteristics of screw working bodies: a) scheme; b) general view

The study of deformation-strength characteristics of screw working bodies using a stand is carried out as follows. The experimental object 8 is placed on the shafts of the generator 1 and the electric motor 10 and by means of the mobile plate, the necessary installation of the radius of the curvature of the spiral is carried out. Due to the possibility of significant displacement of the electric motor 10 in the transverse and longitudinal direction on this stand, screw working bodies of different lengths and configurations can be

tested. Next, the power supply to the converter of the frequency converter (FC) and the personal computer (PC) (Fig. 6) is started and the PowerSuite program is started to set up the Altivar series frequency converters (Gevko *et al.* 2014).



Figure. 6. Regulating and measuring equipment for controlling the electric drive in the study of the deformation-strength characteristics of screw working bodies

The frequency of rotation of the electric motor is regulated in an automated mode from 0 to 1440 rpm. and if necessary, you can use a smooth and sharp start and reversal. Generator 1 acts as a brake and works with independent excitation for the possibility of creating the required load on the experimental object. According to the stabilizer the current enters the laboratory transformer, where its regulation ($U = const$) is made to the required value ($I = 0 \dots 4A$), and then through the rectifier (diode bridge) is fed to the winding of excitation of the generator stator, which provides control of the load of the generator and its power consumption.

The data on the speed of rotation on the engine shaft (error within $\pm 1,5\%$) are fixed using the motor shaft speed sensor (E40S6-10Z4-6L-5) connected to the motor rotor and the FC. Data on energy consumption and torque values on the electric shaft, depending on the load, in the set time as tabular data and graphic dependencies, are displayed on the PC monitor.

Also, for the determination of the stiffness torsion of the screw working bodies the machine used the discontinuous model KM-50-1 and the stand for studying the angle of twist of the sectional screw working bodies, which consists of a housing with a riser, on which the screw working body is fixed, to the free end of which, through a certain mechanism with the vernier scale, there is a tare lever through which the screw working body is subjected to loading, resulting in an angular displacement when the screw is twisted, the magnitude of which is overload capacity screw working body.

In the course of research on this stand, there were dangerous curvature radii and critical loads that caused their destruction for different types of screw working bodies with different structural parameters. During tests, measurements of the twist angle of the sectional screw working bodies on the stand were performed to study the angle of twisting of the sectional screw working bodies (Gevko *et al.* 2014).

In fig. 7 it is shown the dependences of peak moments arising in flexible screw conveyers at startup, on the load factor ($K_s = 0.3 \dots 0.7$) for smooth (for 10 s) and sharp ($n = 454.4$ rpm) start-up for spiral and sectional screw working body (SWB) with a hinged connection (internal diameter of the casing $D_k = 100$ mm, diameter SWB - 96 mm, length SWB - 4 m; transport material - sand).

From Figure 7 it is seen that during a sharp start the magnitude of the peak moment is greater in 1,59 ... 2,02 times for the spiral SWB and in 1,67 ... 2,13 times for the sectional SWB, in comparison with the magnitude of the peak moment when the acceleration of the flexible SC for 10 s., and with increasing loading of the screw conveyor, it increases.

Analyzing the results of the research it can be concluded that, both for hard screw conveyors, and for flexible screw conveyors, in order to reduce the peak torque at starting in the loaded state, it

is necessary to ensure their smooth dispersal, or to avoid it. Also, with the launch of a flexible screw conveyor, to reduce the peak moment, it is necessary to straighten the SWB or, if not possible, to provide the maximum radius of the curvature of its highway. When designing a SWB it is necessary to observe the conditions of its uniformity, which proceeds from the necessity of maintaining the uniformity of the permissible load over its entire length (the most loaded links in the place of attachment of the SWB with the drive shaft).

In addition, the housings for the designs of flexible screw conveyors are appropriate to choose such that provide a minimum friction on its own internal surface.

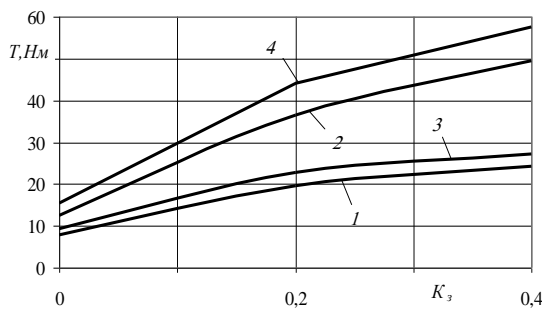
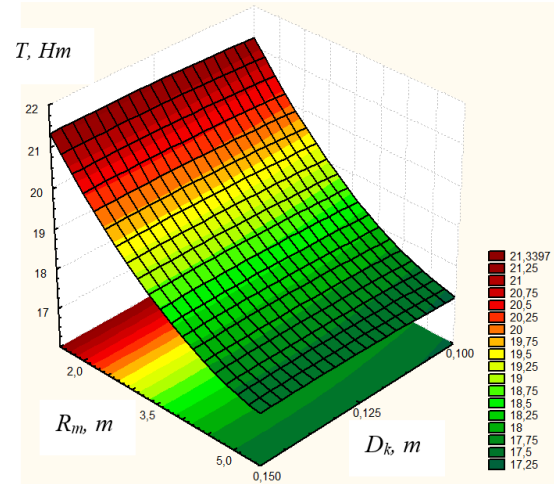
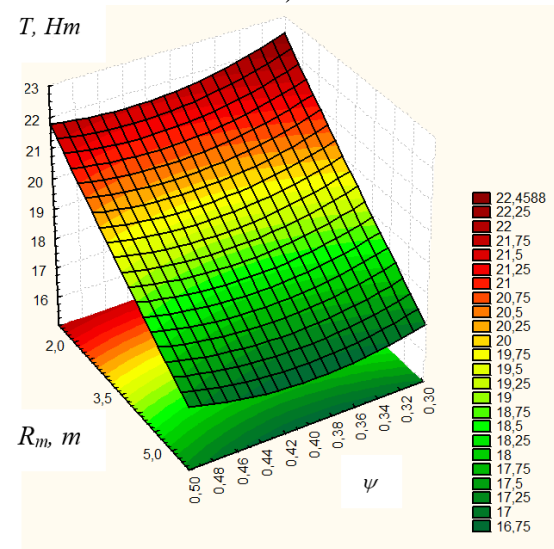


Figure. 7. Dependence of the magnitude of the peak torque when starting a flexible FC from the load factor at: 1 - smooth start (spiral SWB); 2 - a sharp start (spiral SWB); 3 - smooth start (section SWB); 4 - sharp start (section SWB)

In fig. Fig. 8 it is shown the dependence of the torque value on the change in the radius of the curvature of the line R_m for sectional SWB with an internal diameter of the casing $D_k = 0,125$ m at a rotational speed $n = 454$ rpm, based on which the torque increases with decreasing the radius of the curvature of the line for flexible screw conveyors with sectional: a) hinged connection; b) a safety connection.



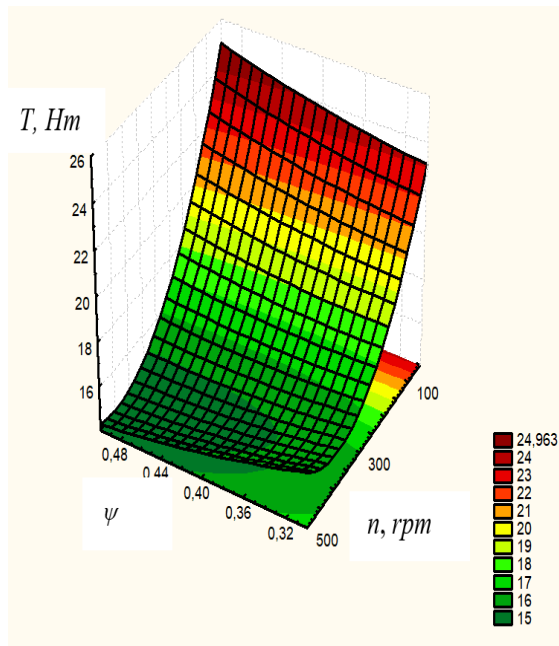
a)



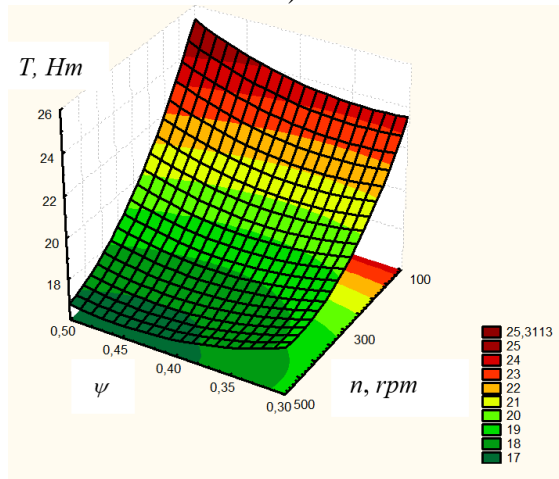
b)

Figure. 8. Influence on the magnitude of the torque FSC of the radius of the curvature of the main line at $D_k = 0,125$ m and $n = 454$ rpm. for: a - technical salt (with a hinged connection); b) - technical salt (with safety connection)

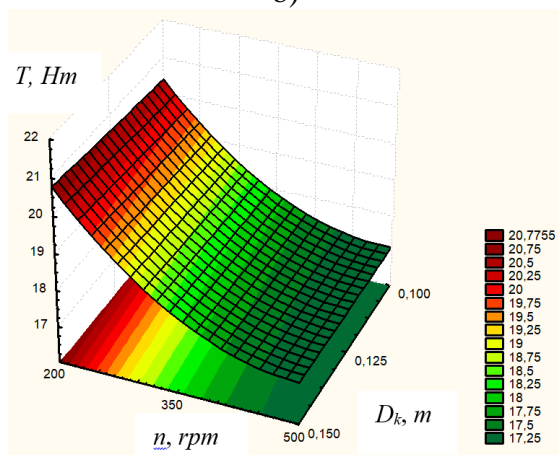
In fig. 9 shows the torque dependence from the change in the frequency of rotation of the SWB (straight line), where it is evident that the torque decreases with an increase in the frequency of rotation of the SWB.



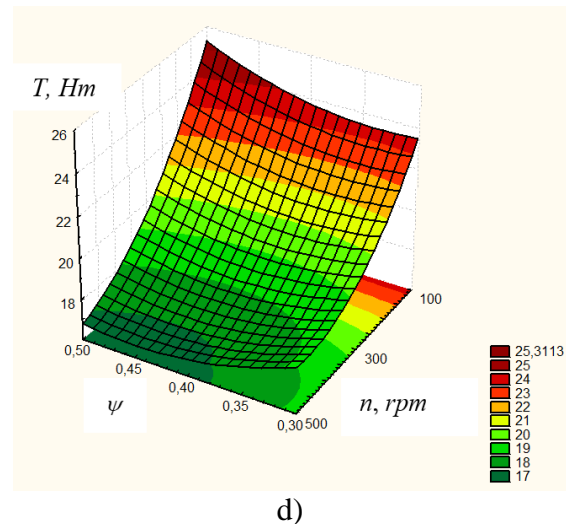
a)



b)



c)



d)

Figure. 9. Frequency of rotation of SWB on the magnitude of torque of screw conveyor at $D_k = 0,125$ m a-technical salt (hinge connection); b-technical salt (safety connection); in - barley (hinged connection); barley (safety connection)

CONCLUSIONS

Experimental studies have shown that when designing flexible screw conveyors, the rotor speed must be set at 454 rpm, which is necessary to reduce the friction of the SWB in the casing, where it is centered on the axis of rotation. Before starting the test, the angle of twisting for the screw working bodies did not exceed 3.2° . At the initial stage of resource testing (after 10 hours of operation) the twist angle for both sectional screw working bodies has increased sharply, which can be explained by the clamping of individual elements of the screw constructions, and then there was a slowing down of its growth and stabilization.

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