RESEARCH ON POWER PARAMETERS OF A SCREW CONVEYOR WITH BLADED OPERATING BODY FOR TRANSPORTING AGRICULTURAL MATERIALS
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LAUKSAIMNIECĪBAS BERAMKRAVU MATERIĀLU TRANSPORTĒŠANAS GLIEMEŽTRANSPORTIERA JAUDAS PARAMETRU PĒTĪJUMI

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ABSTRACT
The article presents the results of theoretical and experimental laboratory investigations of an improved screw conveyor for bulk agricultural materials that has been created, which, instead of a solid spiral winding, fixed to the drive shaft, uses a spiral winding, formed by separate curvilinear planes (blades), which are also separately fixed to the shaft, yet as a whole form a single spiral. An analytical dependence was obtained for determination of the magnitude of the torque on the drive shaft of this transport working element. The numerical values, obtained as a result of the laboratory experiments, made it possible, when conducting a regression analysis, to derive a new analytical expression in the form of a regression equation. The analysis of the regression equation shows that these factors, which have a significant impact upon the increase in the torque, are the factors: x1 (D) – the diameter of the fixed casing in which the screw is installed and x2 (ψ) – the filling factor of the conveyor with the transported bulk material. Increasing the value of the factor x3(n), i.e., the rotation speed of the vane working body leads to a decrease in the torque value.

ANOTĀCIJA
Šajā rakstā ir sniegti teorētisko un eksperimentālo pētījumu rezultāti par pilnveidotu gliemežtransportieri lauksaimniecības materiālu beramkravu transportēšanai, kurā pie piedziņas vārpstas piestiprināta nepārtraukta spirāles tinuma vietā tiek izmantots spirāles tinums, ko veido atsevišķas izliektas plāksnes (lāpstiņas), kas arī ir piestiprinātas pie vārpstas, bet kopumā veido vienu spirāli. Veikti teorētiski un eksperimentāli pētījumi, lai noteiktu šī uzlabotā gliemežtransportiera jaudas parametrus, jo īpaši tā piedziņas vārpstas griezes momentu dažādu beramo lauksaimniecības materiālu transportēšanas laikā. Tika iegūta analītiska sakarība, lai noteiktu šīs piedziņas vārpstas griezes momenta vērtību. Eksperimentālo pārbaužu rezultātā iegūtās skaitliskās vērtības ļāva regresijas analīzes laikā iegūt jaunu analītisku izteiksmi regresijas vienādojuma formā. Šis vienādojums atspoguļo citu parametru, kas šajā gadījumā izmantoti kā kontrolējamie faktori, ietekmes pakāpi uz griezes momenta vērtību. Regresijas vienādojuma analīze liecina, ka faktori, kas būtiski ietekmē griezes momenta pieaugumu, ir: x1 (D) - fiksētā korpusa, kurā uzstādīta spirāle, diametrs un x2 (ψ) - transportiera piepildījuma koeficients ar transportēto beramo materiālu. Tika konstatēts, ka, palielinoties faktora x3 (n) -spirāle, kurā spirālveida vijums veidots no izliektu plākšņu (lāpstiņu) komplektiem, kas piestiprināti pie piedziņas vārpstas, rotācijas kustības ātruma - vērtībai, turpretī griezes momenta vērtība samazinās.

INTRODUCTION
Screw conveyors in the agricultural industry are widely used in the transportation of bulk materials, in particular grain, seed materials, granulated fertilizers, feed, etc. However, existing screw conveyor designs do not fully meet all operational requirements.

Their main disadvantages are higher energy costs, damage to the bulk material and the complexity of manufacturing screw conveyor operating bodies, especially with their large overall dimensions.

From the analysis of studies of screw conveyors, it can be concluded that the vast majority of the authors paid attention to the conclusion of analytical relationships to determine the design and kinematic parameters of the screw operating bodies and, to a lesser extent, their energy-power parameters (*Klendii, 2016; Olt et al., 2022; Lyashuk et al., 2018*).

Known experimental studies are mainly aimed at determining the parameters of the operating bodies, which would ensure their high functional and operational performance with the minimum permissible mass of the operating body, thus reducing energy consumption for the transportation process (*Mondal, 2018; Hevko et al., 2016a; Hristov et al., 2016*).

In addition, the previously published works, devoted to the study of transportation of bulk agricultural materials deserve attention.

Thus, in the work by *Fan et.al., (2023)* the mechanism of transportation of mixed corn stalks in a screw conveyor was investigated and the parameters, influencing the transportation performance of the screw conveyor were determined. Besides, using the discrete element method, the author had created a simulation model of the process of transporting the corn stalks by a screw conveyor. Multifactorial modeling was also performed.

Zhang et.al., (2020), have shown an analysis of the bulk material conveying process by a horizontal screw feeder using the EDEM software. The work determines the influence of the feed upon the productivity, filling rate and the conveying speed of the feeder.

Zhou et al., (2019), presented a simulation test analysis of three factors (the screw inclination angle, the screw pitch, the screw rotation speed) that affect the ability of the screw to convey the grain materials. The author obtained the significance ratio of the transportation parameters and the best combination of the three specified design and kinematic factors.

There are also investigations of the screw conveyors to determine their productivity depending on the angle of inclination of the conveying line, the rotation speed of the screw itself, its length when transporting conventional granular materials, such as rice, corn, sorghum and gari, with a moisture content of 13% *(Li et al., 2022; Pezo et al., 2015)*.

The previously published works point to significant intentions of the foreign authors to optimize the transport capabilities of he screw conveyors, used specifically for transportation of bulk agricultural materials by changing various parameters of these working bodies.

Known experimental studies are mainly aimed at determining the parameters of the operating bodies, which would ensure their high functional and operational performance with the minimum permissible mass of the working body, thus reducing energy consumption for the transportation process. In some publications, as an alternative to the helical body of conventional design, a bladed body in the form of flat blades forming a helical surface is considered (*Hevko et al., 2016b; Bulgakov et al., 2022a; Hevko et al., 2021*).

The purpose of this study is to determine the torque on the drive shaft of a screw conveyor with a bladed operating body when transporting bulk materials agro-industrial production to eliminate the occurrence of drive breakage during operation.

MATERIALS AND METHODS

The screw working element that was improved is a conventional screw conveyor which, instead of a solid spiral winding, welded to the drive shaft, uses a similar winding, which is formed by separate curvilinear planes (blades), that are also separately fixed to the shaft, yet, as a whole, this makes up a single spiral. As it is known, the use of a solid spiral winding, fixed on the drive shaft, has a number of essential disadvantages. Thus, it significantly complicates the technology of obtaining (rolling from sheet steel) the spiral itself. Further, there are significant costs for its fixation (welding) on the drive shaft. As it turned out, the working element of the screw conveyor of an improved design, proposed by us, is mounted from separate stamped curvilinear blades. In this case the spiral winding retains all its properties, its manufacture is possible for any length of the screw conveyor, the repairability of the structure will be significantly increased since the replacement of a damaged or deformed blade will be much easier than repairing a solid spiral. It is much easier to weld these small blades onto the drive shaft. Thus, in this case the production of an improved design is significantly simplified and the material consumption of these transport working bodies is reduced.

Figure 1 shows the bladed operating body, which is used for conveying bulk materials.

Fig. 1 – General view of the bladed operating body

This operating body is made in the form of a drive shaft, on the surface of which inclined flat blades, bounded by semi-ellipses, alternate with each other, and their angles of inclination also alternate in sign, which allowed to reduce the material intensity and simplify the design of these screw conveyors. It is expedient to manufacture such blades by a simpler method, by stamping sheet material with subsequent welding of the blades to a cylindrical shaft.

To carry out experimental studies, an experimental setup for the study of the conveyor with a bladed operating body, the general view of which is shown in Fig. 2., was built.

Fig. 2 – General view of a conveyor in which a bladed operating body is used to transport loose materials:
1 – frame; 2 – fixed cylindrical cover; 3 – shaft of the bladed operating body; 4 – electric motor; 5 – hopper

The experimental study to determine the value of torque transmitted by the shaft of the bladed operating body of the screw conveyor was as follows. First, the software in the personal computer was started to control the process and signal to the appropriate speed of the electric motor *4*. Frequency converter (Altivar 71) with Power Suite v.2.5.0 software was used for starting the electric motor and regulating the speed of rotation, thus allowing to perform smooth starting and regulation of the necessary speed of the electric motor *4*.
The electronic system the Altivar 71 was used as a modern system that, due to the ability to be connected to a computer network has a virtual oscilloscope that allows you to track the change in the parameters you are looking for over time with specific numerical values.

At setting the required rotation speed with the help of computer via Altivar 71 system, the command to electric motor *4* was transmitted and it started rotating the shaft of the bladed operating body *3,* with the set parameters. Bulk material from the hopper *5* was fed through the open slide gate to the experimental setup under the stationary cylindrical cover *2*. Further the loose material was transported, and the data on the magnitude of the load transmitted to the bladed operating body was recorded on a personal computer.

For theoretical determination of the energy-power parameters of the screw conveyor, in particular, to determine the torque on the shaft with a bladed operating body, the known dependencies ar used. First of all, let's consider the analytical dependence for determining the conveying power of the screw conveyor, which will be equal to (*Gevko and Rogatynsky, 1989*):

$$N = \rho \cdot g \cdot Q \cdot W \cdot L \tag{1}$$

where:

ρ – bulk density of the transported material; g – acceleration of gravity; Q – volume flow; W – coefficient of specific friction losses along the length of transportation; L – conveying length.

Since the mass flow rate of the load given by the operating body can be determined as $Q_m = \rho\ g\ Q$ then the load portion Δm, coming down from one blade per its revolution is determined according to the following dependence:

$$\Delta m = 2\pi \cdot \rho \cdot g \cdot Q \cdot \omega^{-1} \tag{2}$$

Power parameters of the new screw conveyor, in particular the torque T, on its shaft can be determined through the impact force acting on the working surfaces of its blades. Thus, such an impact force F, applied to the second blade can be determined through the impact momentum of the angular momentum theorem (*Gevko and Rogatynsky, 1989*):

$$\bar{F} = \Delta m \cdot \left(\bar{V}_{+} - \bar{V}_{-}\right) \cdot \left(\Delta t\right)^{-1} \tag{3}$$

where:

$\tilde{V}_{-}$ and $\tilde{V}_{+}$ – averaged velocity vectors of the array before and after contact with the operational surface; Δt – material contact time with the operational surface.

From the analysis (3) it follows that t is the value of the force F, and therefore, the energy loss for contact and friction of the load will be minimal at $\tilde{V}_{+}$-$\tilde{V}_{-} \rightarrow min$. In addition, the minimum energy loss on the acceleration of the material by the operating body, is determined by the dependence:

$$W_k = \Delta m \cdot \left(V_{+}^{2} - V_{-}^{2}\right) \cdot 2^{-1} \tag{4}$$

In this case, the power spent on overloading the cargo can be determined by a relationship similar to (1):

$$N = \rho \cdot g \cdot Q \cdot W_f \cdot L \tag{5}$$

where:

L – the length of the overload zone given; W_f – overload loss coefficient, exceeding the specific loss coefficient of the conveyor W.

Depending on the design $W_f = (1.2...1.5)$.

The value of torque on the drive shaft of the conveyor with a bladed operating body can be determined by the following dependence:

$$T = N \cdot \omega^{-1} = 9554 \cdot \rho \cdot g \cdot Q \cdot W_f \cdot L \cdot n^{-1} \tag{6}$$

where: n and ω – rotational speed and angular velocity of the screw conveyor drive shaft.

To determine the effect of transportation parameters of bulk material and design parameters of the conveyor on the value of the torque T, a full-factor experiment was conducted *FFE* – 3^3, i.e. determination of the torque dependence on the change of three main factors: the inner diameter of the fixed casing D, conveyor fill factor ψ and the rotation speed of the operating body n.

Since during the experiments the variable independent factors are heterogeneous and have different units, and the numbers expressing the value of these factors are of different orders, they were reduced to a single system of calculations by switching from actual values to coded values presented in Table 1.

Table 1

Setting the coefficients that determine the efficiency of the improved screw coveyor in the form of codes in a multifactorial experiment, as well as the levels of their variation when determining the torque on the drive shaft

Factors	Identification		Variation interval	Levels of variation, natural/coded		
	Coded	Natural				
Inner diameter of the fixed conveyor hood *D*, m	X_1	X_1	0.02	0.06/–1	0.08/0	0.1/+1
Conveyor fill factor, ψ	X_2	X_2	0.2	0.3/–1	0.5/0	0.7/+1
Rotation frequency of the bladed body, *n*, rpm	X_3	X_3	200	200/–1	400/0	600/+1

The experimental investigations, conducted in the laboratory conditions, made it possible to determine the specific values of torque T from the main design and kinematic parameters that characterize the process of screw transportation of the bulk materials.

These parameters are:

– internal diameter of the fixed housing D, coded by the index x_1;

– filling factor of the screw conveyor ψ, coded by the index x_2;

– the speed of rotation of the screw conveyor, designated as its rotation frequency, n and can be designated by code x_3.

Experimental studies to determine the value of torque T of a conveyor with a bladed operating body were carried out during the transportation of wheat with a bulk weight of 760 kg·m^{-3} and humidity W, 12 to 15%, which made it possible to construct analytical regression equations.

The obtained results of the laboratory experimental study were processed by means of modern statistical methods, using a PC. Besides, mainly the regression and correlation analysis methods were used. The purpose of such processing of the results was to obtain regression equations reflecting the dependencies between all the parameters studied.

For these purposes a plan was drawn up of a full-factorial experiment, allowing for the regression model to be created and the optimization parameter to be selected. The plan was carried out in the following sequence.

The response functions (the optimization parameter), i.e. the torque $T=f(D,\ \psi,\ n)$, which was determined as a result of the experiment, can be represented as a complete square polynomial, for there is every reason to consider a mathematical model of the process under study. It should be pointed out that its structure may be similar to the structures of other three-factor experiments:

$$T = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 \qquad (7)$$

where: $b_0, b_1, b_2, b_3, b_{12}, b_{13}, b_{23}, b_{11}, b_{22}, b_{33}$ – coefficients of corresponding values x_i; x_1; x_2; x_3 – relevant coding factors.

The regression equation for determining the value of the maximum torque during transportation of wheat on the experimental unit is as follows:

$$T = 2.35 + 129.5 \cdot D + 21.7 \cdot \psi + 0.00924 \cdot n - 0.0675 \cdot D \cdot n - 0.000008 \cdot n^2 - 12 \cdot \psi^2 . \qquad (8)$$

The resulting regression equation (8) can be used to determine the value of torque T during transportation by a conveyor with a bladed operating body, depending on the diameter of the fixed housing D, coefficient ψ of conveyor filling and frequency n of the rotation of the bladed implement during the transport of wheat within the following limits of input factors: $0.06 \leq D \leq 0.1$ (m); $0.3 \leq \psi \leq 0.7$; $200 \leq n \leq 600$ (rpm).

RESULTS

To determine the torque value theoretically T of the conveyor take the following initial data: the conveyor filling factor ψ - 0.5, bulk weight of wheat ρ - 760 kg·m^{-3}, bulk weight of peas ρ - 700 kg·m^{-3}, bulk weight of corn ρ - 800 kg·m^{-3}, bulk weight of fodder ρ - 250 kg·m^{-3}, outer radius of the bladed operating body R - 0.05 m, radius of the shaft on which the blades are fixed r - 0.023 m, rotational speed of the bladed operating body, n - 200-600 rpm, the length of the overload zone is given L - 1.4 m, overload loss factor W_f - 1.44.

Results of analytical torque determination T on the drive shaft of a screw conveyor with a bladed operating body are shown in Fig. 3.

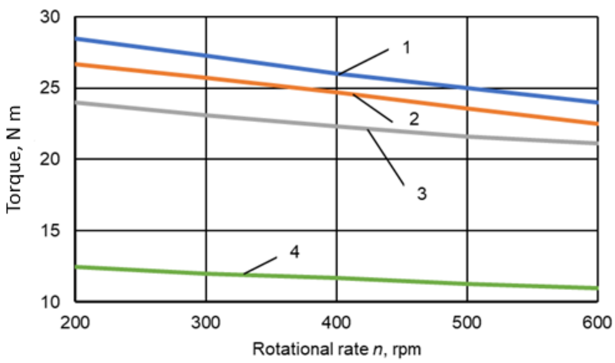

Fig. 3 – Torque dependencies *T* on the drive shaft of a screw conveyor with a bladed operating body from its speed n for the conveyor fill factor ψ = 0.5 during transportation:
1 – corn; 2 – peas; 3 – wheat; 4 – fodder

The analysis of the graphical dependencies shown in Fig. 3 shows that the torque T on the drive shaft of a screw conveyor with a bladed operating body, when transporting grain material with a conveyor filling factor ψ - 0.5, at a speed limit n of the impeller, varying between 200-600 rpm tends to decrease. And this reduction occurs linearly. At the same time, the torque T during transportation of corn varies within 28.73 to 23.92 N·m. In the investigated range of torque values received, the specified reduction is 16.8%. When transporting peas, the torque T decreases within 26.84 to 22.63 N·m, which corresponds to a reduction equal to 15.7%. When transporting wheat, the torque T varies between 24.32 to 20.54 N·m. This torque reduction is 15.5%. And when transporting mixed fodder, the torque T varies within the range of 12.42 to 10.87 N·m. Thus, in this case its reduction is 12.5%.

According to the results of laboratory experimental studies to determine the torque T on the drive shaft of a screw conveyor with a bladed operating body using the application program "STATISTICA 10" graphically reproduced the intermediate general regression models in the form of quadratic responses and their two-dimensional sections of the torque value as a function of two variable factors $x_{i(1,2)}$ a constant level of the corresponding third factor $x_{i(3)}=const$ (Fig. 4).

Analysis of the above regression equation shows that the main factors influencing the increase in the value of torque T are: the diameter of the fixed housing $x_1(D)$ the conveyor fill factor $x_2(\psi)$, the factor value increase $x_3(n)$. The rotation speed of the bladed operating body leads to a decrease in torque.

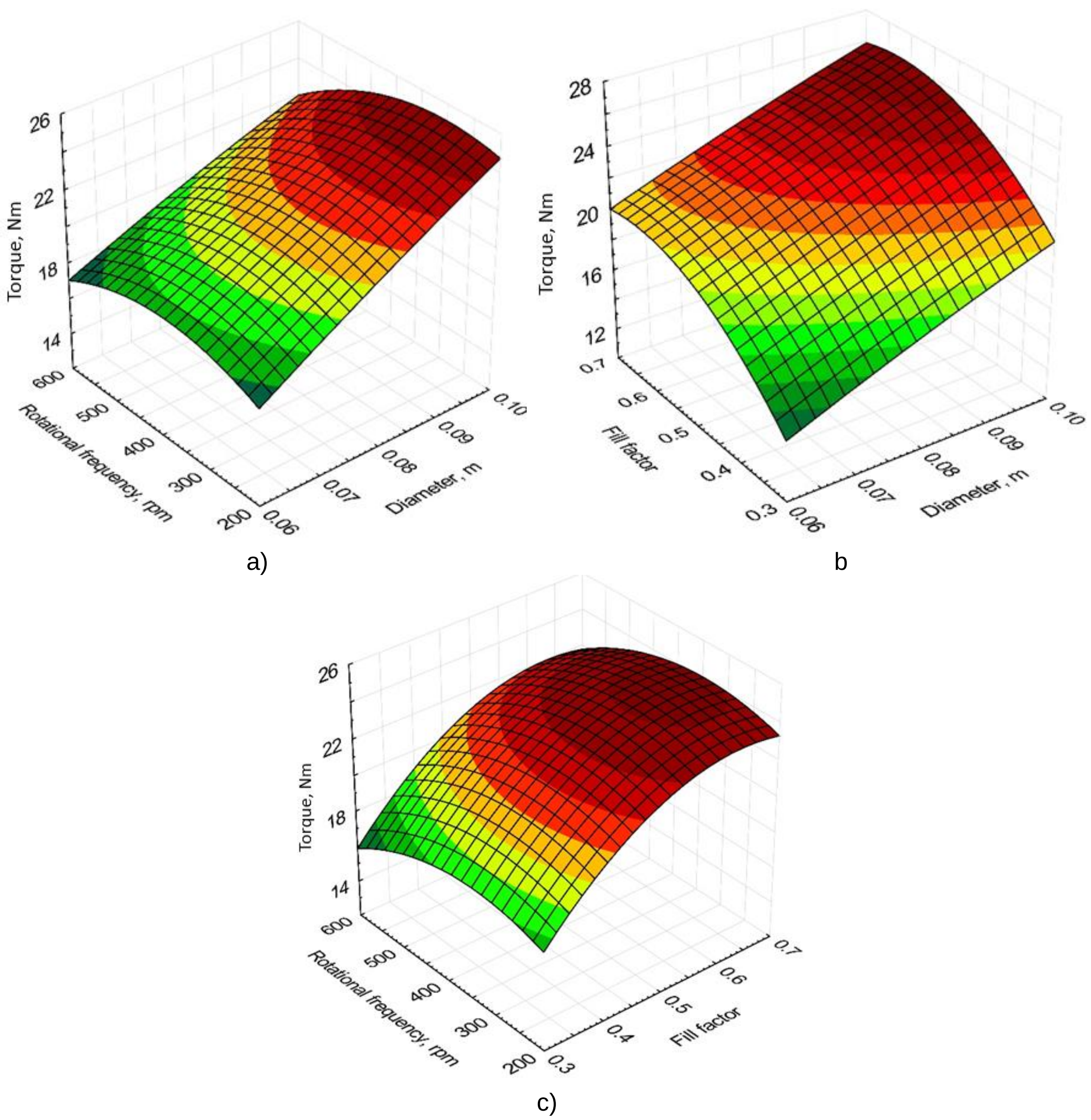

Fig. 4 – Response surfaces of the torque value *T* on the drive shaft of a screw conveyor with a bladed operating body during the transportation of wheat

If the diameter D varies within the range 0.06-0.1 m, the torque T increases by 17.9%, if the conveyor fill factor ψ increases from 0.3 to 0.7 m, the torque T increases by 17.4%, and when changing the rotational speed n of the bladed operating body within the range of 200-600 rpm, the torque T decreases by 4.9%.

A comparison of the results of theoretical and experimental studies has shown that with $n = 400$ rpm, $\psi = 0.5$ and different values of D in the range of 0.06-0.1 m the discrepancy of the obtained values of the torque T is 4.8...15.7%.

As shown by the studies done by *Lyashuk et al., 2018; Pylypaka, et al., 2019; Bulgakov, et al., 2022b; Pastushenko et al., 2021; Bulgakov, et al., 2024*), the values of the torque T of the conveyor with a bladed operating body are almost equal to the values of the torque of the conveyor with a screw operating body when transporting similar bulk solids (error not more than 5%).

Thus, the improved screw working element is a perspective transporting working element, used in agriculture, precisely due to the simplicity of its manufacture. In addition, it has been established that the use of curved blades, attached to the drive shaft instead of a solid spiral, does not lead to a reduction in the transportation capabilities of this working element.

In figure 4 are shown the response surfaces of the magnitude of torque T on the drive shaft of a screw conveyor, using flat curved blades instead of a solid spiral winding during the transportation of wheat depending on: a) $T = f(D; n)$; b) $T = f(D; \psi)$; c) $T = f(\psi; n)$.

Thus, the results of the conducted laboratory experimental studies give every reason to believe that the improved screw conveying working element has undoubted advantages in terms of the power parameters, in comparison with similar working elements. However, if it is taken into account that the production of an improved working element, formed by flat curved blades, obtained by stamping, will be significantly cheaper than the production of similar elements with continuous spiral winding, then its use will be more than efficient.

CONCLUSIONS

Based on the analysis of literary sources and patent search of preliminary exploratory studies, an improved design of a screw working element was developed and manufactured, in which, instead of a solid spiral winding, flat curved blades of small sizes are welded to the drive shaft, which, as a whole, make up a spiral winding. To study the power parameters of the improved screw working element, an experimental setup was created, which made it possible to determine the torque on the drive shaft during the transportation of the bulk agricultural materials.

The analytical dependence for determining the value of the torque on the drive shaft of the conveyor with a bladed operating body was obtained. The analysis of the obtained dependence shows that the torque on the drive shaft of the conveyor with a bladed operating body when transporting grain material tends to decrease with increasing speed. Thus, for the conveyor fill factor ψ - 0.5, within the rotational speed n of the bladed operating body, varying between 200-600 rpm tends to decrease. And this reduction occurs linearly. At the same time, the torque T during transportation of corn varies within 28.73-23.92 N·m. In the investigated range of torque values received, the specified reduction is 16.8%. When transporting peas, the torque T decreases within 26.84 to 22.63 N·m, which corresponds to a reduction equal to 15.7%. When transporting wheat, the torque T varies between 24.32 to 20.54 N·m. This reduction equals 15.5%. And when transporting mixed fodder, the torque T varies within the range of 12.42 to 10.87 N·m in such a way that its decrease is 12.5%.

According to the results of experimental studies, the corresponding regression equation for the response surface to establish the effect on the value of torque of controllable factors was built. Analysis of the above regression equation shows that the main factors influencing the increase in torque value T are the following factors: the diameter of the fixed housing $x_1(D)$ and the conveyor fill factor $x_2(\psi)$. However, an increase in the value of the factor $x_3(n)$, i.e., the rotation speed of the vane working body leads to a decrease in the torque value.

When changing the diameter *D* of the cylindrical shell within 0.06 to 0.1 m the torque *T* increases by 17.9%, the change in the *ψ*-loading ratio of the conveyor from 0.3 to 0.7 m the change of torque *T* increases by 17.4%, a when changing the rotational speed n of the bladed operating body within the range of 200-600 rpm, the torque decreases only by 4.9%.

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