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The Method of Calculating the Maximum Torque When Jamming the Auger of the Screw Conveyor

Abstract. The designs of screw conveyors contain safety clutches that ensure the avoidance of breakdowns in emergencies (e.g., when the auger is jammed). Therefore, the choice of these clutches is a relevant scientific problem, which is related to the calculation of the maximum torque of the auger. The purpose of this study was to develop a method for calculating the maximum torque when the auger of a screw conveyor is jammed. The method developed in this paper article is based on the use of an artificial neural network trained using the "supervised learning" technology. The training and test data set for the artificial neural network was obtained by conducting machine experiments, each of which consisted in the numerical integration of a nonlinear differential equation and the determination of the value of the maximum torque in the elastic connection of the dynamic system based on the obtained solution. The specified differential equation is obtained based on the equation of motion of the non-jammed part of the conveyor (drive, gears, clutch) and the Kloss equation, which corresponds to the model of the mechanical characteristics of the conveyor asynchronous motor. The statistical significance of the results of an artificial neural network was proved by analysing the values of approximation quality indicators. A brief analysis of the influence of the stiffness of the elastic connection of the dynamic conveyor system and the drive gear ratio, as well as the overloading capacity of the engine on the maximum torque that occurs when the screw is jammed, was performed. The practical significance of the results obtained is related to the software implementation of the method, which allows engineers to effectively select safety clutches upon designing screw conveyors

Keywords: mathematical modelling, approximation, numerical experiments, artificial neural network

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INTRODUCTION

Screw conveyors are widely used in modern agricultural and industrial production. This is explained by their high performance, reliability, ease of operation, etc. During the operation of such machines, emergencies may occur that are caused by the jamming of hard particles (cargo, pebbles, etc.) in the gap between the auger edge and the conveyor trough. This case causes the auger to jam and the safety clutch to trigger. Therefore, the correct choice of such a clutch at the stage of conveyor calculations allows avoiding premature failure of the conveyor engine. The main parameter that determines the choice of a particular safety clutch is the maximum torque that it can transmit. Exceeding this torque leads to disconnection of the kinematic connection between the clutch halves and makes it impossible for mechanical gears and the conveyor drive motor to fail.

The calculation of the clutch torque limit value should reflect the main dynamic parameters of the conveyor and its drive parameters. Well-known engineering methods of such calculations only approximately allow considering these factors, which can lead to incorrect choice of the safety clutch. Thus, this issue transcends engineering calculations and is the subject of scientific research. The result of such a study is a scientifically sound method for calculating the maximum drive torque of a screw conveyor when the auger is jammed, which allows considering all significant factors affecting the amount of torque.

To establish the current level of technological developments in the field of designing individual elements of screw conveyors, the website of the German patent office was used [1]. Using this resource, data was obtained on the number of received patents in the world under International Patent Classification (IPC) B65G33/24 "Screw or rotating spiral conveyors. Details", B65G33/34 "Screw or rotating spiral conveyors. Details. Drives". The received data is valid as of 04/16/2022 (Table 1).

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Table 1. Number of patents received in the world by individual classes

Class	Years				
	2018	2019	2020	2021	2022
B65G33/24	856	891	1579	2098	585
B65G33/34	199	272	617	698	138

Source: compiled by the author based on [1]

Analysis of data from Table 1 suggests a substantial increase in the number of patents for both classes since 2020. This trend continued in subsequent years. Admittedly, this reflects the interest of conveyors developers in improving their designs. Certain improvements to screw conveyors should be scientifically sound. Therefore, this study analysed the content of scientific publications related to the design and operation of these machines.

In [2], a model of a screw conveyor is investigated and the influence of the size of a discrete load particle, external and internal friction forces on the main operational and technical parameters of the conveyor was established. The paper also confirms theoretical results by comparing them with experimental data obtained in the laboratory.

In [3], the design of a vertical conveyor screw with a variable diameter was proposed. As shown in this study, this allows increasing the capacity of the conveyor. A common feature of research in [2; 3] is the use of bulk medium models based on the discrete element method.

The study [4] presents a model of a screw conveyor developed in the ANSYS software environment. This research allowed establishing the influence of conveyor parameters on screw vibrations in the vertical and horizontal directions. The results of this study allow avoiding resonant phenomena during the operation of these machines.

Fuzzy logic was used to establish relationships between the technical and operational characteristics of screw conveyors and their parameters in [5]. Here, a rule base was constructed, and a complex functional dependence was obtained on its basis, which allowed obtaining two sets of optimal values for the speed of rotation of the screw, its pitch and the angle of inclination of the conveyor. For the first case, the volumetric capacity of the machine is maximum, and for the second – its energy efficiency.

Thus, the issue of calculating dynamic processes that take place in a screw conveyor is quite an extensive and urgent task. Solving certain aspects of this issue will contribute to more advanced screw conveyor designs. This particularly refers to the problem of determining the maximum value of the conveyor screw torque, since it has a substantial impact on the choice of the safety clutch of its drive.

The purpose of this study was to develop a method for calculating the maximum torque when jamming a screw conveyor auger. Fulfilling this purpose required to solve the following tasks: 1) conduct mathematical modelling of the process of jamming the conveyor auger; 2) conduct numerical experiments and obtain a tabulated function of the maximum torque of the screw conveyor when it is jammed; 3) based on the tabulated function, to train an artificial neural network and prove the statistical significance of the results of its work; 4) assess the influence of individual factors on the value of the maximum torque when the auger of the screw conveyor is jammed and indicate the prospects for further research in this area

MATERIALS AND METHODS

To illustrate the essence of the problem considered in this study, a kinematic diagram of the conveyor is presented below (Fig. 1). It corresponds to typical designs of belt-driven screw conveyors [6-8].

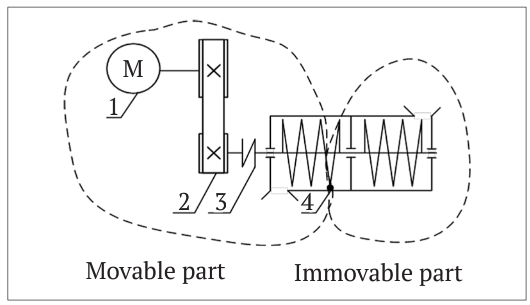

Figure 1. Kinematic scheme of a screw conveyor with a jammed auger

In Figure 1 the following designations are used: 1 – motor; 2 – belt drive (the most elastic element of the drive); 3 – safety clutch; 4 – place of jamming of the conveyor auger. Based on Figure 1, a dynamic model of the movement of a screw conveyor with a jammed auger was developed. For this purpose, the inertial, elastic, and dissipative properties of the dynamic conveyor system, as well as the mechanical characteristics of its drive, were considered (Fig. 2), and when constructing the model, methods of machine dynamics were used [9].

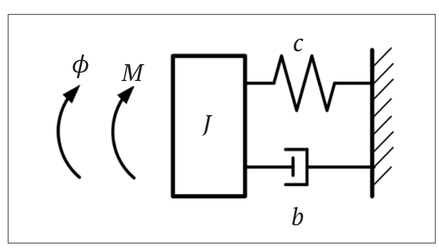

Figure 2. Dynamic model of screw conveyor movement when the auger is jammed: *M* is the driving torque of the drive; *J* is the reduced moment of inertia of the drive; *b* is the reduced drive dissipation factor; *c* is the reduced drive stiffness coefficient (in the case under study – of the belt drive

In Figure 2, all values are reduced to the auger shaft of the elastic connection of the drive.

When constructing a dynamic model, the following assumptions were used: 1) the part of the auger that continues to move after jamming (from position 3 to 4 in Fig. 1), has an insignificant moment of inertia in comparison with the moment of inertia of the drive, and therefore it is not considered; 2) the part of the auger that continues to move after jamming is an absolutely rigid body; 3) there is no dissipation in the part of the auger that continues to move after jamming.

A mathematical model that corresponds to a dynamic model (Fig. 2), is represented by a second-order differential equation (1):

$$M = J\ddot{\phi} + b\dot{\phi} + c\phi. \qquad (1)$$

Driving torque M is created by an asynchronous motor, the mechanical characteristic of which is described by the Kloss equation [10] (2):

$$M = \frac{2\lambda M_n U\eta}{A\dot{\phi} + (A\dot{\phi})^{-1}}, \qquad (2)$$

where A is the constant coefficient, the value of which is determined by the drive parameters

($A = \dfrac{60 f_n U}{p\left(\frac{60 f_n}{p} - n_n\right)\left(1 + \lambda\sqrt{\lambda^2 - 1}\right)}$); f_n is the rated frequency of the motor supply voltage (f_n=50 Hz); n_n is the rated engine speed, rpm; λ is the engine overload capacity; p is the number of pairs of motor poles; U s the drive gear ratio; η is the drive efficiency.

Substituting (2) in (1) allows obtaining a nonlinear differential equation that cannot be integrated analytically. Therefore, to determine the solution, it is necessary to apply one of the numerical methods [11]. For this, one needs to set the initial conditions for the system's movement. Since this study considered the case when auger jamming occurs when the conveyor is operating in the nominal mode, it is obvious that the elastic connection of the drive c is loaded with the torque of resistance M_0, i.e., $\phi(0)=M_0/s$. To find the angular velocity of the system, it is necessary to substitute M_0 in equation (2) instead of M and solve the resulting quadratic equation with respect to $\dot{\phi}$. To simplify calculations, it was assumed that the torque of resistance M_0 corresponds to the rated engine torque $M_0 = M_n U\eta = \frac{30 P_n}{\pi n_n} U\eta$, i.e., the conveyor drive operates in the nominal mode before it gets jammed. From the two roots of the quadratic equation, the authors chose the one that corresponded to the drive motion in the first quadrant of the mechanical characteristic:

$$\dot{\phi}(0) = \frac{\pi}{30 p P_n U^3}\Big(n_n p\big(P_n U^2 \eta\lambda(1 + \lambda\sqrt{\lambda^2 - 1}) + \\ + \frac{P_n U^2}{n_n p}(n_n p - 60f)\sqrt{(\eta^2\lambda^2 - 1)\left(1 - \lambda^2 + \lambda^4 + 2\lambda\sqrt{\lambda^2 - 1}\right)}\big) - \\ - 60 f P_n U^2\big(\eta\lambda(1 + \lambda\sqrt{\lambda^2 - 1}) - 1\big)\Big) \qquad (3)$$

Thus, having found the initial conditions of motion of the system and having the equations of its motion (1), (2), a solution of the equation can be obtained for certain numerical values of system parameters (n_n, P_n, λ, U, c). In this study, it was also assumed that b=0 because, as will be shown later, the duration of the increase in torque to the maximum value during jamming is so insignificant that the influence of dissipative forces can be ignored.

For numerical integration of the nonlinear differential equation (1), a condition was used that sets the moment when the integration stops. This condition corresponds to the zero angular velocity of the dynamic system.

Figure 3 shows the results of integration of equations (1), (2) for the following parameters: n_n=720 rpm, P_n=2.2 kW, λ=2.2, U=10, c=10 kNm/rad. As Figure 3 demonstrates, the duration of the conveyor stop is 0.0283 seconds.

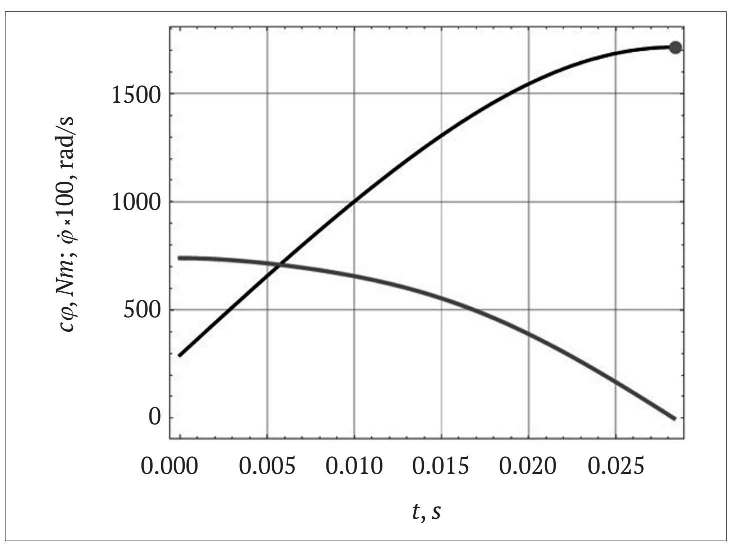

Figure 3. Graphs of changes in the elastic torque and angular velocity of a dynamic system

When the system stops, there is a rapid increase in the elastic torque. To exclude the failure of the mechanical elements of the drive caused by the action of this torque, it is necessary to choose the right safety clutch. However, its definition by numerical integration is irrational. This is explained by the need to attract considerable computational resources, which are spent on direct numerical integration of the corresponding differential equation, tabbing the elastic torque function, and then determining its maximum value $M_{c.max}$ (indicated in Fig. 3 with a grey dot). Therefore, it is advisable to obtain a tabulated function of the maximum values of the elastic torque whose arguments are the parameters n_n, P_n, λ, U, c. In the future, using one of the known approximation methods, one needs to get the function $M_{c.\max}=f(n_n, P_n, \lambda, U, c)$.

Thus, building a tabulated function Mc.max is factually a machine experiment. Therewith, the limits of changes in independent factors n_n, P_n, λ, U, c were selected from the conditions of coverage of screw conveyor structures, which are most often found in practice (Table 2).

Table 2. Independent factors of machine experiment and their levels

Independent factor	Unit of measurement	Value
n_n	rpm	720, 900, 1,400, 2,850
P_n	kW	0.75, 1.1, 1.5, 2.2, 3.0
λ	–	1.8, 1.9, 2.0, 2.1, 2.2, 2.3, 2.4, 2.5
U	–	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21
c	kNm/rad	1, 2, 3, 4, 5, 6, 7, 8, 9, 10

The moment of inertia of the system was determined according to the expression $J=1.3J_{en}U^2$ (here J_{en} is the moment of inertia of the engine, which for various brands of engines of the AIR series is selected from the catalogue [12]; 1.3 is a coefficient that considers the inertial characteristics of other drive elements: pulleys, connecting clutches, etc.).

Consequently, 32,000 machine experiments were performed and a tabulated function Mc.max was formed. The next step in the study was to find a relationship that would be able to approximate the data obtained with a sufficient degree of accuracy. The classical approach to achieving this goal is to apply regression analysis [13]. However, it did not allow getting the desired model. To illustrate this thesis without delving into the method for calculating regression models, see Table 3, where the main results of this approach are presented (for compactness of writing, independent factors are indicated by symbols x with the corresponding indexes respective to their order).

Table 3. Results of applying regression analysis to calculate the model $M_{c.\max}=f(n_n, P_n, \lambda, U, c)$

Model	Value of the determination coefficient R^2
$A_0+\sum_{i=1}^{5}A_i x_i$	0.644
$A_0+\sum_{i=1}^{5}\sum_{j=1}^{5}A_{i.j}x_i x_j$	0.814
$A_0+\sum_{i=1}^{5}\sum_{j=1}^{5}\sum_{k=1}^{5}A_{i.j.k}x_i x_j x_k$	0.863
$A_0+\sum_{i=1}^{5}\sum_{j=1}^{5}\sum_{k=1}^{5}\sum_{q=1}^{5}A_{i.j.k.q}x_i x_j x_k x_q$	0.888

Analysis of R^2 values shows that an increase in the complexity of the regression model does not lead to a substantial improvement in the quality of the approximation. This means that none of the regression models used can qualitatively approximate the tabulated function $M_{c.max}$. Therefore, this approach should be considered ineffective for this task.

An alternative to regression analysis in approximation problems is the use of artificial neural network (ANN) technologies [14]. Based on these considerations, the authors of this study attempted to develop such an ANN that would allow obtaining a high-quality approximation of the tabulated function $M_{c.max}$. For this, the architecture of the ANN was set as follows: it has five inputs (according to the number of independent factors) and one output (value $M_{c.max}$); two hidden layers of the ANN include ten neurons each; the activation function of each neuron is a hyperbolic tangent.

According to the generally accepted approach to ANN training, the overall data sample should be normalised. In this study, the following equation (4) was used:

$$\tilde{x}_i = 2\frac{x_i - x_{i.min}}{x_{i.max} - x_{i.min}} - 1, \tag{4}$$

where $\tilde{x}_i$ is the normalised value of i^{th} independent factor that changes within [-1, 1]; $x_{i.\max}$ and $x_{i.min}$ are the maximum and minimum values of the ith independent factor. In the future, the normalised data sample should be divided into training (includes 25,645 elements) and test (includes 6,355 elements), and the individual elements of the original sample with this division are selected randomly so that the trained ANN can cover as many possible sets of parameters of screw conveyors as possible.

ANN training was performed using the ADAM method [15]. The metaeuristic methods ME-D-PSO [16] and RotRing-PSO [17] were used for the same purpose.

RESULTS AND DISCUSSION

The use of these metaeuristic methods [16; 17] leads to almost identical results. They were as follows:

– weight matrix of the first layer W_1=[{-0.11, 0.529, 0.119, 0.227, -0.073}, {-1.397, 0.434, -0.067, -0.05, 0.079}, {0.404, -0.331, 0.09, 0.128, 0.102}, {-0.063, 0.012, -0.017, -0.015, -0.616}, {0.607, 0.197, -0.009, 0.036, 0.084}, {0.126, -0.31, 0.008, 0.004, -0.391}, {0.193, -1.768, -0.019, -0.018, 0.072}, {-0.412, -2.058, -0.019, -0.01, 0.361}, {0.934, -0.288, -0.074, -0.127, 0.182}, {-1.339, -0.04, 0.035, -0.083, -0.11}];

– vector of biases of the first layer B_1=[-0.7, -0.844, 0.072, 0.051, 0.099, -0.14, 0.442, -0.346, -0.733, 0.042];

– weight matrix of the second layer W_2=[{1.517, 0.742, -0.317, -0.172, -3.434, 0.063, 0.552, 0.741, -0.178, 0.307}, {0.526, 0.432, 0.272, 0.171, 0.641, -0.086, 0.584, -0.451, 0.646, 0.336}, {-0.133, 0.034, -0.22, -0.732, 0.733, -0.575, -0.105, -0.309, 0.535, 0.223}, {-0.499, -0.921, 0.296, 0.151, -0.976, 0.502, 0.112, 0.288, -0.742, 0.195}, {0.064, -0.028, -0.257, -0.104, -0.473, 0.257, -0.011, -0.381, -0.169, 0.155}, {-0.57, 0.111, -0.017, -0.1, 0.02, -0.04, -0.456, -0.398, 0.135, -0.952}, {1.345, 2.308, -1.444, -0.673, -0.978, 0.552, -3.741, -0.366, -0.33, 1.042}, {0.047, 1.848, 0.728, 0.821, 0.291, -1.917, -0.143, -2.253, 0.492, 0.517}, {0.668, -0.566, -0.553, 0.585, -1.201, 0.082, 0.543, 0.454, -0.64, -0.266}, {-0.253, -0.536, 0.32, -0.257, -0.474, 0.408, -0.908, -0.11, 0.184, -0.628}];

– vector of biases of the second layer B_2=[-0.054, 0.13, -0.453, 0.447, -0.005, 0.155, -0.502, -0.326, 0.36, 0.008];

– weight matrix of the third layer W_3=[-0.498, 0.986, -0.517, -0.677, -0.913, -1.091, -0.836, 1.337, -0.648, -0.835];

– bias of the third layer B_3=0.103.

The presented numerical data allow reproducing the ANN in software environments (this is relevant for the practical implementation of the research results).

Thus, a trained ANN was obtained that can approximate the tabulated function $M_{c.max}$, i.e., it is a contender for the sought model $M_{c.max}=f(n_n, P_n, \lambda, U, c)$. To determine whether the resulting ANN can represent a model $M_{c.max}$=f(n_n, P_n, λ, U, c), a test sample was used to calculate several statistical indicators of approximation quality (Table 4).

Table 4. Approximation quality indicators using ANN

Statistical indicator	Unit of measurement	Value
Scope of variation	Nm	334.3
Standard deviation	Nm	23.3
Variation coefficient	%	1.7
*Determination coefficient R^2	–	0.9996

Note: *R^2 value was calculated based on a training sample

Analysis of the data from Table 4 shows a fairly high-quality approximation, which is performed using a trained ANN. To evaluate it in more detail, here is Figure 4 (index n shows the item number in the sample).

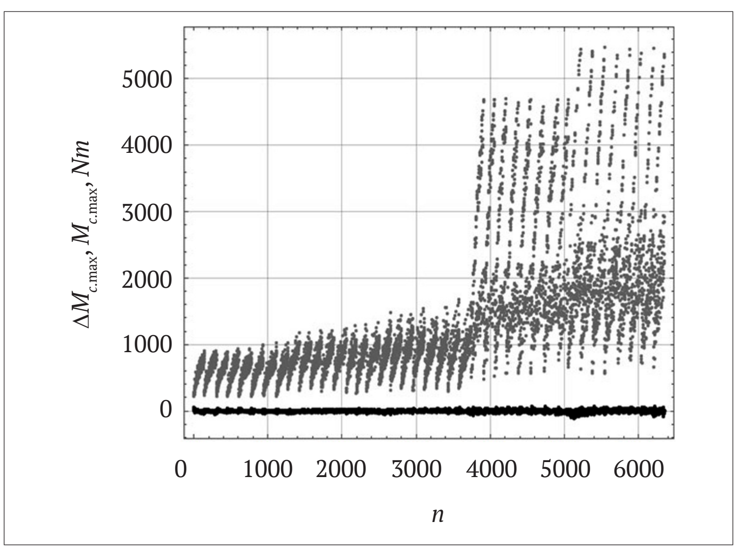

Figure 4. Test sample data (grey points) and absolute approximation error $\Delta M_{c.max}$ (black points)

From Figure 4, it is impossible to follow the dependence of the response on independent factors; however, this dependence is non-linear. This factor prevented the construction of a working regression dependence (Table 3).

Numerical values of indicators (Table 4), as well as a graphical dependency (Fig. 4) allow drawing a conclusion about the acceptability of using a trained ANN to assess the values of $M_{c.max}$. Thus, the results (trained ANN) fully correspond to the methodology for obtaining a dependency model $M_{c.max}=f(n_n, P_n, \lambda, U, c)$, which is described in the previous section.

In practical terms, estimating the value of $M_{c.max}$ must be performed using specially developed software. It can be a separate module, or it can be integrated into a common set of software products that are used by design engineers to build screw conveyors.

To present the results of the work of the trained ANN, calculations of Mc.max were performed for several variants of independent factors *c* and *U* (Fig. 5). It should be recalled that the latter considerably affects the inertial properties of the system.

Figure 5 shows equipotential lines that indicate which levels of $M_{c.max}$ they correspond to. Analysis of graphic dependences presented in Figure 5 show that their nature of change for different λ is somewhat similar. Furthermore, the graphs (Fig. 5) show the influence of *c* and *U* on the value of $M_{c.max}$: an increase in each of them leads to an increase in $M_{c.max}$. It is also worth noting the nonlinear nature of dependencies (Fig. 5).

Comparing the obtained results with those corresponding to the engineering methods of calculating the value of $M_{c.max}$ [18-20], it can be said that the discrepancy is –23.6…34.8%. Such discrepancies can be explained by the fact that engineering methods do not fully consider the dynamic parameters of the system (inertial and elastic properties of the system). Therefore, the results obtained will contribute to further improvement of engineering methods for calculating the elements of transport machines.

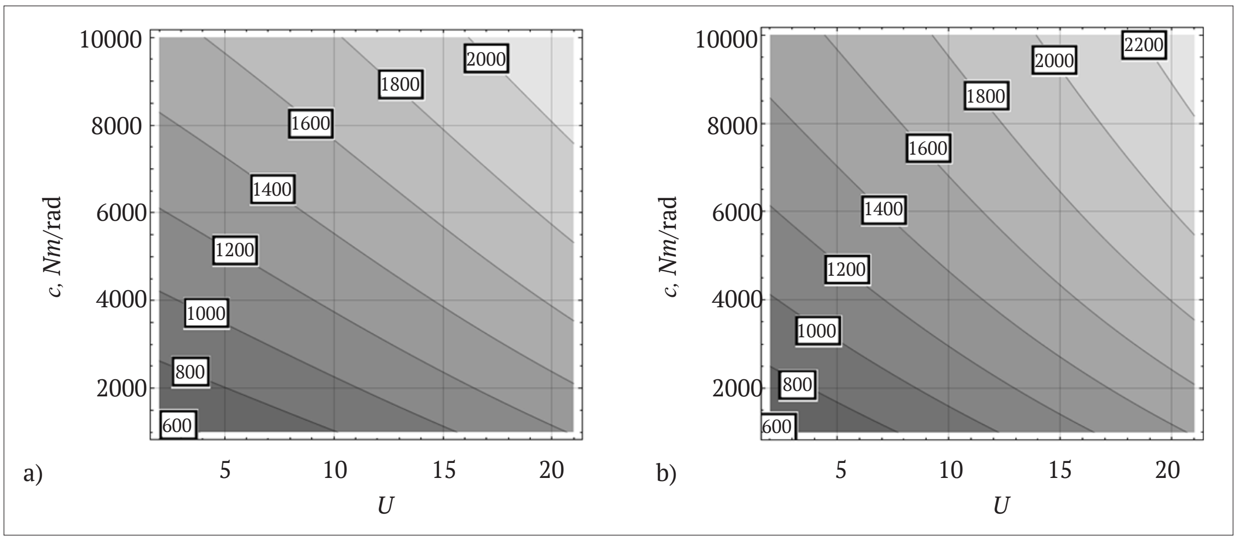

Figure 5. Graphs of dependence of $M_{c.max}$ on *c* and *U*: a) λ=1.8; b) λ=2.5

Summarising the results obtained, the purpose of this scientific study was successfully achieved. The resulting calculation method for $M_{c.max}$ is based on the ANN. The ANN was trained based on data reflecting the influence of the main factors of the transport machine and its drive on the value of $M_{c.max}$.

Returning to considerations regarding the software implementation of this method, its use will lie in entering numerical values n_n, P_n, λ, *U*, *c* in the appropriate fields of the software. Based on this data, the software should calculate the value of $M_{c.max}$ and select the appropriate safety clutch for the conveyor drive (or at least offer the user several options for clutches corresponding to the value of $M_{c.max}$).

CONCLUSIONS

1. A dynamic and corresponding mathematical model of the movement of the screw conveyor when it jams was built, which is represented by a nonlinear differential equation of the second order. The edge values of the system movement were obtained, which correspond to the operation of the conveyor in the nominal mode.

2. A series of 32,000 machine experiments was conducted, in which the nominal rotation frequency n_n and power P_n of the conveyor drive motor, the overload capacity of the motor λ, the gear ratio *U* and the combined stiffness *c* of the drive were the independent factors. The result was a tabulated function $M_{c.max}=f(n_n, P_n, \lambda, U, c)$.

3. Based on data of the tabulated function $M_{c.max}=f(n_n, P_n, \lambda, U, c)$, the ANN was trained and the statistical significance of the results of its work was proved. Furthermore, the influence of factors *c*, *U* and λ on the value of $M_{c.max}$ was briefly analysed.

4. The results obtained require validation by conducting experimental studies. If they do not fully reflect all significant factors that affect the value of $M_{c.max}$, it is necessary to include these factors in model (1) and repeat the calculations. The essence of calculations does not change. This represents the prospect of further research in this area.

5. It is proposed to implement the resulting method in the form of software that can be used in the design of screw conveyor drives.

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Метод розрахунку максимального крутного моменту при заклинюванні шнека гвинтового конвеєра

Анотація. Конструкції гвинтових конвеєрів містять запобіжні муфти, що забезпечують уникнення поломок в аварійних ситуаціях (наприклад, при заклинюванні шнека). Тому вибір цих муфт представляє собою актуальну наукову задачу, яка пов'язана із розрахунком максимального крутного моменту шнека. Метою дослідження є розробка методу розрахунку максимального крутного моменту при заклинюванні шнека гвинтового конвеєра. Розроблений у статті метод ґрунтується на використанні штучної нейронної мережі, навченої за технологією «навчання з учителем». Навчальний і тестовий набір даних для штучної нейронної мережі отримано за допомогою проведення машинних експериментів, кожен з яких полягав у чисельному інтегруванні нелінійного диференціального рівняння та визначенні на основі отриманого розв'язку значення максимального моменту у пружному зв'язку динамічної системи. Вказане диференціальне рівняння отримано на основі рівняння руху незаклиненої частини конвеєра (привод, передачі, муфта) та рівняння Клосса, що відповідає моделі механічної характеристики асинхронного двигуна конвеєра. Було доведено статистичну значимість результатів роботи штучної нейронної мережі шляхом аналізу величин показників якості апроксимації. Проведено короткий аналіз впливу жорсткості пружного зв'язку динамічної системи конвеєра та передаточного числа приводу, а також перевантажувальної здатності двигуна на максимальний момент, що виникає при заклинюванні шнека. Практична значимість отриманих результатів пов'язана із програмною реалізацією методу, яка дасть змогу інженерам ефективно проводити вибір запобіжних муфт при конструювання гвинтових конвеєрів

Ключові слова: математичне моделювання, апроксимація, машинні експерименти, штучна нейронна мережа