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Research Paper

## The Dynamics of the Working Body of the Tubular Conveyor with the Chain Drive

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**Abstract.** The theoretical calculations of the dynamics of the conveyor drive chain oscillations for different speeds of bulk material movement as a result of motion internal perturbations have been presented in the article. Resonant oscillations have been studied. It has been established that the amplitude of the transition through the resonance is greater for higher speeds of the conveyor drive chain and the maximum dynamic tension in the chain increases with increasing speed of transportation of bulk material. The dependences of the natural frequency of the system "drive chain of the conveyor line - grain" on the parameters of the system and the amplitude, as well as the amplitude of the resonant oscillations of the system on the speed of grain movement have been obtained. The dependence of the resonance amplitude of the system "conveyor chain drive - grain mass" on the speed of the drive chain at certain parameters has been determined. Taking into account the obtained theoretical data, an improved construction of a tubular chain conveyor with various working bodies and stand equipment using the Altivar 71 frequency converter for complex tasks of the electric drive from 0.75 to 630 kW has been developed. The experimental researches have been carried out and the dependences for definition of productivity and a rotation moment at transportation by the tubular scraper conveyor on curvilinear routes for loose material (wheat and peas) have been received.

**Keywords:** Tubular scraper conveyor, transportation, loose materials, conveyor performance.

### 1. Introduction

The conveyors of different types are widely used in the transportation of grain products and feed mixtures for feeding animals and poultry. The use of pneumatic screw conveyors is one of the ways to transport bulk feed mixtures. According to studies [1-3], the movement of bulk materials by such conveyors has been characterized by high mobility and productivity of the technological process. However, energy consumption in the use of pneumatic transport is several times higher than in the operation of screw conveyors, indicating their limitations when used in agricultural production, especially for small mechanization. Improving the reliability of screw conveyors screw through the combination of working with safety devices has been described in the study [4-6].

The modeling of bulk materials movement processes and establishment of optimum parameters and operating modes of screw conveyors for increasing functional and operational indicators, at their various arrangement and loading has been described in scientific researches [7-12].

Based on the analysis of literature sources and experimental results of studying the processes of transportation of bulk materials in closed actions it has been found that the vast majority of screw conveyors have limited functionality; therefore, they can be used only on short paths of material movement. To increase the conveyors' performance, the material flow movement should be intensified by means of pneumatic devices and screw and tubular conveyors.

To study the dynamic processes of machines and mechanisms based on linear computational models do not allow explaining many of the phenomena that accompany them. At the same time oscillating processes that accompany technological processes, which leads to undesirable phenomena: as deformations that ultimately reduce the durability of the mechanisms. For tubular conveyors, the drive element is a circuit that allows at the design stage to determine the spectrum of natural frequencies, select parameters and modes of operation to avoid resonant phenomena and ensure their long-term operation.

Tubular conveyors reliably and efficiently ensure the movement of a given amount of feed mixture at a certain distance at a settled time. Moreover, traditional tubular scraper conveyors that move bulk materials in guide tubes of different configurations have been characterized by limited functionality because they perform only transport functions [13-14].

Therefore, an important area of further development is the study of the dynamics of the working body of a tubular conveyor



with a chain drive that moves unevenly distributed mass (bulk material) with the speed of longitudinal movement while transporting and mixing bulk components of feed mixtures along curved paths of tubular conveyors.

### 2. Materials and Methods

The dynamic elastic properties of the ropes are significantly different from the chains. If the basic relation describing the elastic properties of the ropes with a sufficient degree of accuracy can be described by a linear or quasilinear relation [14], then for chains it is essentially nonlinear [15]:

$$\sigma = E\epsilon^{\nu_k+1} \tag{1}$$

where  $\sigma$  - tensions arising in the chain,  $\nu$  - nonlinearity parameter,  $E$  - elastic modulus. Moreover, the nonlinearity parameter  $\nu$  and elastic modulus  $E$  for different types of circuits vary accordingly within  $1,1 < \nu_k < 2,8$  ;  $1,9 \cdot 10^{11} \text{ N / m}^2 < E < 7 \cdot 10^{11} \text{ N / m}^2$  [16]. This means that for tubular conveyors that transport grain, the mathematical model of the process will have a qualitatively new look compared to the considered in the study [17-18] rope working body. This requires the chain conveyor to develop a method for analyzing the impact of a wide range of external and internal factors on the grain transportation process.

To obtain a differential equation that describes the dynamics of the transportation process, the following simplification system has been used:

- The chain to which the round scrapers are attached is considered to be a one-dimensional body, the elastic properties of which have been described by a nonlinear dependence (1);
- Barrel scrapers are connected by round elastic elements, which allow them to move concerning to the latter;
- On the horizontal and vertical parts of the scraper conveyor the displacements of the barrel-shaped scrapers relative to the drive chain are small and are neglected;
- The  $V$  speed value of the chain movement is constant;
- Grain mass between adjacent pairs of scrapers (round and barrel-shaped) is distributed according to the same laws. Its displacements relative to the drive chain are small (relative displacements of the grain and the chain are neglected);
- The resistance force of the movement of the drive chain system - "grain mass" is proportional to the speed of movement. Moreover, it is a small value compared to the maximum value of the elastic force of the chain.

Note. Pairwise arrangement of barrel-shaped and round scrapers have been used to increase the productivity of the conveyor. It is a question of grain mass movement in places of conjugation of horizontal and vertical parts of the conveyor Fig. 1.

The given calculation scheme (Fig. 1) allows for the conditionally selected element of the horizontally placed part of the conveyor length  $dx$  to write the basic ratio of dynamics [19] in the form:

$$m(x) dx \frac{d^2 u(x,t)}{dt^2} = EA \left[ \left( \frac{\partial u(x,t)}{\partial x} \right)_{x+dx}^{\nu_k+1} - \left( \frac{\partial u(x,t)}{\partial x} \right)_{x}^{\nu_k+1} \right] - R \left( \frac{\partial u(x,t)}{\partial t} \right) dx \tag{2}$$

where  $m(x)$  - law of mass distribution of the studied system drive chain - grain mass along the horizontal part of the conveyor;

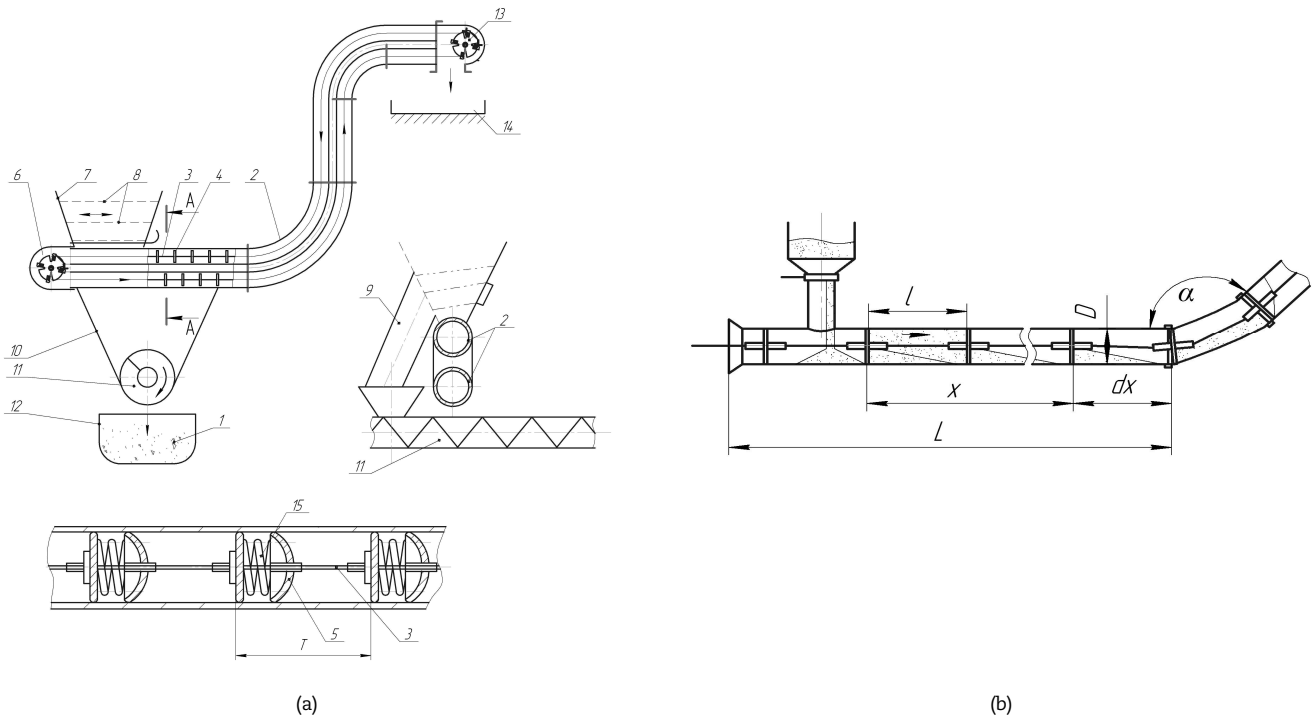


Fig. 1. The scheme of a tubular chain scraper conveyor a) the calculation scheme of the horizontal branch of the conveyor b); 1 - bulk material; 2 - S-shaped pipes; 3 - working body (chain); 4 guide scrapers; 5 - barrel-shaped scrapers; 6, 13 - special drive sprocket; 7 - loading hopper; 8 - the working body of the hopper; 9 - outlet pipe; 10 - hopper; 11 - screw working body; 12, 14 - capacity; 15 - connecting spring of scrapers.



$u(x, t)$  - the chain cross section movement with the Lagrange [19] coordinate  $x$  at an arbitrary time;  $EA(\partial u(x, t) / \partial x)_{|x}^{\nu_k+1}$  - the force acting on the left end of the selected element from the "cut off" part ( $A$  - chain cross-sectional area);  $EA(\partial u(x, t) / \partial x)_{|x+dx}^{\nu_k+1}$  - the force acting on the right end of the selected element from the "cut off" part;  $R(\partial u(x, t) / \partial t)dx$  - the equivalent resistance force acting on the selected element.

The expression in square brackets of the last ratio (increase in the function  $(\partial u(x, t) / \partial x)^{\nu_k+1}$  due to the increase in the linear variable) takes the form:

$$\left[ \left( \frac{\partial u(x, t)}{\partial x} \right)_{|x}^{\nu_k+1} - \left( \frac{\partial u(x, t)}{\partial x} \right)_{|x+dx}^{\nu_k+1} \right] = \frac{\partial}{\partial x} \left( \frac{\partial u(x, t)}{\partial x} \right)^{\nu_k+1} dx = (\nu_k + 1) \left( \frac{\partial u(x, t)}{\partial x} \right)^{\nu_k} \frac{\partial^2 u(x, t)}{\partial x^2} dx \tag{3}$$

However, the differential equation of the lower part of the drive chain-grain mass system takes the form:

$$m(x) \frac{d^2 u(x, t)}{dt^2} = (\nu_k + 1) EA \left( \frac{\partial u(x, t)}{\partial x} \right)^{\nu_k} \frac{\partial^2 u(x, t)}{\partial x^2} - R \left( \frac{\partial u(x, t)}{\partial t} \right) \tag{4}$$

Given that the drive circuit moves at a constant relative velocity  $V$  along the horizontal axis, then moving on to Euler variables [19] for which:

$$\begin{aligned} \frac{d}{dt} &= \frac{\partial}{\partial t} + v \frac{\partial}{\partial x}, \\ \frac{d^2}{dt^2} &= \frac{\partial^2}{\partial t^2} + 2v \frac{\partial^2}{\partial x \partial t} + v^2 \frac{\partial^2}{\partial x^2}. \end{aligned} \tag{5}$$

The differential equation of longitudinal oscillations of the horizontal branch of the conveyor line takes the form:

$$m(x) \left( \frac{\partial^2 u(x, t)}{\partial t^2} + 2v \frac{\partial^2 u(x, t)}{\partial x \partial t} + v^2 \frac{\partial^2 u(x, t)}{\partial x^2} \right) - (\nu_k + 1) EA \left( \frac{\partial u(x, t)}{\partial x} \right)^{\nu_k} \frac{\partial^2 u(x, t)}{\partial x^2} = -R \left( \frac{\partial u(x, t)}{\partial t} \right) \tag{6}$$

To the equation (4) boundary condition have been attached, which for a chain working element are similar to those for a rope [17] and therefore they take the form:

$$u(x, t)_{|x=0} = 0 ; u(x, t)_{|x=L} = l(1 - \cos \alpha) \tag{7}$$

where  $L$  - the length of the horizontal branch of the conveyor line,  $l$  - the distance between adjacent barrel-shaped and round scrapers,  $\alpha$  - the angle of the chain in the angular point located between the scrapers.

One of the causes of oscillations in the drive chain of the conveyor - grain mass is the perturbation of movement, which the specified system receives when passing through corner points. Given that the distance between adjacent scrapers of the conveyor in question is much larger than the diameter of the pipe of the conveyor line, the first defined limit allows to replace  $\sin \alpha$  by  $\alpha$  (the angle is measured in radians). In this case, the boundary condition at the right end of the pipe of the conveyor can be given in the form:

$$u(x, t)_{|x=L} = \left( \frac{D}{2l} \right)^2 \cos^2 \frac{v}{l} t \tag{8}$$

Note. The differential equation of longitudinal oscillations of the vertical branch of the chain conveyor also has a similar form. But with the only difference that the force of the weight of the "cut off" part is additionally applied to the conditionally selected element [17].

It has been assumed that the mass of the studied system is a continuous function of a linear variable. Moreover, it can be described as a dependence with a sufficient degree of accuracy  $m(x) = m_0 + m_1 \cos(\pi x / 2l + \varphi_0)$  ( $m_0, m_1, \varphi_0$  - constants), and  $m_0 \gg m_1$ . Taking this into consideration, it is possible to represent differential equation (4) in Euler variables in the form:

$$\frac{\partial^2 u(x, t)}{\partial t^2} - \eta^2 \left( \frac{\partial u(x, t)}{\partial x} \right)^{\nu_k} \frac{\partial^2 u(x, t)}{\partial x^2} = \mu f \left( x, \vartheta, \frac{\partial u(x, t)}{\partial t}, \frac{\partial^2 u(x, t)}{\partial t^2}, \dots, \frac{\partial^2 u(x, t)}{\partial x^2} \right), \tag{9}$$

where  $\eta^2 = EA(\nu_k + 1) / m_0$ ,  $\vartheta = \pi Vt / 2l + \varphi_0$ ,  $\mu f(x, \vartheta, \partial u(x, t) / \partial t, \partial^2 u(x, t) / \partial t^2, \dots, \partial^2 u(x, t) / \partial x^2)$ . Known function:

$$\begin{aligned} \mu f(x, \vartheta, \partial u(x, t) / \partial t, \partial^2 u(x, t) / \partial t^2, \dots, \partial^2 u(x, t) / \partial x^2) &= -m_1 \partial^2 u(x, t) / \partial t^2 \times \cos(\pi(x - vt) / 2l + \varphi_0) - m(x)(2V \partial^2 u(x, t) / \partial x \partial t + v^2 \partial^2 u(x, t) / \partial x^2) \\ &- R(\partial u / \partial t) / m_0. \end{aligned}$$

The obtained equation (9) holds under the condition  $V \ll \eta^2$ . Because exactly such case - the case of limited speed has been considered. The difference between the differential equations (6 and 9) is as follows:

- For the equation (9), the parameter  $\nu$  varies within  $-1 < \nu_k < 0$ , but for the equation (4) -  $\nu_k > 0$ ;
- For the equation (9) the boundary conditions are homogeneous, and for the equation (6) are of non-autonomous type.

However, these differences cannot be an obstacle to limit the application of the general provisions set out in the works [17] to study the dynamics of the drive chain - grain mass. First of all, it has been shown that the technique described in [20-21] can be generalized to the case of inhomogeneous boundary conditions. For this equation (9) the change of variables according to the ratio has been made:

$$u(x, t) = U(x, t) + \mu w(x, t) \tag{10}$$



It has been accepted that twice differentiated by two variables function  $w(x,t)$  is a solution of differential equation:

$$\frac{\partial^2 w(x,t)}{\partial x^2} = 0 \tag{11}$$

and satisfies the boundary conditions  $w(x,t)|_{x=0} = 0$ ,  $w(x,t)|_{x=L} = (D/2l)^2 \cos^2(vt/l)$ . Then the function  $U(x,t)$  should also be the solution of the equation:

$$\frac{\partial^2 U(x,t)}{\partial t^2} - \eta^2 \left( \frac{\partial U(x,t)}{\partial x} \right)' \frac{\partial^2 U(x,t)}{\partial x^2} = \mu \left[ f \left( x, \vartheta, \frac{\partial U}{\partial t}, \frac{\partial^2 U}{\partial t^2}, \dots, \frac{\partial^2 U}{\partial x^2} \right) - \frac{\partial^2 w}{\partial t^2} \right] \tag{12}$$

and satisfy homogeneous boundary conditions  $U(x,t)|_{x=0;L} = 0$ .

For the solution of equation (10) above inhomogeneous boundary conditions chosen:  $w(x,t) = (D/2l)^2 x \cos^2(vt/L)$ . Substituting the corresponding expression into the right-hand side  $\partial^2 w / \partial t^2$  of equation (12), the boundary value problem for the nonautonomous equation (12) under homogeneous boundary conditions has been obtained.

The main results of, which are obtained for non-autonomous equation (3) under homogeneous boundary conditions, can be used for equation (6) under similar boundary conditions. To obtain the main results that determine the oscillations of the drive chain - grain mass the following parameters have been set:

- Natural frequency of system oscillations -  $\Omega_n(a)$ :

$$\Omega_n(a) = \sqrt{\frac{EA(\nu_k + 1)}{m_0} \left( \frac{\Pi_x}{L} \right)^{\nu_k + 2} a^{\nu_k}} \tag{13}$$

- Condition of resonant oscillations existence -  $\Pi / \Omega_n(a) = \pi l / v$ .

### 3. Results and Discussion

To determine oscillations amplitude of the drive chain at a given speed of bulk material transportation, the following ratio has been given. It allows to obtain resonant oscillations of the system:

$$a_\rho = \left( \frac{\Pi v}{\pi l} \sqrt{\frac{m_0}{EA(\nu_k + 1)}} \right)^{\frac{2}{\nu_k}} \left( \frac{L}{\Pi_x} \right)^{\frac{\nu_k + 2}{\nu_k}} \tag{14}$$

The inverse dependence - the speed of grain transportation, at which (at a given amplitude of chain oscillations) occur resonant oscillations:

$$v = \sqrt{\frac{EA(\nu_k + 1)}{m_0} \left( \frac{\Pi_x}{L} \right)^{\frac{\nu_k + 2}{2}} \frac{\pi l}{\Pi} a^{\frac{\nu_k}{2}}} \tag{15}$$

Graphical representation of the dependence of the natural frequency of the drive chain of the conveyor line - grain on the parameters of the system and the amplitude has been given in Fig. 2, and the amplitude of resonant oscillations of the system from the speed of grain movement - in Fig. 3.

From the obtained results, it follows that for the drive chains of the conveyor: - with a larger value of the nonlinearity parameter  $\nu$  at a fixed amplitude, the natural frequency of oscillations is lower; - grain transportation is greater for the same chain of resonance amplitude values for higher speeds; - for chains with a larger nonlinearity parameter  $\nu$  the grain movement resonance amplitude is larger.

The amplitude of the transition through resonance has been described by relations for the case of principal resonance

$$\frac{da}{dt} = - \frac{2\beta(\nu_k + 2)^2 a}{(3\nu_k + 4)\Pi P \rho} \frac{\sqrt{\pi} \Gamma \left( \frac{3}{\nu_k + 2} \right)}{\Gamma \left( \frac{1}{2} + \frac{3}{\nu_k + 2} \right)} - \frac{\hat{H} \omega^2}{2Pa\rho\Omega(a)} \sin \vartheta, \tag{16}$$

$$\frac{d\vartheta}{dt} = \alpha a^{\frac{\nu}{2}} \frac{\Pi}{\pi} \left( \frac{\Pi_x}{L} \right)^{\frac{\nu_k + 2}{2}} - \omega - \frac{(\nu_k + 2)^2 a^{-\frac{\nu_k}{2}} V^2}{(3\nu_k + 4)\Pi_T P \alpha \left( \frac{k\Pi_x}{l} \right)^{\frac{\nu - 2}{2}} \Gamma \left( \frac{1}{2} + \frac{3}{\nu_k + 2} \right)} \frac{\sqrt{\pi} \Gamma \left( \frac{3}{\nu + 2} \right)}{\Gamma \left( \frac{1}{2} + \frac{3}{\nu_k + 2} \right)} + \frac{\check{H} \omega^2}{2Pa\rho\Omega(a)} \cos \vartheta,$$

where  $\hat{H} = \frac{1}{2\Pi} \int_0^{2\Pi} sa(1, \nu_k + 1, \psi) \sin \left( \frac{\pi}{\Pi} \psi \right) d\psi$ ,  $\check{H} = \frac{1}{2\Pi} \int_0^{2\Pi} ca(\nu_k + 1, 1, \psi) \cos \left( \frac{\pi}{\Pi} \psi \right) d\psi$ .

For some parameters values, the qualitative and quantitative picture (fig. 4) of transition through the main resonance with amplitude definition of transition through resonance has been presented.

The presented dependences show that the amplitude of the transition through resonance has been larger for: higher speeds of the conveyor drive chain that transports grain; chains  $\nu$ ; grain of its greater mass per unit length; greater distance between scrapers.



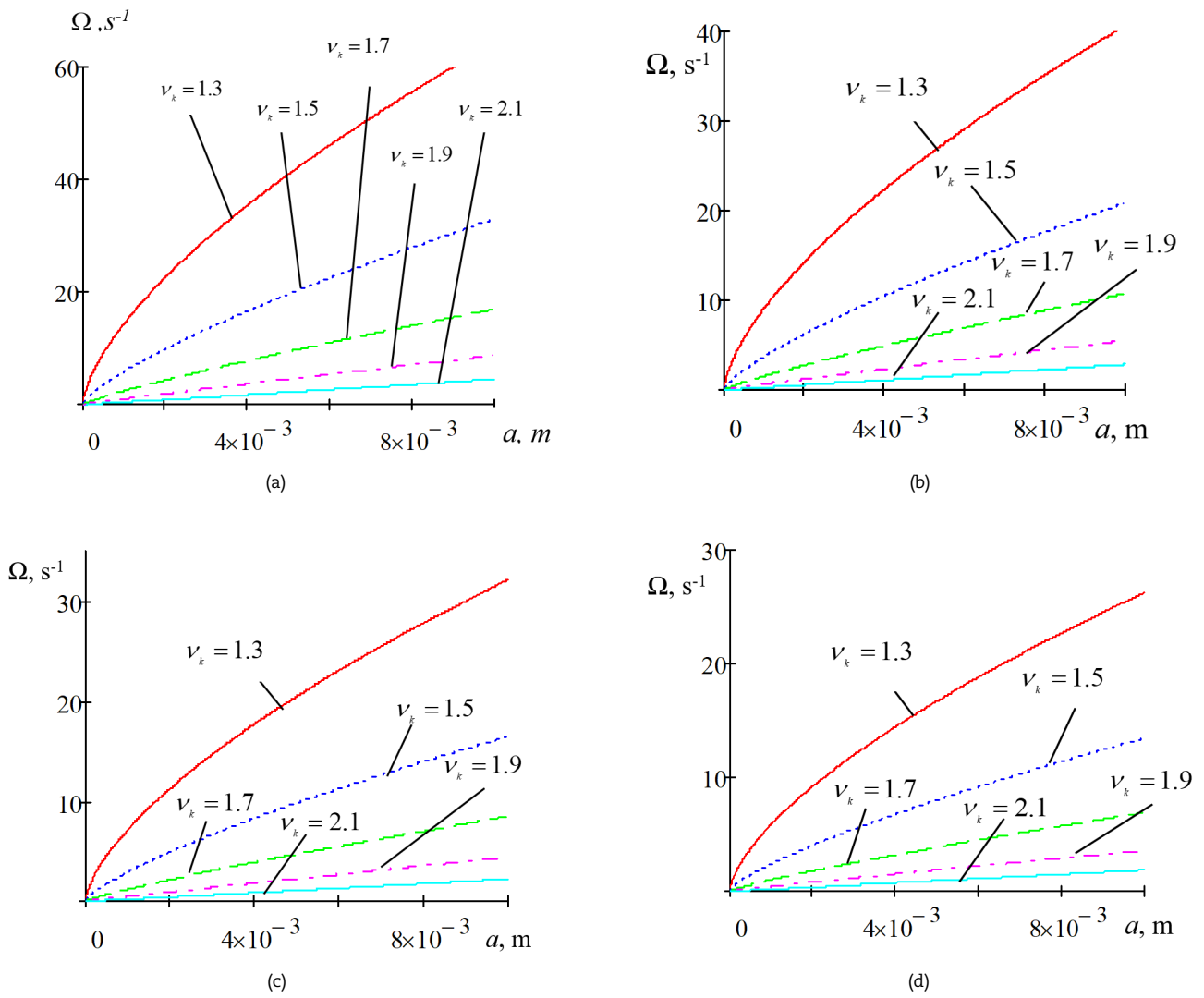


Fig. 2. The dependence of oscillations natural frequency of the conveyor chain drive - grain mass at different values of parameters and running masses a) 10 kg/m; b) 25 kg/m; c) 40 kg/m; d) 60 kg/m ( $E = 1.9 \cdot 10^{11} N / m^2; d = 0.1 m$ ).

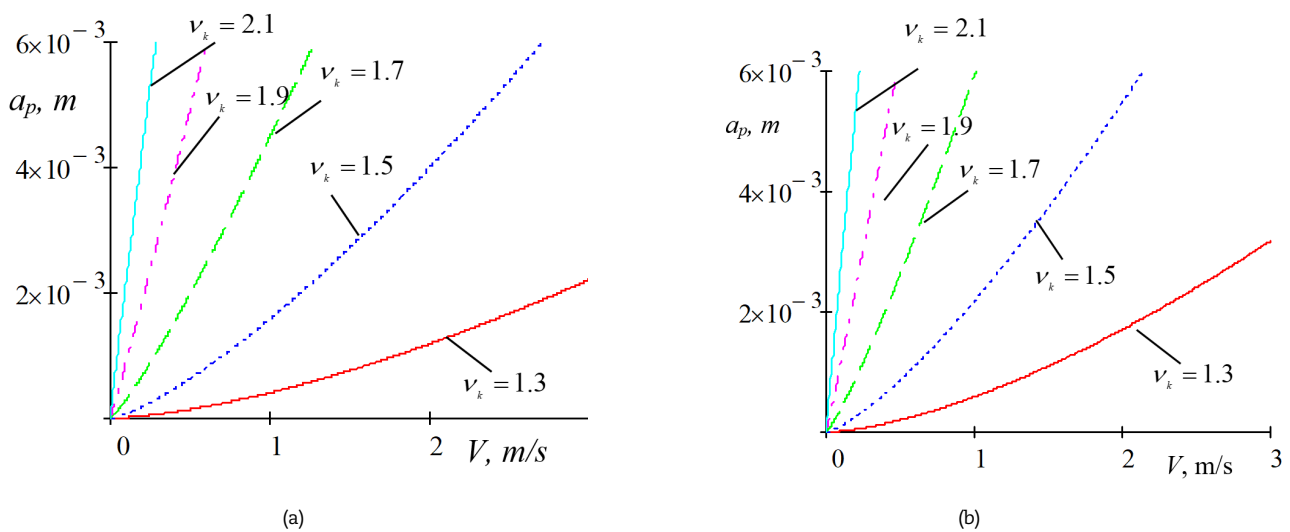
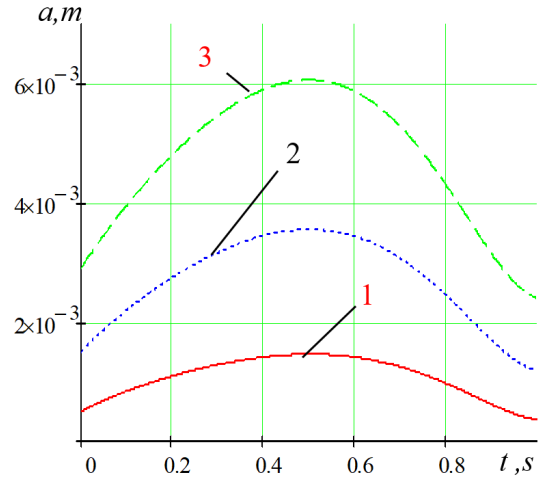
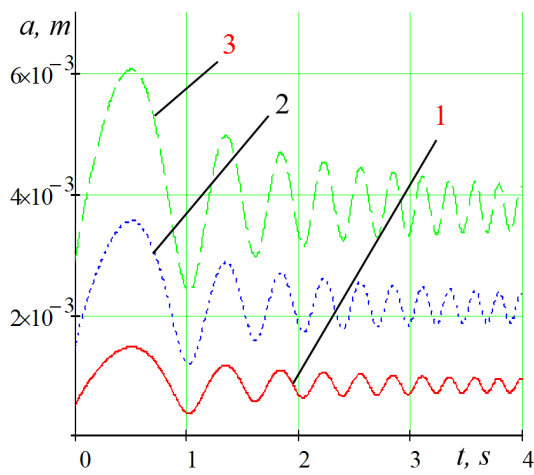
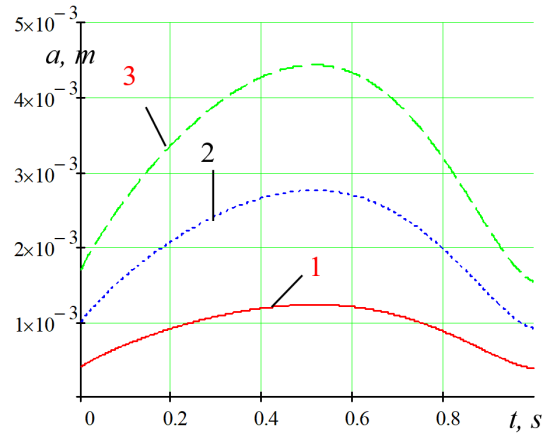
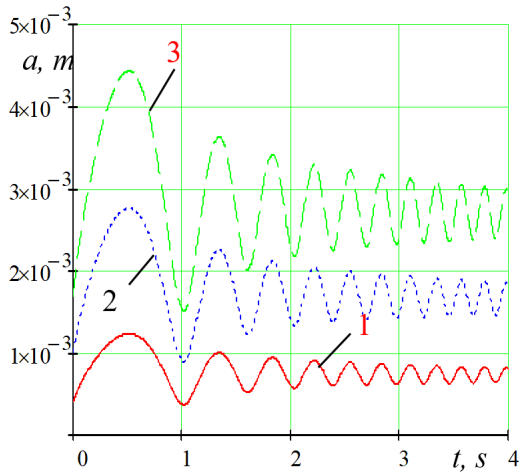


Fig. 3. The dependence of the amplitude of the resonance system of the conveyor chain drive - grain mass on the speed of the drive chain for the following parameters and running masses a) 25 kg/m; b) 40 kg/m ( $E = 1.9 \cdot 10^{11} N / m^2; d = 0.1 m$ ).

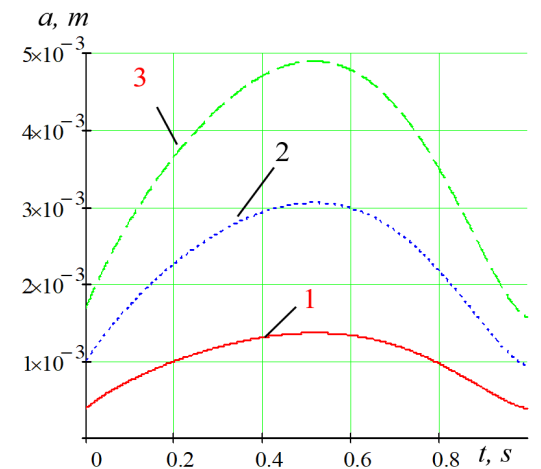
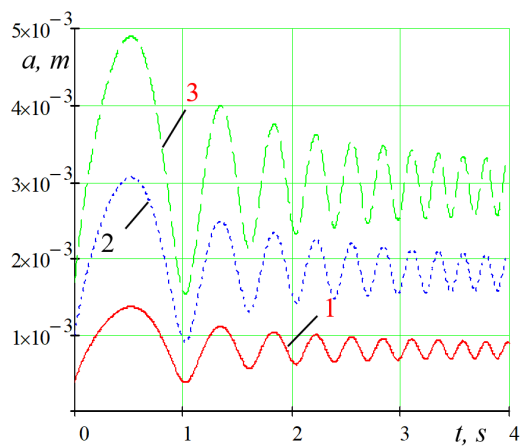




$E = 2 \cdot 10^{11} \text{ N/m}^2$ ;  $L = 20\text{m}$ ;  $m_0 = 40\text{kg/m}$ ;  $D = 0.1\text{m}$ ;  $\nu_k = 1.3$ ; 1 -  $v_1 = 1\text{ m/s}$ ; 2 -  $v_2 = 2\text{ m/s}$ ; 3 -  $v_3 = 3\text{ m/s}$ ;  
 1 -  $a_{p1} = 5.64 \cdot 10^{-4}\text{ m}$ ; 2 -  $a_{p2} = 1.638 \cdot 10^{-3}\text{ m}$ ; 3 -  $a_{p3} = 3.057 \cdot 10^{-3}\text{ m}$



$E = 2 \cdot 10^{11} \text{ N/m}^2$ ;  $m_0 = 40\text{kg/m}$ ; 1 -  $v_1 = 1\text{ m/s}$ ; 2 -  $v_2 = 2\text{ m/s}$ ; 3 -  $v_3 = 3\text{ m/s}$ ;  $l = 0.2\text{m}$   
 $\nu_k = 1.5$ ; 1 -  $a_{p1} = 4.171 \cdot 10^{-4}\text{ m}$ ; 2 -  $a_{p2} = 1.05138 \cdot 10^{-3}\text{ m}$ ; 3 -  $a_{p3} = 1.805 \cdot 10^{-3}\text{ m}$ ;  $L = 10\text{ m}$



$E = 2 \cdot 10^{11} \text{ N/m}^2$ ; 1 -  $v_1 = 1\text{ m/s}$ ; 2 -  $v_2 = 2\text{ m/s}$ ; 3 -  $v_3 = 3\text{ m/s}$ ;  $l = 0.2\text{m}$ ;  
 $\nu_k = 1.5$ ; 1 -  $a_{p1} = 4,171 \cdot 10^{-4}\text{ m}$ ; 2 -  $a_{p2} = 1,05138 \cdot 10^{-3}\text{ m}$ ; 3 -  $a_{p3} = 1.805 \cdot 10^{-3}\text{ m}$ ;  $L = 10\text{ m}$ ;  $m_0 = 60\text{kg/m}$

Fig. 4. The law of change of oscillations amplitude of the drive chain during transition through resonance at various parameters values.



## 4. Experiment Results

An experimental installation of a chain conveyor has been made for providing the experimental research [13] (Fig. 5). Practical studies that confirmed the results of theoretical data have been conducted. The experiments have been refined and carried out by installing an automated electric drive in the kinematic circuits of the stands. The stand presents a three-phase asynchronous motor, which has been controlled by a frequency converter (ALTIVAR-71 to determine the main characteristics of transportation using a frequency converter type E40S6-10Z4-6L-5 (error within  $\pm 2\%$ ).

The studies to determine the productivity of the conveyor have been carried out during the transportation of such materials with the appropriate bulk density: peas –  $700 \text{ kg/m}^3$ ; wheat –  $760 \text{ kg/m}^3$  with a moisture of  $W=10\text{...}18\%$ , which allowed to construct analytical regression equations. Scrapers made of polyamide PA-6 or PA-12 with a surface roughness of  $R_a \approx 2.5\mu\text{m}$  have been used to transport the bulk material through the metal pipe. Such scrapers are in direct contact with the seed and do not injure it,  $f = 0.20$  while the coefficient of friction-sliding on the pipe is, which creates less torque than when using metal scrapers, the coefficient of friction-sliding which reaches.  $f = 0.60$  Thus, when transporting wheat, the reduction of torque is 7% -12%, peas 3% - 5% for the range of filling factor of bulk pipe material 0.4 ... 0.8.

The results of experimental studies of productivity and torque of transportation of bulk material by tubular scraper chain conveyor have been shown in the research. On the basis of the conducted multifactor experiment productivity  $Q=f(D, K, v)$  and torque  $T=f(D, K, t_1)$ , have been determined experimentally and constructed the corresponding graphical dependences (Fig. 6-7).

After checking the adequacy of the approximating model and evaluating the significance of the coefficients of the regression equation according to the Fisher and Student criteria, the regression equation has been obtained as a function  $Q=f(D, K, v)$ ,  $T=f(D, K, t_1)$ . Numerical values of statistical indicators that characterize the obtained regression dependences for the torque: multiple determination coefficient  $D = 0.579$ , multiple correlation coefficient  $R = 0.0761$ , fisher criterion  $F = 1.750$ . These criteria describes the nature of the change in the performance of the tubular scraper conveyor and the torque, from the change of three main factors: fill factor  $K$ , the inner diameter of the pipe  $D$ , m, linear speed of transportation  $V$ , m/s and the step of the working body  $t_1$ , m.

The General view of the performance regression equation according to the results of the full factor experiment (FFE33) in the coded values is equal to:

$$Q_{\text{wheat}} = 4.181 - 54.3D - 17.69v + 66.26DK + 144.64Dv - 7.61K^2 + 15.63Kv \quad (17)$$

Maximum torque transmission values for different bulk materials on the experimental setup:

$$T_{\text{wheat}} = 19.282 - 0.638 \cdot 10^3 D + 35.52t_1 + 2.999 \cdot 10^{-3} D^2 + 0.638 \cdot 10^3 DK - 19.19K^2 - 88.76Kt_1 \quad (18)$$

Based on the conducted multifactor experiment the response surfaces have been constructed and the maximum productivity at transportation of loose materials mixes by the tubular scraper conveyor (wheat, peas) has been defined. The factor field of research is for productivity within  $0,08 \leq D \leq 0,12$  (m);  $0,4 \leq K \leq 0,8$ ;  $0,24 \leq v \leq 0,48$  (m/s), and for torque  $0,08 \leq D \leq 0,12$  (m);  $0,4 \leq K \leq 0,8$ ;  $0,1 \leq t_1 \leq 0,2$  (m).

On the basis of the conducted researches, graphic dependences have been constructed (see Fig. 6). From which it has been seen that productivity of the tubular scraper conveyor for loose material (wheat) depends on internal diameter of a pipe  $D$  and linear velocity  $v$  and from the conveyor load factor  $\psi$ . Thus, with increasing pipe diameter and speed, productivity increases and reaches  $3675 \text{ kg/h}$ . Significant sizes of pea grains fall between the surface of the scraper and the surface of the pipe to a lesser extent than during wheat transportation, so energy consumption is the highest. Because the elliptical shape of the grain, forms the so-called effect of jamming the scrapers, when part of the grains falls into the gap between the scraper and the pipe. The translational speed of the working body in this range of changes in its magnitude leads to a slight increase in productivity.



Fig. 5. General view of the experimental setup: 1 - conveyor drive; 2 - filling hopper; 3 - working body of the tubular scraper chain conveyor; 4 - drive sprocket; 5 - scraper; 6 - transport way; 7 - frequency converter; 8 - personal computer.



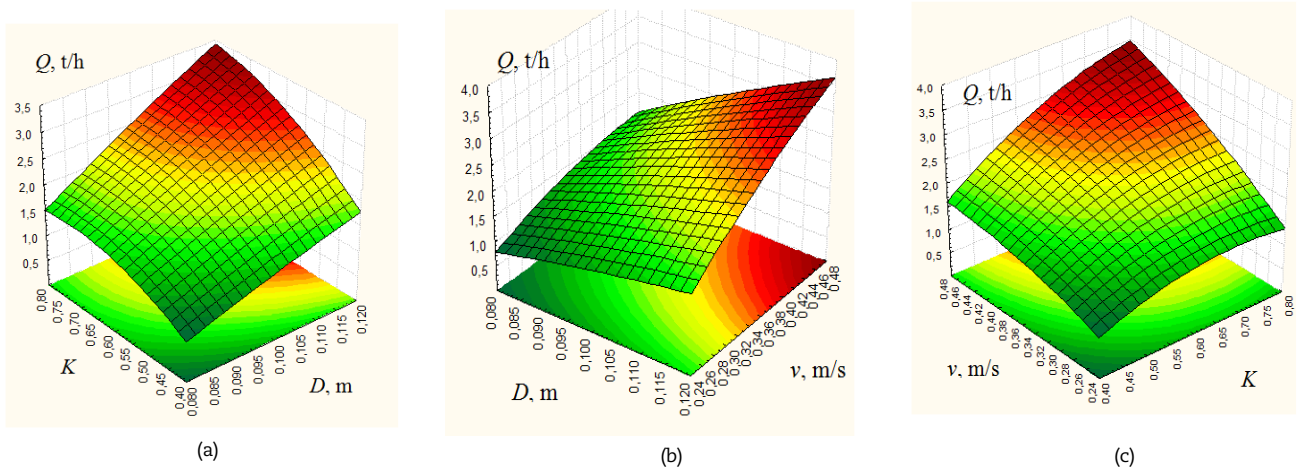


Fig. 6. The response surfaces of transportation productivity of loose material: a)  $Q_{\text{wheat}} = f(D, K)$ ; b)  $Q_{\text{wheat}} = f(v, D)$ ; c)  $Q_{\text{wheat}} = f(K, v)$ .

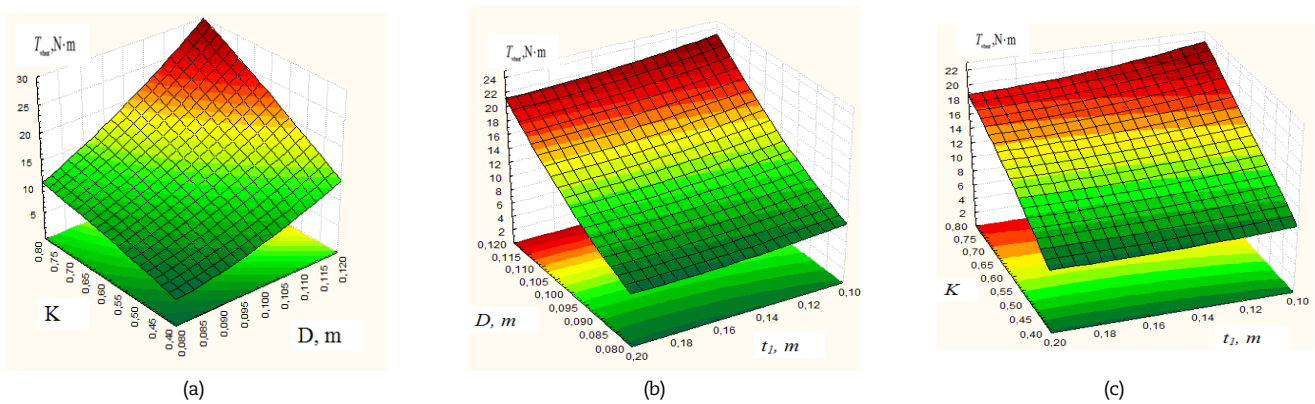


Fig. 7. The response surfaces of the torque of bulk material transportation: a)  $T_{\text{wheat}} = f(D, K)$ ; b)  $T_{\text{wheat}} = f(D, t_1)$ ; c)  $T_{\text{wheat}} = f(K, t_1)$ .

In Fig. 7, it has been shown that the factor that affects the amount of torque  $T_{\text{wheat}}$ , is the value of the inner diameter of the pipe  $D$  and the load factor of the conveyor  $\psi$ . However, the step of placing the scrapers of the working body  $t_1$ , is in the range  $t_1 = 0,1 \dots 0,2$  m, which significantly affects the value of torque  $T_{\text{wheat}}$ . From the graphical dependences it has been seen that with increasing inner diameter of the pipe  $D = 0,12$  m and the step of placing the scrapers of the working body  $t_1 = 0,15$  and the load factor of the conveyor  $\psi = 0,6$  torque is reduced for the transportation of bulk materials (peas, wheat).

### 5. Conclusion

The theoretical calculations of oscillations of the conveyor drive chain, which transports bulk material and caused internal disturbances, have been conducted. The conditions for the existence of resonant oscillations for different speeds of the bulk material movement have been established. It has been shown that the maximum dynamic tension in the chain is greater for larger values of the speed of bulk material transportation. The transportation speed increasing from 1 m/s to 2 m/s, which causes at  $\nu = 1,3$  and length of the route  $L = 20$  m increase in dynamic stress by 5.2 times, and increase in speed from 2 m/s to 3 m/s for the same parameters - 3 times. At the same time, the amplitude of oscillations of the chain that transports the grain during the transition through resonance has been smaller for smaller lengths of rectilinear branches of the conveyor. Based on the conducted multifactor experiment the response surfaces have been constructed and the maximum productivity at transportation of loose materials mixes by the tubular scraper conveyor (wheat, peas) has been determined. Moisture of material has been like  $W = 10 \dots 18$  %. For peas, the productivity has been within  $Q_{\text{peas}} = 1125 \dots 4500$  kg/h, which is 20-25% more than for wheat.

### Author Contributions

The manuscript was written through the contribution of all authors. All authors discussed the results, reviewed and approved the final version of the manuscript.

### Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship and publication of this article.

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