



*Research article*

## **Research of the work of the sieve mill of a grain-cleaning machine with a linear asynchronous drive**

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**Abstract:** This article presents the results of a study of the sieve mill of a grain cleaning machine with a drive based on a linear asynchronous motor instead of a classic mechanical drive. The purpose of this work is to describe the structural and technological parameters of a sieve mill with a linear asynchronous drive to implement a mathematical model of the technological process of a grain cleaning machine work. A kinematic study of the flat hinged mechanism of the sieve mill of a grain cleaning machine was carried out, for which all geometric dimensions are known and the laws of motion of the leading link – the electric drive of the sieve mill based on a linear asynchronous motor are determined. As a result, the following were determined: kinematic modes  $k_P > k_B > k_H$  of sieve mill vibrations under various technological conditions; laws of motion of all parts of the mechanism of the sieve mill, movement, speed (0.34 ... 0.36 m/s) and acceleration (5.8 ... 6.9 m/s<sup>2</sup>) of the driven links; a mathematical model of the kinematic scheme of a sieve mill of a grain cleaning machine with a drive from a linear induction motor has been developed. The use of a linear induction motor compared to existing (classical) drive designs as a drive of a sieve mill in a grain-cleaning machine significantly reduces the metal consumption of the structure (drive shafts, transmission mechanisms, connecting rods, bearings are excluded from the structure), and energy consumption is also reduced due to pulse drive operation; makes it possible in a wide range of technological parameters regulation for various crops, including various physical and mechanical parameters of the crop being cleaned.

**Keywords:** kinematic scheme; linear induction motor; mathematical model; sieve mill; technological process

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## 1. Introduction

Increasing the volume and improving the quality of agricultural products, reducing their cost and energy costs are closely related to the development and use of high-performance machines, the effectiveness of which is largely determined by the used electric drive [1,2]. The current trend in the development of electric drives is the reduction of resources and consumables due to the improvement and expansion of the functionality of control devices, which has become possible due to the development of technologies in power and microprocessor electronics [3].

Among technological processes in agriculture, food and mining, separation occupies a large share of labor and energy costs. At the same time, the productivity and technological efficiency of separating machines decisively affects the production capacity of enterprises, the yield of finished products and their quality [1,2].

Universal and popular are separating machines with the oscillatory movement of flat separating sieves: oscillation and vibration separators, in which separation is carried out due to gravitational forces with the action of vibrational forces that ensure the separation of particles relative to the sieve holes [4,5]. The vibrational forces are composed of the forces of forced and natural vibrations of the sieve and the kinematic drive system [4–8], therefore, the more complex the kinematic drive scheme, the more are the factors affecting the efficiency of the process, which become more and more negative as their mechanical parts wear out and become older [9–12].

In Aradwad et al. [13], the authors developed, manufactured, and tested a solar screen cleaner for separating impurities from soybean, lentil, and chickpea grains. This machine aims to provide good grain quality at an affordable cost of energy for small farmers in rural India. However, the drive of the presented machines in the works of Aradwad et al. [13], Ma et al. [6], Popov et al. [7], Shevtsov and Beznosov [8], Steponavičius et al. [5], is built on a traditional complex scheme with a converter of rotating motion into reciprocating. The complexity of the kinematic scheme of the machine's drive increases the cost of the machine, reduces energy efficiency and reliability due to the large number of rubbing and wearing surfaces and metal consumption. The metal consumption increases due to inertial flywheels designed to smooth out periodic force pulses, which is confirmed by the results of Vyngra et al. [14]. Due to the large inertia of the drive, the acceleration time of the drive also increases, which also increases energy losses, and, moreover, it is possible that the drive will not be able to accelerate to rated speed. In the work of Yarullin et al. [15], the design of a vibratory machine with widely adjustable parameters of the frequency and amplitude of oscillations using the vibrator counterbalances is proposed, in which the amplitude is automatically adjusted with increasing frequency during operation of the machine according to the hyperbolic law using a complex mechanical system. In this paper, the launching problem is proposed to be solved at the cost of even more complicated kinematics—the use of additional spring-loaded counterbalances.

Faced with the impossibility of further growth along the path of the classical sieve drive circuit, in the work of Modrzewski and Wodziński [16] it is proposed to use two rotational vibrators with the same or different static moments. The trajectory of the sieve (screen) is characterized by two different speeds of rotation of the drive eccentric vibrators. Based on the results of studies on a two-frequency screen on a laboratory scale, a concept has been developed for constructing an industrial screen: the inclination of the sieve relative to the level, the installation of motors relative to the middle part of the sieve, the exciting forces generated by the engines, and the engine speed. In the work, the novelty of the drive design consists only in complicating the kinematics by cascading superposition of two drives

with rotary electric motors.

The work Linenko et al. [17] is also based on the theory that the efficiency of separating machines with complex vibrations of the working body is higher than that of machines with rectilinear vibrations due to an increase in the orienting ability of the material, the complex oscillation is realized through the use of the normal component of the force of a plane linear asynchronous motor (LAM). The authors proposed an adaptive LAM control system, which allows maintaining the oscillation parameters of the sieve mill constant, despite the effect of destabilizing factors. LAM allows to directly receive the movement of the working body, bypassing various kinds of transducers of the type of movement, and to implement an energy-efficient electric drive of oscillatory motion with adjustable vibration parameters together with the elastic elements. Similarly, in the work of Aristov et al. [18] it is emphasized that gearless oscillatory electric drives based on LAM allow, in particular, to provide almost the entire necessary range of vibration parameters generated and controlled by these drives. However, the present work does not talk about the introduction of LAM in specific technological machines, and their study.

In addition to linear asynchronous motors, reciprocating motion can be obtained by other electric machines. For example, Chen et al. [19] presented a linear reciprocating pulse jet engine for refrigeration compressors. A control system is proposed in which the reciprocating movement is achieved using leaf springs and a pushing regulator. The position controller is designed to control movement. To monitor the maximum efficiency of the engine, an efficiency controller is used, based on the method of searching for the optimal mode. The motor current is regulated through a PWM driver and a current regulator. The results of studies are presented in which the unidirectional power engine control system is simple, efficient, and can stably control the refrigerator compressor. The proposed technical solution is aimed at working with power from a single-phase network, however, in the presence of a three-phase network, there is the possibility of using a three-phase electric motor, the efficiency of which is considered to be higher, including LAM.

In the work of L. A. Neyman and V. Y. Neyman [20], it is noted that linear electromagnetic transducers are widely used in vibration engineering systems. The development of the mechatronic approach to dynamic analysis and modern methods of analysis and synthesis of such systems require the improvement of mathematical models. A mathematical model of an electromechanical system with reciprocating motion of interacting inertial masses connected by spring bonds and excited by a coil of an alternating electromagnetic field is proposed. In the work of Solomin and Chekhova [21], it is proposed to change the resistance of the secondary LAM element and control the speed with starting and traction forces in a wide range. The resistance of the short-circuited winding of the secondary LAM element is changed using a movable element capable of shorting a different number of conductors in each groove. Adjustable linear induction motors can be used as traction machines for magnetic levitation transport. However, in electric drives with reciprocating movement of the working bodies in the frequency range of the oscillations of the sieves of grain cleaning machines, it is not advisable to constantly change the resistance of the secondary element circuit in the proposed way, because this method leads to intensive wear of the rubbing parts and creates additional resistance to movement.

In the considered works with LAM, mathematical models are given that make it possible to analyze electromechanical processes in transient, stationary and resonant modes of an electric drive, taking into account the degree of mobility of inertial masses and the properties of spring bonds.

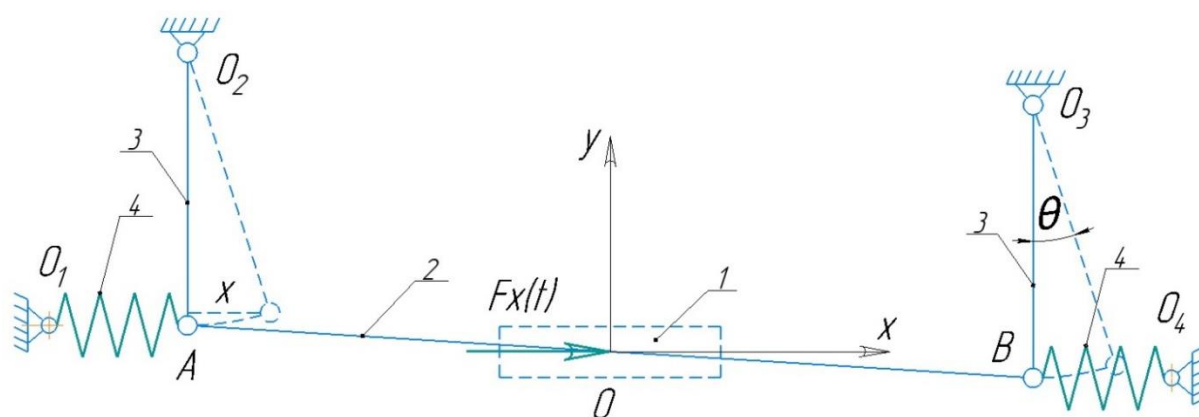
However, when modeling and researching machines, the question of the influence of the features of the drive with LAM drive directly on the separation process is not considered, which is possibly related to the specifics of modeling these processes, the difference in scientific directions and the research goals pursued.

The purpose of this work is to study the structural and technological parameters and modes of oscillation of a sieve mill driven by a linear induction motor.

## 2. Materials and methods

One of the most important functional evaluating parameters of the movement of the cleaned grain heap on the surface of the sieve is the Froude number, which is expressed by the ratio of the forces acting on the grain material lying on the sieve, the amplitude of oscillations of the sieve and gravity [4,5].

Figure 1 shows the calculation scheme for determining the coordinates of the nodal points of the sieve mill 2 of the grain cleaning machine for calculating their speed and acceleration of motion, inertia forces acting on the grain heap lying on the surface of the sieve. The given oscillatory system of the sieve mill of the grain cleaning machine is a “hybrid” of the mathematical and spring pendulum. The sieve mill  $AB$  is a link in the parallel four-link mechanism  $ABO_2O_3$ . Elastic elements 4 (springs) are attached to the sieve mill suspended on suspensions 3 of length  $l$  on both sides, placed in a horizontal plane and perpendicular to the suspension. In the equilibrium position, the suspensions are vertical and the springs are not deformed. The installation of the plane of the sieve mill  $AB$  is determined by the angle  $\alpha$  of inclination to the horizontal (in our case,  $\alpha = 7^\circ$ ).



**Figure 1.** Design scheme of the sieve mill of a grain cleaning machine with a linear asynchronous electric drive. 1 – LAM, 2 – sieve mill, 3 – suspensions, 4 – elastic elements.

Let  $a_{i,x}$  and  $b_{i,y}$  be the coordinates of the fixed reference points  $O_i$ ,  $i = 1, 2, 3, 4$ . As a reference system, we take a right-handed Cartesian coordinate system, and place the origin of the coordinate system at the drive point  $O$  of the sieve mill  $Fx(t)$ . Let us single out the nodal points of the sieve mill to compose the equations of geometric constraints, the trajectories of which are known:  $A$  and  $B$ . These points move along circles of radii  $l = O_2A = O_3B$ . Point  $A$  simultaneously belongs to crank  $O_2A$  and connecting rod  $AB$ , point  $B$  simultaneously belongs to crank  $O_3B$  and also connecting rod  $AB$ .

The sieve mill is driven into oscillation when it deviates from the equilibrium position by an angle

$\theta$  due to the positive horizontal direction of the force pulse  $Fx(t)$  created by the linear induction motor  $l$ . If we denote by  $x$  the linear displacement of the sieve mill from the equilibrium position along the arc with a radius of equal length suspensions  $l$ , then its angular displacement is  $\theta = x / l$  (Figure 1).

Let us consider the oscillatory system of a sieve mill, on which, at displacements  $x$  in the interval  $x_{start} \dots x_{stop}$  and in motion in the positive direction, the LAM force  $Fx$  acts:

$$Fx(t) = \begin{cases} Fx, & \text{if } x_{stop} - |x| \geq 0, \text{ и } \dot{x} \geq 0 \\ 0, & \text{otherwise.} \end{cases}$$

LAM is controlled by the control unit according to the parameters of the sieve oscillations. The control unit can adjust the duration and amplitude of the pulses of the forces  $Fx$ .

The work of the control unit in the model is implemented using the Heaviside function:

$$\Phi(x) = \begin{cases} 1, & x \geq 0, \\ 0, & x < 0. \end{cases}$$

When the sieve mill deviates from the equilibrium position, a torque  $M$  arises, which tends to return it to the equilibrium position.

$$M = J\varepsilon, \quad (1)$$

where  $J = ml^2$  is the moment of inertia,  $\varepsilon = \frac{d^2\theta}{dt^2}$  is the angular acceleration.

Torque  $M$  is created by three forces: elasticity, gravity, resistance.

The equation of the dynamics of the oscillatory motion of a sieve mill with small deviations  $\theta$  under the action of a disturbing force  $Fx(t)$  created by a linear induction motor

$$ml^2 \cdot \frac{d^2\theta}{dt^2} = -mgl \cdot \sin \theta - kl^2 \cdot \sin \theta \cdot \cos \theta - f \cdot \frac{d\theta}{dt} \cdot l^2 + Fx(t), \quad (2)$$

where  $k$  is the stiffness coefficient,  $H/M$ ,  $g$  is the acceleration of gravity,  $m/s^2$ ,  $f$  is the resistance coefficient.

$$\frac{d^2\theta}{dt^2} = -\frac{g}{l} \cdot \sin \theta - \frac{k}{m} \cdot \sin \theta \cdot \cos \theta - \frac{f}{m} \cdot \frac{d\theta}{dt} + \frac{Fx(t)}{m}, \quad (3)$$

This second-order nonlinear differential equation in ordinary functions is not integrated. Given small deviations  $\theta$ , if we expand  $\sin \theta$  in a series

$$\sin \theta = \theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} - \dots$$

and neglect the terms of the expansion above the first order, we obtain a second-order inhomogeneous differential equation with constant coefficients

$$\frac{d^2\theta}{dt^2} + \left(\frac{g}{l} + \frac{k}{m}\right) \cdot \theta + \frac{f}{m} \cdot \frac{d\theta}{dt} = \frac{Fx(t)}{m}, \quad (4)$$

or, if we denote by moving  $x$ ,

$$\frac{d^2x}{dt^2} + \left(\frac{g}{l} + \frac{k}{m}\right) \cdot x + \frac{f}{m} \cdot \frac{dx}{dt} = \frac{Fx(t)}{m}, \quad (4^*)$$

We denote  $\frac{f}{m} = 2\beta$ , where  $\beta$  is the damping coefficient,  $\omega_0 = \sqrt{\frac{g}{l} + \frac{k}{m}}$  is the circular frequency

of oscillations. The oscillation period  $T = 2\pi \sqrt{\frac{ml}{2kl+mg}}$ . The frequency of the damped oscillations  $\omega_z = \sqrt{\omega_0^2 - \beta^2} \omega -$  has physical meaning at  $\omega_0 \geq \beta$ .

The left side of the expression (4) is a second-order linear differential equation that describes damped free oscillations, and the right side, which clearly depends on time, is a driving force.

To find the law of motion of a sieve mill, it is necessary to solve this equation under certain initial conditions:  $t = 0; x = x_0; \frac{dx}{dt} = v_0$ . The general solution to this equation is the sum of two functions

$$x(t) = x_1(t) + x_2(t), \quad (5)$$

where  $x_1(t)$  is the general solution of the homogeneous equation (left side (4\*)),  $x_2(t)$  is the particular solution of the inhomogeneous equation (right side (4\*)).

The type of general solution of the left-hand side (4\*) is known, which is a damped oscillation that disappears over time:

$$\begin{aligned} x_1 &= C_1 \sin \omega t + C_2 \cos \omega t \equiv C \sin(\omega t + \gamma), \\ (C_1 &= \text{const}, C_2 = \text{const}, C = \text{const}, \gamma = \text{const}), \end{aligned} \quad (6)$$

where ( $C = \text{const}, \gamma = \text{const}$ ) are the integration constants,  $C = \sqrt{C_1^2 + C_2^2} = A \cdot e^{-\beta t}$  is the amplitude of free vibrations of the sieve mill,  $(\omega t + \gamma)$  – the oscillation phase of the mill,  $\gamma$  is the initial oscillation phase. Or

$$x_1|_{t \rightarrow \infty} = \lim_{t \rightarrow \infty} (A \cdot e^{-\beta t} \sin(\sqrt{\omega_0^2 - \beta^2} t + \gamma)) = 0. \quad (6^*)$$

The steady-state oscillations of the sieve mill  $x_{steady} = x_1|_{t \rightarrow \infty}$  will consist only of forced oscillations under the action of a forcing force, which is determined by the right-hand side (4\*). A particular solution to this equation must be sought in the form

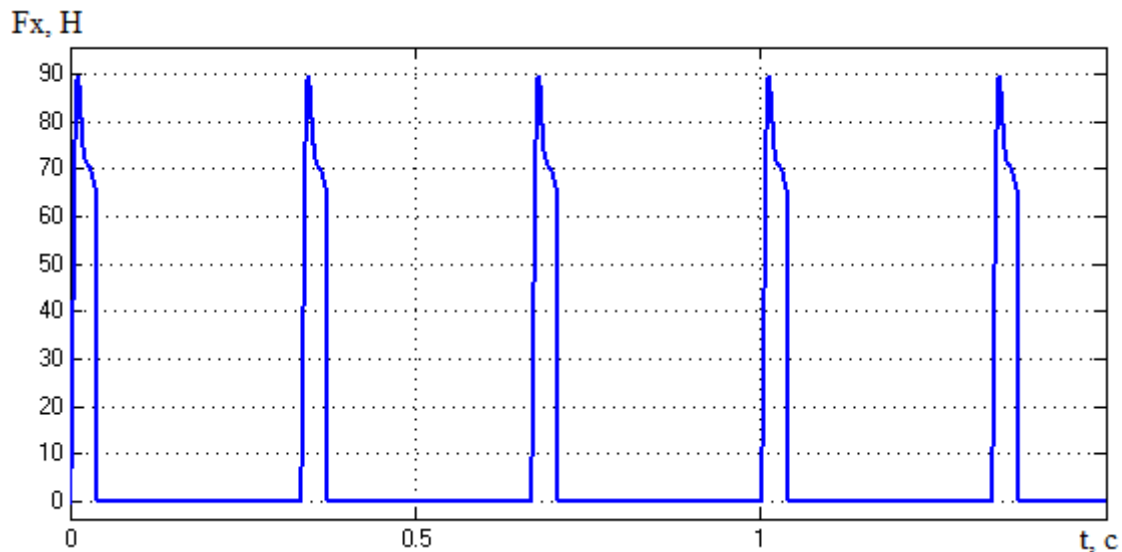
$$x_2 = B \sin(\delta t + \mu), \quad (7)$$

where B is the amplitude of the forced oscillations,  $B = \frac{Fx(t)}{m\sqrt{(\omega_0^2 - \delta^2)^2 + 4\beta^2\delta^2}}$ ;  $\sin \mu = \frac{2Bm\beta\delta}{Fx(t)}$ ;  $\cos \mu = \frac{Bm(\omega_0^2 - \delta^2)}{Fx(t)}$ ;  $\delta$  is the frequency of forced oscillations;  $\mu$  is the angle determining the phase shift of the forced oscillations and the disturbing force.

The forced oscillations of the sieve mill described above under the action of a disturbing force  $Fx(t)$  are harmonic (undamped) oscillations with a frequency  $\delta$ . Under any initial conditions, the vibrations of the sieve mill over time, free vibrations will disappear, only forced vibrations will remain, supported by the driving force  $Fx(t)$  (Figure 2), which during modeling is determined by the electromechanical energy conversion equation – the Park-Gorev differential equation with  $ODQ$  coordinate system, motionless relative to the traveling magnetic field [22]:

$$\left\{ \begin{array}{l} \varphi_{d1} = \int_0^T \left( U_{d1} - \frac{\pi}{\tau} V_0 \cdot \frac{R_1 X_r}{X_s X_r - X_m^2} \varphi_{d1} + \frac{\pi}{\tau} V_0 \cdot \frac{R_1 X_m}{X_s X_r - X_m^2} \varphi_{d2} + \frac{\pi}{\tau} V_0 \varphi_{q1} \right) dt; \\ \varphi_{q1} = \int_0^T \left( U_{q1} - \frac{\pi}{\tau} V_0 \cdot \frac{R_1 X_r}{X_s X_r - X_m^2} \varphi_{q1} + \frac{\pi}{\tau} V_0 \cdot \frac{R_1 X_m}{X_s X_r - X_m^2} \varphi_{q2} - \frac{\pi}{\tau} V_0 \varphi_{d1} \right) dt; \\ \varphi_{d2} = \int_0^T \left( -\frac{\pi}{\tau} V_0 \cdot \frac{R_2 X_s}{X_s X_r - X_m^2} \varphi_{d2} + \frac{\pi}{\tau} V_0 \cdot \frac{R_2 X_m}{X_s X_r - X_m^2} \varphi_{d1} + \frac{\pi}{\tau} (V_0 - V_b) \varphi_{q2} \right) dt; \\ \varphi_{q2} = \int_0^T \left( -\frac{\pi}{\tau} V_0 \cdot \frac{R_2 X_s}{X_s X_r - X_m^2} \varphi_{q2} + \frac{\pi}{\tau} V_0 \cdot \frac{R_2 X_m}{X_s X_r - X_m^2} \varphi_{q1} - \frac{\pi}{\tau} (V_0 - V_b) \varphi_{d2} \right) dt; \\ F_x = 3\pi^2 \frac{f}{\tau} \cdot \frac{X_m}{X_s X_r - X_m^2} (\varphi_{d2} \varphi_{q1} - \varphi_{d1} \varphi_{q2}). \end{array} \right. \quad (8)$$

Where  $\tau$  is the pole division of the winding LAM, m;



**Figure 2.** Graph of the disturbing fluctuation of the force  $F_x(t)$  of the sieve mill of the grain cleaning machine.

$X_s = X_l + X_m$ ,  $X_r = X'_2 + X_m$  are the resistance values of the inductor circuit and the secondary LAM element, respectively, Ohm;

$R_l$ ,  $X_l$ ,  $R'_2$ ,  $X'_2$  – respectively, the active and reactive resistances of the inductor and the secondary element, reduced to the coil of the inductor, Ohm;

$X_m$  is the mutual induction resistance between the inductor and the secondary element, Ohm;

$V_0$  is the velocity of the magnetic field of the LAM,  $V_0 = 2\tau f$ , m/s;

$V_b$  is the velocity of the secondary LAM element, m/s;

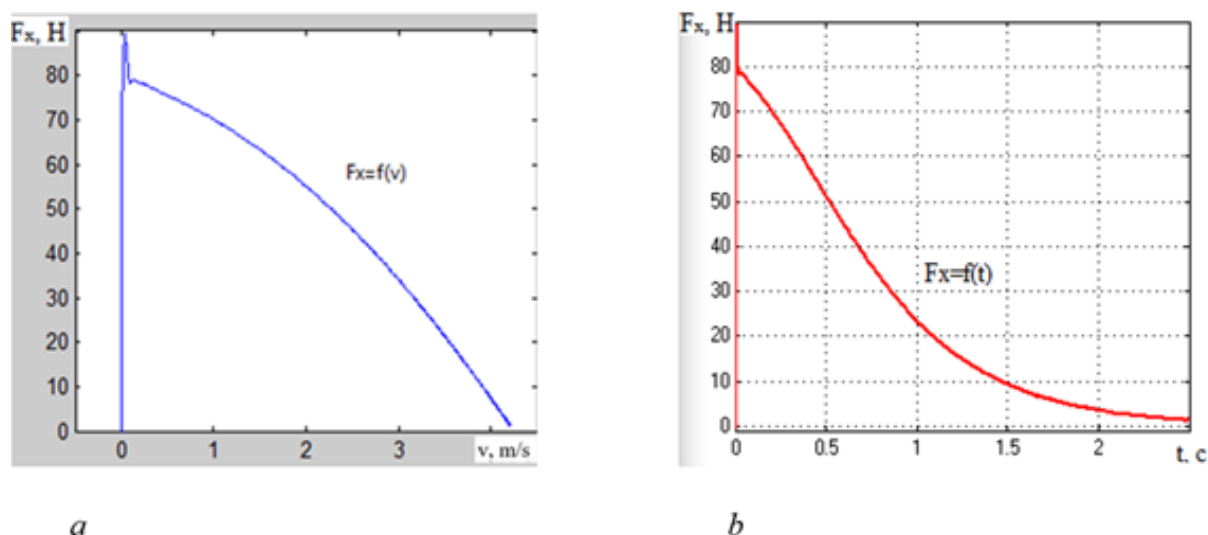
$\varphi_{d1}$ ,  $\varphi_{q1}$ ,  $\varphi_{d2}$ ,  $\varphi_{q2}$  are the flux linkages along the axes  $OD$ ,  $OQ$ , respectively of the inductor and the secondary element,  $Wb$ ;

$\omega_0$  is the circular frequency of the supply network,  $s^{-1}$ ;

$U_{d1}$ ,  $U_{q1}$  is the inductor voltage along the axes  $OD$ ,  $OQ$ , V.

As can be seen from expression (8), the power of the LAM is determined by the parameters of the motor equivalent circuit and the network parameters, including voltage and current frequency in the network.

Figure 3 shows the mechanical and acceleration characteristics of the LAM installed in the drive of the test machine. The characteristics are obtained by modeling in the program MATLAB-Simulink.



**Figure 3.** Graph of the dependence of the power of the LAM  $F_x$ : a) on speed  $v$  of the secondary element; b) on time  $t$  during continuous acceleration with a mass of the moving part  $m = 15$  kg.

The parameters of the equivalent circuit determine the form of the mechanical characteristic – the dependence of the electric motor on the speed of the secondary element (Figure 3a), and the force, as is known, is quadratic depending on the voltage.

Electric motors operating in intermittent operation are at risk of overheating due to high inrush currents. In addition, reducing the supply voltage of an induction motor is considered to be ineffective, moreover, a destructive method of speed regulation. However, if the LAM is designed and manufactured with the expectation of such a regime, then the starting currents for it will be considered nominal (normal).

The practical implementation of the model was carried out by the fourth-order Runge-Kutta method according to the standard method in the Mathcad application program.

### 3. Results

The condition ensuring the movement of grain heaps on the surface of a sieve mill  $AB$  oscillating with frequency  $\omega$  and located at an angle  $\alpha$  to the horizontal. Provided that the movement of the grain heap is carried out down the sieve, the inertia acting on the grain will be directed downward, the friction force on the sieve will be upward along the surface of the sieve, the gravity downward and the normal reaction of the sieve will be upward perpendicular to the surface of the sieve. By the direction of the acting forces on the particle of the grain heap, it is possible to establish the nature of their trajectory of movement relative to the oscillating sieve mill. The mode of moving the grain heap over the sieve is set in this way: the contact time of the particles of the grain heap with the sieve should be maximum to ensure more efficient separation, and at the same time, to increase the performance of the grain cleaning machine, the contact time of the particles of the grain heap with the sieve should be minimal (the speed of movement of the grain heap on a sieve should be maximum in order to increase productivity). These requirements contradict each other. Thus, it becomes necessary to solve the optimization problem.



One of the most important functional parameters of the motion of the layer on the surface of the sieve is the Froude number (an indicator of the kinematic mode of operation  $k_p$ ), which expresses the ratio of the forces acting on the particle lying on the sieve, the amplitude of oscillations of the sieve and gravity. This number can be expressed as follows

$$F_r = k_p = \frac{\varepsilon}{g}, \quad (9)$$

In order for the grain material to move along the sieve without separation from the plane with sliding down and up, and more down than up, the indicator of the working kinematic mode  $k_p$  should be in the ratio:

$$k_p > k_B > k_H, \quad (10)$$

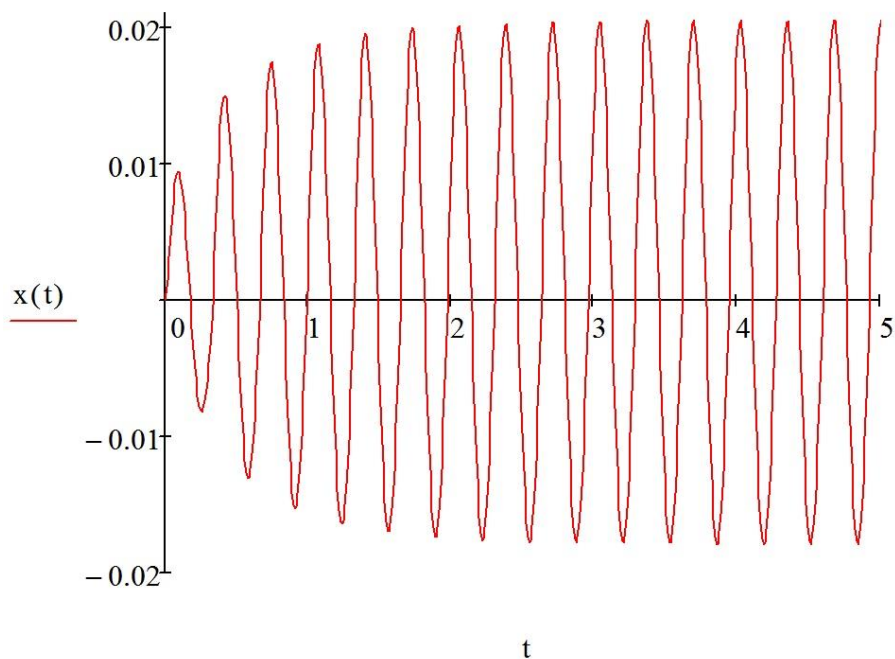
where  $k_B$  is the indicator of the kinematic mode at which the grains move up along the plane of the  $AB$  sieve mill,  $k_H$  is the indicator of the kinematic mode in which the grains move down along the plane of the  $AB$  sieve mill.

$$k_B = \tan(\alpha + \varphi) \quad (11)$$

where  $\varphi$  is the angle of friction of the particles of the grain heap on steel ( $\operatorname{tg}\varphi = f$ , where  $f$  is the coefficient of friction),  $\varphi = 18 \dots 30^\circ$ .

$$k_H = \frac{\sin(\varphi - \alpha)}{\cos(\alpha - \varphi)}, \quad (12)$$

The trajectories of the velocity and acceleration of the links, which are obtained by the results of modeling and calculation in the Mathcad program, are presented in Figures 4–10.



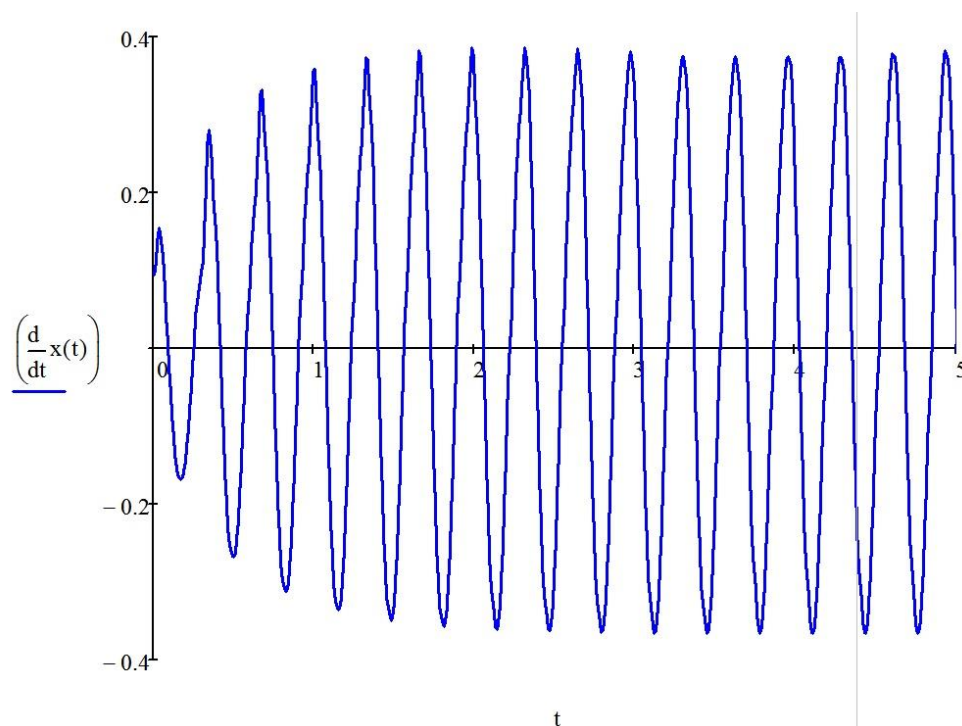
**Figure 4.** Graph of oscillations of the sieve mill of a grain cleaning machine.

Figure 4 shows that the (harmonic) oscillations of the sieve mill begin and increase under the action of the driving force  $Fx(t)$  created by the linear induction motor, and after  $t = 2$  s stabilize, it goes into steady state.

Analyzing Figure 5, according to the results of a numerical solution, it was determined that the maximum speed of the sieve mill of the grain cleaning machine is 0.34 ... 0.36 m/s.

The acceleration developed by the sieve mill is 5.8 ... 6.9 m/s<sup>2</sup>.

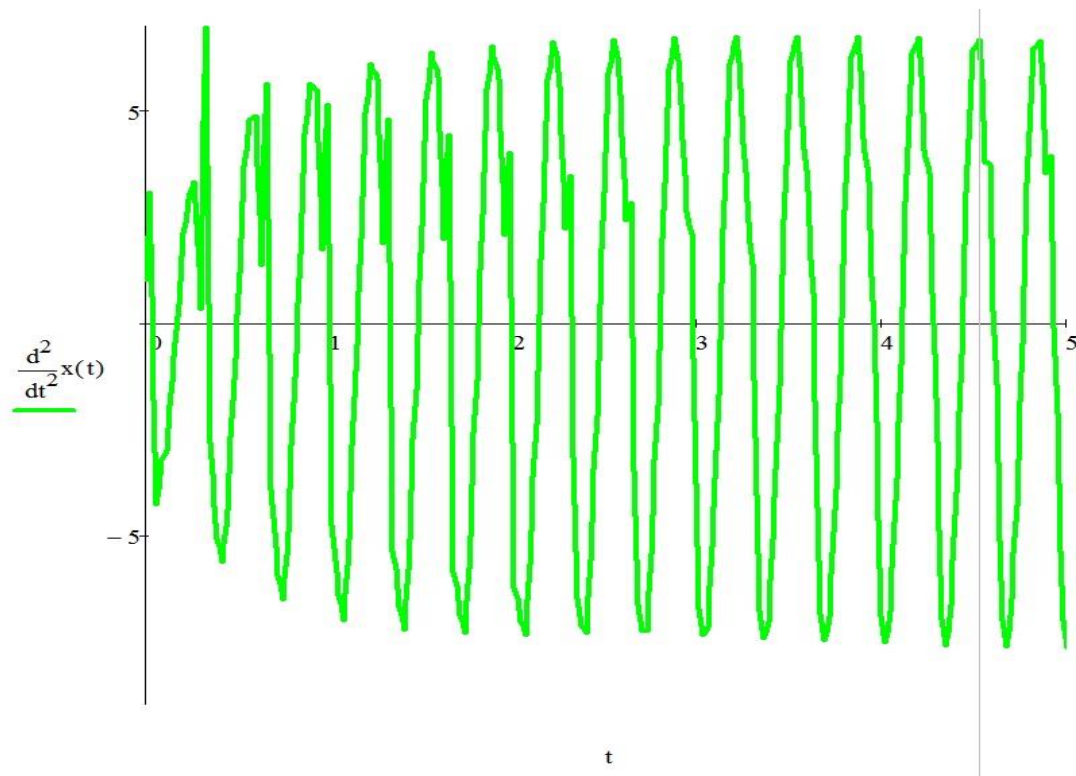
For  $\varphi = 18^\circ$ , condition (10) is fulfilled, so the grain heap moves down and up along the oscillating sieve mill, but mainly down, and for  $\varphi = 30^\circ$  it turns out  $k_B \geq k_P > k_H$ , which means that the grain heap moves only down on the sieve mill.



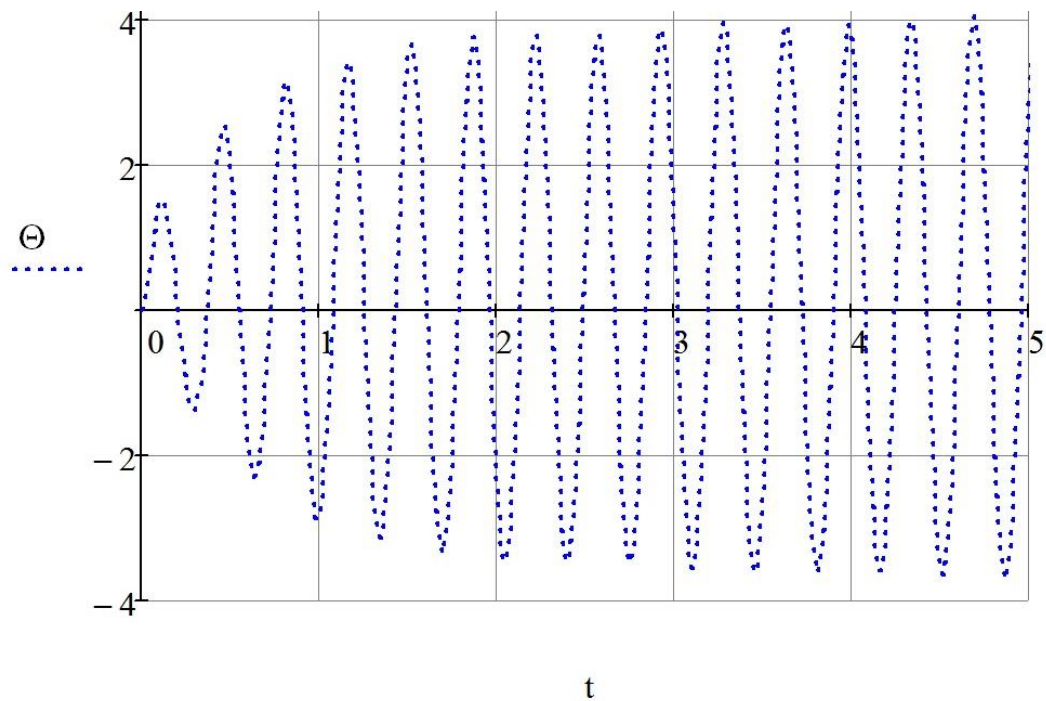
**Figure 5.** Graph of the speed change of the sieve mill of a grain cleaning machine.

Figure 7 shows that the sieve mill oscillates and the angle of deviation of the suspensions relative to the vertical axis varies within  $-3.78^\circ \leq \theta \leq 4.11^\circ$ .

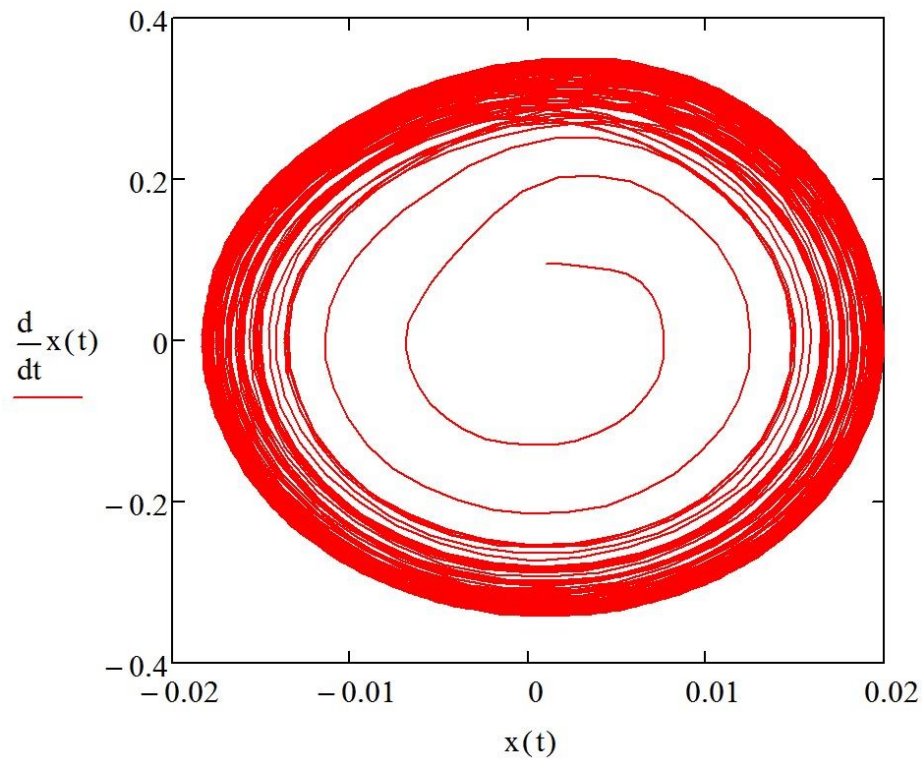
On the phase curve (Figure 8), speed jumps are clearly visible, leading to an increase in the oscillation amplitude when the next portion of the force impulse  $Fx(t)$  created by the linear asynchronous motor is transmitted to the sieve mill. Over time (steady state), the phase curve approaches many lines (attractor).



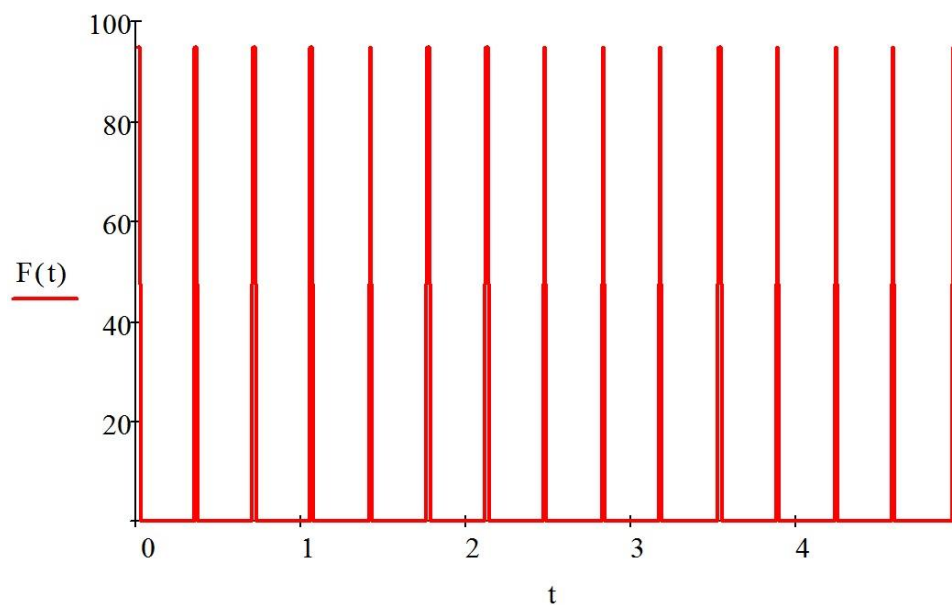
**Figure 6.** Graph of changes in the acceleration of the sieve mill of a grain cleaning machine.



**Figure 7.** Graph of the angle of deviation  $\theta$  of the suspensions of the sieve mill relative to the vertical.



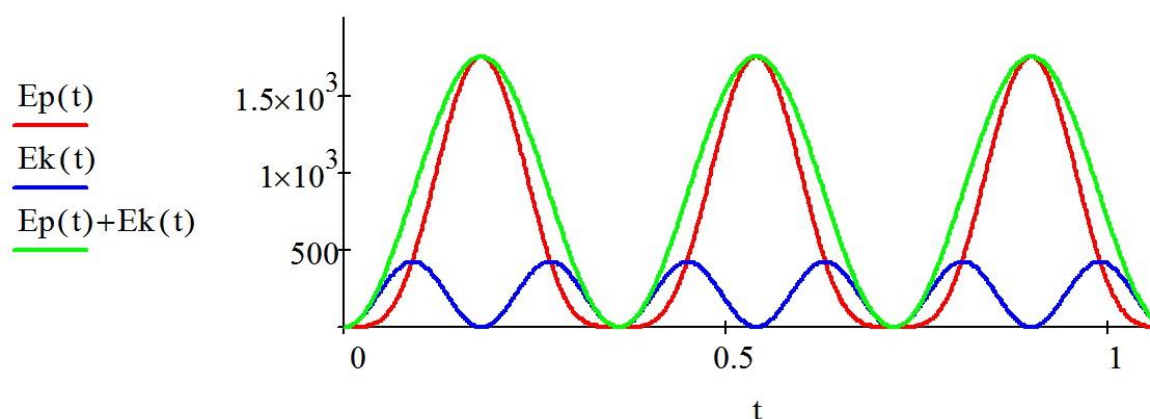
**Figure 8.** Curve of the phase trajectory of the sieve mill of the grain cleaning machine.



**Figure 9.** Pulses of force  $F_x(t)$  created by a linear induction motor acting on the sieve mill of a grain cleaning machine.

Let us consider the energy ratio.

Figure 10 shows the calculation results of the potential  $E_p(t)$ , kinetic  $E_k(t)$  and total energy  $E_o(t) = E_p(t) + E_k(t)$ . It can be seen from the figure that the kinetic energy oscillates with a doubled circular frequency with respect to the sieve mill vibration. When the potential energy is maximum, then at this time the kinetic energy is minimal, and vice versa. The oscillation process of the sieve mill under consideration is explained by the transition of one type of energy to another. Thus, the energy ratios in the system are decisive. In our case, they reflect the law of conservation of energy.



**Figure 10.** Kinetic, potential, full energy of the system.

#### 4. Discussion

The experimentally obtained data on the kinematic mode of operation of the sieve mill driven by a linear induction motor showed compliance with a workable effective state (Figures 8 and 9), and at the same time, the LAM turns on and transfers the force to the sieve mill in a pulsed mode. Thus, the load on the LAM is reduced, the efficiency of the drive and the resource are increased. Since the main share of grain cleaning units is sieve machines, most of which have exhausted their life and the main cause of the main failures and breakdowns is the drive mechanism of the sieve mill, this is described in Mudarisov and Badretdinov [1], Mudarisov et al. [2], Shevtsov and Beznosov [8]. Also, due to wear or incorrect operation of the drive mechanism, structural vibrations and a violation of the kinematic mode can be observed. The influence of the kinematic regime on the cleaning process was studied by the authors [4–6,9,12,23–26]. A comparative analysis of the separation process at sieve mills and the possibility of representing in the form of laws: normal, Weibull, gamma and beta distribution were carried out by the authors of Voicu et al. [26]. A statistical analysis of the versatility of the physico-mechanical characteristics of crops and their impact on the cleaning process was carried out by Dal-Pastro et al. [24]. The mathematical model for the separation of seeds on flat sieves using the theory of dimensional analysis was performed by Casandroi et al. [23], and Ma et al. [6].

Shevtsov and Beznosov [8] studied the effect of the drive device of the sieve mills of grain cleaning machines, which ensures the operation of sieves of different purposes in different kinematic modes. The disadvantage of the classic drive sieve mills which they found out is that spike and sowing sieves, performing different functions, work in the same kinematic mode.

The study of determining the inertia and mobility of bulk material and its effect on the inertial and

dissipative loads, calculations and comparative analysis of the kinematic schemes of grain sorting machines with eccentrics shifted by  $\pi$  and  $\pi / 2$  were carried out by Popov et al. [7].

The obtained characteristics of the functioning of the sieve mill from LAM in this work allow to develop recommendations for optimizing the structural and technological parameters of the sieve mill of the grain cleaning machine itself, improving the sieve drive itself, which in the future will significantly increase the resource and efficiency of the grain cleaning machine, and reduce energy consumption.

## 5. Conclusions

The mathematical model of the kinematic scheme of the sieve mill of a grain cleaning machine with an electric drive from a linear induction motor has been developed. Based on the simulation results, the nature of the oscillatory movement of the sieve mill is determined, its graphs of movement, speed, and acceleration are constructed. The maximum speed of the sieve mill was 0.34 ... 0.36 m/s, and the acceleration developed by the sieve mill varies within 5.8 ... 6.9 m/s<sup>2</sup>. During oscillatory movement of the sieve mill, the suspension angles on which the sieve mill is mounted deviate relative to the vertical axis by an angle  $\theta \in [3.78^{\circ}; 4.11^{\circ}]$ .

The kinematic operating mode  $k_P > k_B > k_H$  was determined for various angles of friction of the particles of the grain heap against steel  $\varphi = 18 \dots 30^{\circ}$  (the coefficient of friction of the grain heap against steel). So at smaller friction angles  $\varphi$ , the grain heap moves up and down along the oscillating sieve mill, but mainly down, and for large  $\varphi \geq 30^{\circ}$ ,  $k_B \geq k_P > k_H$  is obtained, in this case the grain heap moves only down the sieve mill, there is no moving up. The Froude number, which characterizes the ratio between the forces of inertia and gravity, in the field of which the movement occurs, for the sieve mill is  $Fr = 0.7$  and corresponds to the condition  $Fr < 1$ , which according to the accepted classification corresponds to the “calm flow” mode. The proposed method for modeling grain cleaning machines with a sieve cleaning system makes it possible to study the kinematics of the drive mechanism, the separation process by flat oscillating working bodies, to analyze the degree of contact of the particles of the grain pile components with the sieve, to identify problem areas and makes it possible to improve the design and technological parameters of the sieve mill of any seed cleaning machine. The developed model can be used repeatedly, so there is no need for investment in the manufacture and conduct of laboratory verification tests. You can set the correct modes of operation of the separation process for different crops and make recommendations for production.

## Conflict of interest

Authors declare that they have no conflict of interests.

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