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Experimental Vibro-Centrifugal Grain Separator with Linear Asynchronous Electric Drive

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Abstract: The economic efficiency of grain production largely depends on the use of energy-efficient, resource-saving equipment capable of ensuring high quality of the technological process. In this connection, the original design of a vibro-centrifugal grain separator is proposed and in it as a vibratory drive a flat linear asynchronous motor is used. The linear asynchronous electric motor allows you to bypass various kinds of motion transducers and to obtain direct progressive motion of the working element and together with the elastic elements realize an energetically efficient electric drive of oscillatory motion with adjustable oscillation parameters. The proposed technical solution allows to reduce the installed capacity of a vibratory drive by 37.5%, to increase the service intervals by 18.2% and due to the possibility of adjusting the oscillations parameters of the working element it will increase separation efficiency of grain mix by 2.5-4%, depending on the seed kind and moisture. Experimental dependences characterizing the oscillations parameters of the working element on kinematic parameters of the drive are obtained which in their turn affect the productivity and efficiency of the vibro-centrifugal separator. A mathematical model of a vibro-centrifugal grain separator with a linear electric drive has been developed. It is implemented in the environment of object visual modeling MATLAB (Simulink). The adequacy of this model is confirmed experimentally, the discrepancy between the experimental data and the data obtained by mathematical modeling does not exceed 9%

Key words: Separator, cleaning, linear motor, electric drive, vibration, environment, experimental

INTRODUCTION

Over the past two centuries, the world's population has increased almost 8 times and every year continues to increase steadily. "The growth in agricultural productivity is only 1 or 2%/year", warned Joachim von Braun, general director of the Washington Research Institute of World Food Policy. "This is too little to keep pace with population growth and increased demand for food products" (Al Maidi, 2015).

One of the most important tasks of world agriculture is increase in the production of grain while harvesting processing becomes particularly topical. Grain mixtures coming in after harvesters must be cleaned of weeds, broken grains and other impurities. Peeled grain must be sorted into fractions for sowing and food purpose of the population (2007).

A number of authors have carried out scientific studies of separation of grain mixtures in grain separators: purification of mixtures from light impurities was investigated by Baturin (1959) moving particles in a layer by Blekhman (1979) seed sifting through sieve holes by Zaika (1997).

However, for farms engaged in crop production for cleaning and sorting the grain mixture it is better to use vibro-centrifugal grain separators, since, their specific

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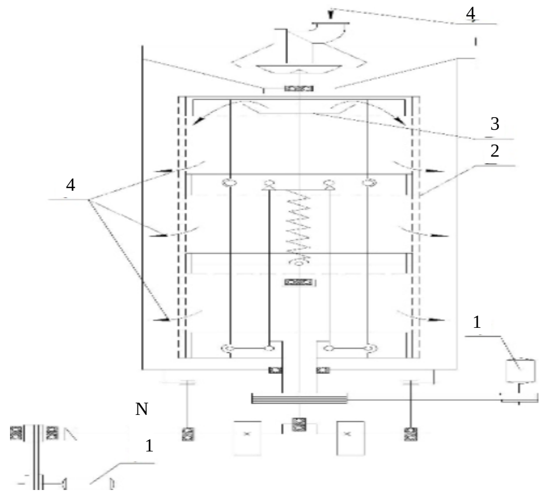

Fig. 1: The kinematic scheme of the VCS: 1) Electric motors; 2) Sieve; 3) Spreader and 4) Grain mix

productivity is 3-5 times higher than that of the known flat-screen grain cleaning machines noted above.

In these Vibro-Centrifugal Separators (VCS) under the influence of inertial forces of rotating and vibrating motion of the working element, intensive separation of the particles of the processed material occurs. The working elements are cylindrical sieves rotating and vibrating in a vertical plane with centrifugal serving the grain material in them (Fig. 1).

The existing installations of VCS have understated performance characteristics associated with the need to use complex converters of rotating movement of the motor shaft into the vibrating movement of the working element which significantly increases the mass-dimensional parameters (Aipov and Linenko, 2013; Linenko, 2015). Also, the amplitude (A = 3 mm) and the oscillation frequency (ω_{osc} = 4 Hz) of the working element are stable in the whole model series of the VCS and do not depend on the material supply, thus, further increasing the productivity and separation efficiency of the VCS is constrained by the lack of possibility of adjusting the oscillation parameters of the working element.

The separation efficiency of the grain mixture is determined by the efficiency of the processes occurring in the VCS. The analysis of the research revealed that the main kinematic parameters that determine the separation efficiency of the grain mixture are frequency and amplitude of the vibrations of the working element which must be regulated smoothly and consistently with one another.

Purpose of the research: Increasing the efficiency of a vibro-centrifugal grain separator using a flat linear asynchronous electric motor

Objectives of the research: Taking into account the fact that nowadays small farms producing small volumes of agricultural products are becoming popular, the following tasks are set in the work: to develop the design of the vibratory drive of VCS based on a Flat Linear Induction Motor (FLIM) with adjustable oscillations parameters of the working element and of low productivity up to 5 ton/h which combines compactness, reliability and high efficiency of operation, to develop a mathematical model of the vibratory drive of VCS with FLIM, to carry out an experimental evaluation of the dependence of the grain separation efficiency in the VCS on the frequency and amplitude of the oscillations of the working element, check the adequacy of the developed mathematical model.

MATERIALS AND METHODS

Based on the research results a kinematic scheme of the experimental installation for obtaining rotational movement from the motor and vibration motion from the FLIM of the working element was developed (Fig. 2) (Patent No. 2,624,702). The installation includes a spreader 11, a working element that is a sieve 5 and is connected to the secondary element 2 of the FLIM and is made of material with a high electrical conductivity (Alanis *et al*., 2015; Eremeikin *et al*., 2016). The secondary element 2 is connected to a horizontally arranged driven pulley 9 which by means of V-belts 6 receives rotation from the drive pulley 10 fixed to the shaft of the electric motor 7. When the driven pulley 9 rotates, the working element is rotated about its vertical axis through a slot connection 8.

The electric drive of the vibratory movement of the working element in the vertical plane is a FLIM consisting of several inductors 1 which are electrically connected in series (Ahmadinia, 2014). The inductors are symmetrically and rigidly attached to the base. The working element is spring-loaded relative to the base by means of rollers 3 and elastic elements 4 (Fig. 2) (Sampath *et al*., 2016).

Figure 3 shows photographs of the experimental VCS, realized according to the kinematic scheme shown in Fig. 2. The inductors 1 are rigidly fixed on the base (Fig. 3c), the sieve 5 (the working element) is rigidly connected with the secondary element 2 of the FLIM

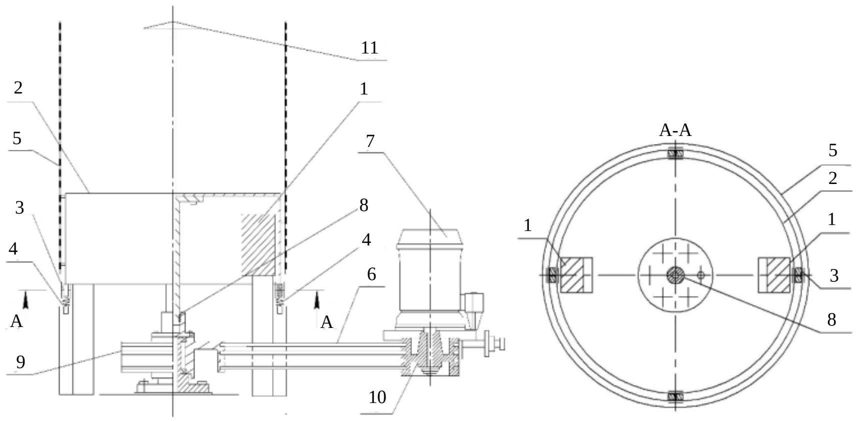

Fig. 2: A kinematic scheme of the experimental installation of the VCS with FLIM (symbols in the text)

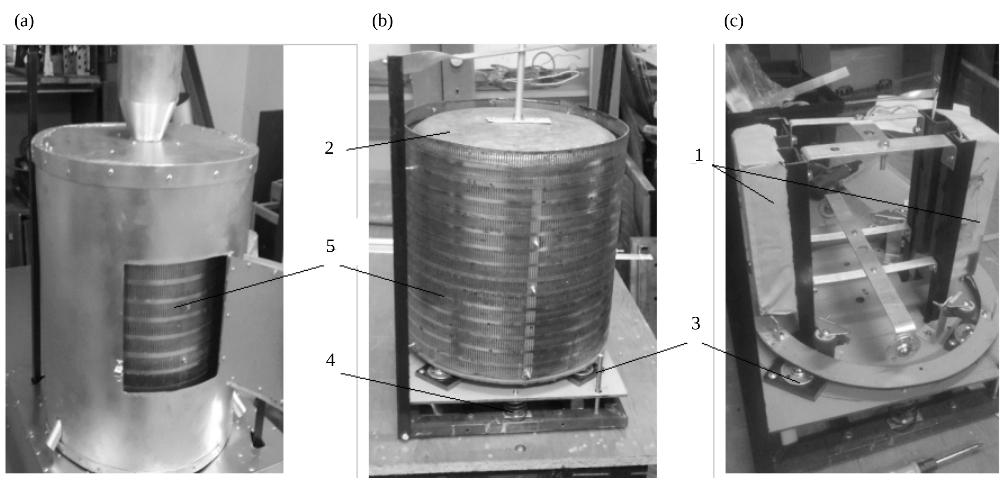

Fig. 3: General view: a) The experimental installation of the VCS; b) Working element with working sieves and c) Inductors of FLIM (symbols in the text)

(Fig. 3b). The sieve with the secondary element is mounted on the rollers 3 which are spring-loaded relative to the (Fig. 3b) base on the elastic members 4.

The process of separation on a vertical cylindrical sieve proceeds as follows (Fig. 4). The cylindrical sieve of radius R is rotated about its axis with an angular velocity ω transmitted through a splined connection and vibrating movement along the axis of rotation realized with the help of the FLIM. When power is applied to the FLIM, the secondary element along with the sieves performs translation movement downward in the vertical plane and elastic elements are deformed. When the FLIM inductors are disconnected from the source of power due to the potential energy accumulated in the elastic elements, the secondary element with the sieves returns to the initial state while continuing to rotate around its axis. After a certain period of time the inductors are reconnected to the power source and the described process is repeated. Thus a simpler and more reliable electric drive with vibration and rotational movement in the working element of the VCS (Jiao *et al*., 2017) and operating in the “On-off” mode is provided, having the required frequency ω_{osc} and the amplitude of the $\underline{A}_{osc}$ oscillations (Patent No. 2,624,702). Adjustment of the oscillations parameters of the working element is provided by changing the switched on and off state of the linear motor.

The grain mixture is fed by the spreader to the inner surface of the receiving section of the sieve (Fig. 4a) at the top of it forming an annular layer and under the force of gravity F_g and vibration the mixture moves from the top to the bottom. The free surface of the mixture layer forms a cylindrical surface of radius R_0.

To determine the productivity Q of VCS for food grains a simplified version of the model was used in which

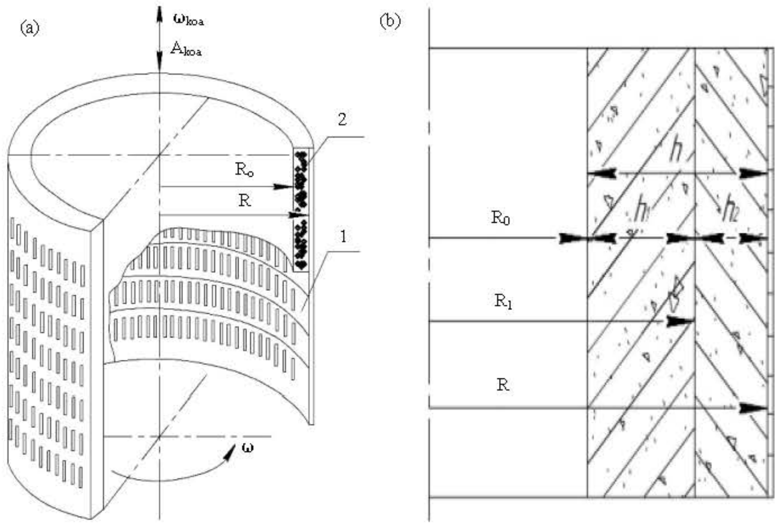

Fig. 4: Distribution of the grain mixture on the sieve: a) A diagram of a cylindrical sieve and b) Model of the distribution of the grain mixture over the surface of a cylindrical sieve; 1) Sieve and 2) Layer of grain

the annular layer of variable viscosity is divided into two homogeneous annular sublayers (Fig. 4b) with different coefficients of dynamic viscosity μ.

The sublayer that is closer to the surface of the sieve has greater viscosity coefficient μ_1 than the viscosity coefficient of μ_2 the sublayer which borders on the surface free of grain mass (Fig. 4b):

$$Q=\pi\left\{\begin{array}{l}\left(R_1^2-R_o^2\right)\cdot\left[\begin{array}{l}\frac{\frac{pg}{\mu_1}}{8}\cdot\left(R_1^2-R_o^2\right)-\frac{pg}{\mu_1}+\\ \left(\begin{array}{l}\frac{\frac{pg}{\mu_1}}{8}\cdot R^2-\frac{pg}{2R}\cdot\left(R_1^2-R_o^2\right)+\\ \frac{\frac{pg}{\mu_2}-\frac{pg}{\mu_1}}{2}\cdot\left(\frac{R_1^2}{2}-R_o^2\cdot\ln\frac{R_1}{R}\right)\end{array}\right)\end{array}\right]+\\ \frac{\frac{pg}{\mu_1}}{2}\cdot R_o^2\cdot\left(R_1^2\cdot\ln\frac{R_1}{R}-R_0^2\cdot\ln\frac{R_o}{R}\right)+\\ \left(R_1^2-R_o^2\right)\cdot\left[\begin{array}{l}\frac{\frac{pg}{\mu_2}}{8}\cdot\left(R^2-R_o^2\right)+\frac{\frac{pg}{\mu_2}}{4}\cdot R^2-\frac{pg}{2R}\cdot\left(R_1^2-R_o^2\right)-\\ \frac{\frac{pg}{\mu_2}}{2}\cdot R_o^2\end{array}\right]-\\ \frac{\frac{pg}{\mu_2}}{2}\cdot R_o^2\cdot R_1^2\cdot\ln\frac{R_1}{R}\end{array}\right\} \quad (1)$$

Where:

- R = The sieve radius (m)
- R_0 = R-h = The radius of the free surface of the layer (m)
- p = The density of the grain mixture layer (kg/m^3)
- h = The thickness of the grain mixture layer (m)
- μ_1, μ_2 = The dynamic viscosity coefficients of the sublayers of the grain mixture
- h_1, h_2 = The thickness of the sublayer of the grain mixture bordering on the free surface and the thickness of the sublayer bordering on the surface of the sieve, respectively (m)
- g = The acceleration of gravity (m/sec^2)

As you can see on the Eq. 1, the productivity Q of the VCS for grain depends to a large extent on the coefficient of dynamic viscosity μ of the grain mixture. Since, the vibratory drive of VCS in our case includes twisted cylindrical springs and in order to determine this coefficient we proposed a formula taking into account the influence of the elasticity coefficient of the elastic elements on the coefficient of dynamic viscosity of the grain mixture and consequently on the productivity of the VCS:

$$\mu=\frac{4fpr_c^2}{\omega_{osc}\cdot\left(\left(-\frac{k}{M\cdot a}\right)^2-\left(\frac{3}{\pi}\right)^2\cdot\left(\frac{p}{\omega_{osc}^2\cdot r_c\cdot\rho}\right)^2\cdot f_c^2\right)^{1/2}} \quad (2)$$

Where:

- $p = h.\rho.R.\omega^2$ = The pressure associated with the action of the centrifugal force at the surface of the sieve (Pa)
- ρ = The density of the grain mixture layer (kg/m^3)

k = Rigidity of the elastic elements (H/m)
M = Mass of the oscillatory system (kg)
a = Acceleration of the working element (m/sec^2)
ω_{osc}, ω = The oscillation frequency (Hz) and the angular velocity (rad/sec) of rotation of the working element, respectively
r_c = The radius of one grain particle (m)
f_c = The coefficient of dry friction between grain particles

For the qualitative separation of seeds with a change in the type of agricultural crops and its parameters, it is required to change the angular velocity of rotation ù and the oscillations frequency ω_{osc} of the working element in the VCS.

An effective way to regulate the parameters of oscillations is to change the frequency and duration of connection of LIM inductors to the source of power (Aipov and Linenko, 2013; Linenko *et al*., 2016).

The switching frequency of the FLIM ω_{on} is adjusted to the required limits depending on the type, sort and humidity of the processed grain mixture and can be more or less than the frequency of the natural oscillations of the working element ω_{osc} which is determined by the rigidity k of the elastic elements 4 and the mass of the oscillatory system M:

$$\omega_{osc} = \sqrt{\frac{k}{M}} \quad (3)$$

When $\omega_{on} = \omega_{osc}$ VCS will work in resonance mode which improves its dynamic and energy parameters.

As you can be se on Eq. 4, the switching frequency of the FLIM ω_{on} and the vibrations amplitude of the working element A_{osc} are in inverse proportion, i.e. an increase in the switching frequency ω_{on} of the FLIM to the power supply affects the decrease in the oscillations amplitude A_{osc}:

$$A_{osc} = \sqrt{\left(\frac{\sqrt{L}\cdot 4\cdot f\cdot p\cdot r_c^2}{\left(1-\frac{\rho}{\rho_c}\right)\cdot m_c\cdot g\cdot 4\cdot f^2\cdot \omega^4\cdot R^2\cdot \omega_{osc}}\right)^2 + \left(\frac{3}{\pi}\right)^2\cdot f^2\cdot\left(\frac{p}{\omega_{osc}.r_c\cdot\left(\rho_c+\frac{\rho}{2}\right)}\right)^2} \quad (4)$$

Where:

ρ_c = The particle density (kg/m^3)
f = The coefficient of friction of the grain mixture on the surface of the sieve
m_c = The mass of one particle (kg)
r_c = The radius of one particle (m)
ω_{osc} = The oscillation frequency (Hz)
L = The length of sieve holes (m)

RESULTS AND DISCUSSION

The mathematical model of the developed electric drive of VCS is implemented in MATLAB (Simulink) the environment of object-visual modeling. The linear asynchronous electric motor is realized according to the Park-Gorev differential equations. The elastic elements are realized according to Hooke's law (Aipov and Linenko, 2013).

Figure 5 shows the amplitude-frequency characteristics of the experimental installation of the VCS with FLIM for various rigidities of the elastic elements. The VCS has a cylindrical sieve of radius R = 0.3075 m and a height H = 0.5 m and rotating with a nominal angular velocity ω = 11.3 rad/sec with a capacity Q = 1 ton/h.

The VCS has maximum productivity when there is high intensity of loosening of the grain mixture which is achieved by increasing the oscillation frequency ω_{osc} of the working element by increasing the frequency of connection of the FLIM inductors to the power supply. In this case, the loosening efficiency and porosity of the grain mixture increases, the

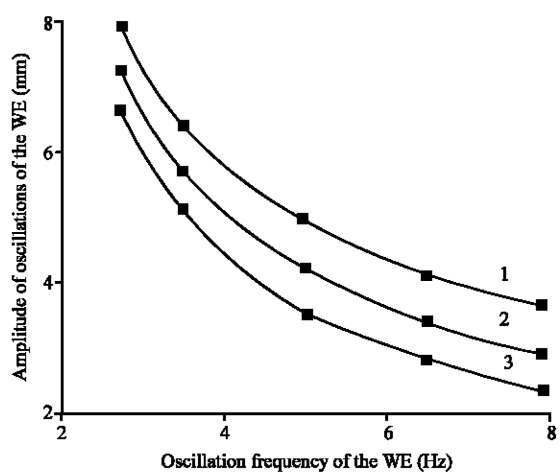

Fig. 5: Amplitude-frequency characteristics of the VCS with FLIM for various rigidities of elastic elements: 1) For k = 1000 H/m; 2) For k = 1100 H/m and 3) For k = 1200 H/m

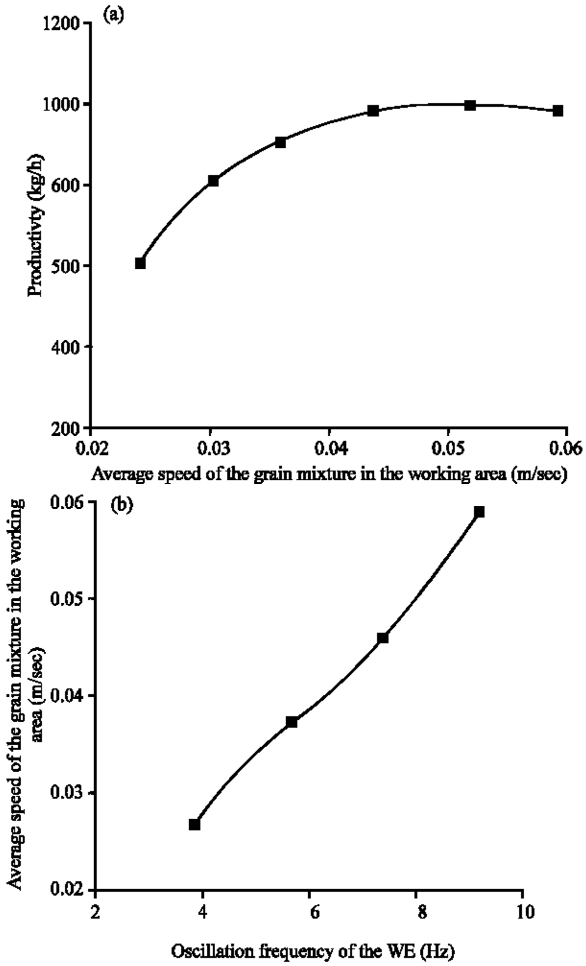

Fig. 6: Experimental dependencies: a) Productivity of the VCS on the speed of the grain mixture and b) The speed of the grain mixture on the frequency of oscillation of the working element

productivity rises, reaches a certain value and subsequently decreases because the dynamic coefficient of friction of the grain mixture decreases which leads to an increase in the average velocity of the grain mixture v_{av} along the sieve and consequently, to a decrease in the probability of the particles sinking into the sieve holes (Fig. 6).

The efficiency of separating the grain mixture is greatly influenced by the angular velocity of rotation of the sieve u and its specific load, q which is determined by the thickness of the grain mixture h and equals to the difference in the radii R_1-R_2:

$$q = \frac{h\upsilon_{av}\rho}{H} \quad (5)$$

where, H is the sieve height (m).

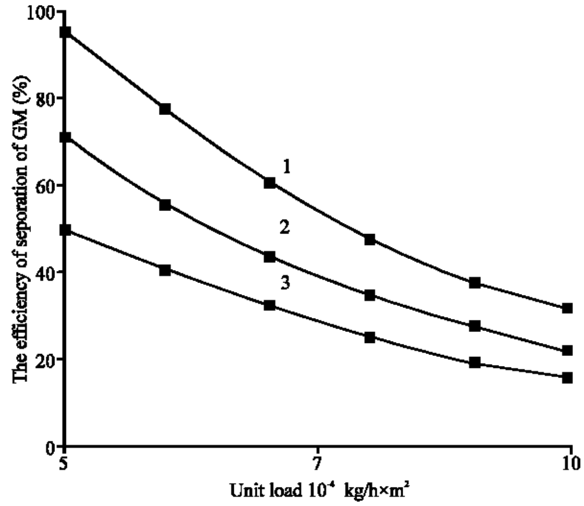

Fig. 7: Dependence of the separation efficiency of the grain mixture on the load and the angular velocity of the sieve rotation; 1 At ω = 11.3 rad/sec; 2) At ω = 14.6 rad/sec and 3) At ω = 16,0 rad/ess

With an increase of the angular velocity of rotation ω greater than 17 rad/sec, the centrifugal force that presses the grain mixture to the sieve grows, the grain mixture becomes compressed by the upper layers and reduces its porosity. As a result the intensity of layer-by-layer motion decreases which leads to a decrease in the rate of penetration of particles through the pores of the layer and a decrease in separation efficiency.

When an increase of the specific load q is above 10 kg/hm^3, the efficiency of the separation of the grain mixture is significantly reduced and this is explained by the decrease in the particles velocity. It is due to the increase of the compaction of the mixture with above lying layers and their flow downwards under the action of gravity (Fig. 7). It is also worth noting that the specific load q can not be less than 4 10^{-4} kg/ Hm^3 as the porosity of the grain mixture increases and the process of its vibroboiling begins.

The productivity of the experimental installation in cleaning food wheat with a moisture content of up to 16%, density of 755 kg/m^3 and a contamination of up to 10% amounts to 1 ton/h with an installed capacity of P = 1360 W. In this case, the nominal angular velocity is ω = 11.3 rad/sec; the amplitude of oscillations of a cylindrical sieve A = 2 mm; the nominal frequency of oscillations of the working element is ω_{osc} = 6 Hz.

The analysis of the results of well-known studies established that to increase the specific productivity and quality of the separation process, it is necessary to intensify the process of grain separation by increasing the porosity and the speed of layer-by-layer movement of the grain mixture.

To determine the rational parameters of the operation of the VCS with the FLIM its mathematical model is developed and investigated. The regularities of productivity and the coefficient of dynamic viscosity are determined by the amplitude and frequency of the working element, the rigidity of the elastic elements and the speed of the grain mixture. It is established that the efficiency of separation of the grain mixture decreases nonlinearly with increasing the sieves loading. The complex analysis of the results of theoretical and experimental studies has established that the use of FLIM in a vibratory drive of the VCS increases the separation efficiency, improves the quality of the grain mixture because by adjusting the parameters of the oscillations of the working element the grain is less injured on the surface of the sieves. The use of controlled oscillations increases the durability of sieves, cleaners, eliminates the additional damage of stuck grains, provides a better grain placement on the sieves which reduces blockage and also has a positive effect on the quality of the separation process and significantly improves the productivity of separator. The obtained results of the VCS research do not contradict the well-known scientific concepts and the results of other resarches studies.

CONCLUSION

In the course of the research an experimental installation of a VCS with a FLIM was developed and theoretical dependences were obtained to determine the productivity of Q of food grains. A comparison of the theoretical and experimental dependences showed that their maximum discrepancy does not exceed 9% which allows us to consider the mathematical model as adequate reflection of physical processes and to use it in practical calculations. Experimental electric drive VCS with a FLIM can be recommended to be introduced into small farms.

The advantage of the proposed design of the VCS with a FLIM in comparison with flat-grid grain cleaning machines is due to higher quality of separation and higher productivity with equal sieve areas and smaller occupied production area.

The creation of a vibratory electric drive of VCS with FLIM due to the direct conversion of electric energy into vibrating motion of the working element allows to decline the mechanical converter of motion. This in its turn will reduce operating costs by 31%, reduce the weight and dimensions as well as provide the opportunity to adjust the parameters of the vibrations of the working element in the vertical plane compared to the existing designs of the VCS.

Thanks to the use of FLIM in the vibratory drive of VCS the economy of the metal is achieved by reducing the installed power of the vibratory drive by 37.5% (from 2 to 1.25 kW) and the energy consumption is reduced. Also, the possibility of adjusting the oscillations parameters of the working element depending on the sort and moisture of the seeds increases the efficiency of separating the grain mixture by 2.5-4%, the intervals for servicing the vibratory drive increase by 18.2% from 180-220 h.

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