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Theoretical Study of Vibrocentrifugal Separation of Grain Mixtures on a Sieveless Seed-cleaning Machine

Valerii Adamchuk¹, Volodymyr Bulgakov², Iaroslav Gadzalo³, *Semjons Ivanovs⁴,
Serhiy Stepanenko¹, Ivan Holovach², Yevhen Ihnatiev⁵

¹National Scientific Centre "Institute for Agricultural Engineering and Electrification", Ukraine;

²National University of Life and Environmental Sciences of Ukraine, Ukraine;

³National Academy of Agrarian Sciences of Ukraine;

⁴Latvia University of Life Sciences and Technologies, Latvia;

⁵Dmytro Motornyi Tavria State Agrotechnological University, Ukraine

Abstract. The article presents an analysis of known developments on creation of sieve-less pneumatic vibration centrifuges separating devices and processes of separating seed mixtures into fractions according to the complex of physical and mechanical properties of components. Mechanistic and mathematical models for studying the movement of particles over the sieve-free surface of pneumatic vibration separators were developed, theoretical studies of movement of seed mixture components were conducted and the most acceptable pneumatic vibration centrifugation process was determined by likeness to the process occurring on the separating surface of pneumatic sorting tables. To achieve the greatest separation of particles on the complex of their physical and mechanical properties (density, geometric dimensions, aerodynamic properties of seeds) is possible with the same direction of oscillatory motion and rotation of the separating surface performing the rotation in the direction from a larger radius to a smaller radius of the surface, in the "fluidization" mode, i. e. i. e. with periodic separation of the lower particles of the layer from the separating surface at simultaneous blowing of the layer by an air stream.

Key words: seed mix, division, pneumatic vibration centrifugation, density, mathematical model.

Introduction

Sowing with high-quality seeds is one of the sources of further increase in crop yields (Poltoretskyi *et al.*, 2017; Nazarova *et al.*, 2021; Arifa & Oleh, 2018). It has been established that the selection of seeds by density before sowing allows to increase the yield on average up to 25%.

The pneumatic vibration method of seed density separation using pneumatic sorting tables is the most widely used (Bracacescu *et al.*, 2018; Shepelev *et al.*, 2020; Drincha, 2006). In developed grain-producing countries, pneumatic sorting tables are used mandatorily for obtaining high-quality seeds (Straksas *et al.*, 2016; Bulgakov *et al.*, 2020), which cannot be obtained by other methods. However, the disadvantage of this class of machines, despite the highest quality indicators of separation of seed mixtures by density of components, is insufficient specific capacity of the separating surface – decks, caused by the low intensity of separation of the seed mixture, due to the limited action of gravitational forces, the main factor of the separation process. Because of this, pneumatic sorting tables in technological processes of

preparation of high-quality seeds are used to a limited extent. Significantly accelerate the separation process of the seed mixture mainly by the density of its components is possible through the use of centrifugal forces of inertia of the particles as the main factor of separation, under the influence of which to accelerate the process, increase the level of separation, reduce the size of the machine and, ultimately, increase its productivity.

The idea of using the centrifugal forces of inertia of rotational motion for the purpose of intensifying the process of separating grain materials by density was suggested (Prilutsky, 2004; Nesterenko *et al.*, 2017).

The work (Bredikhin, 2003) is devoted to the study of processes using centrifugal forces of inertia for the separation of seed mixtures in a sieveless manner.

Theoretical and experimental studies of centrifugation and vibrocentrifugation processes are discussed in works of Nesterenko *et al.*, 2017, Badretidinov *et al.*, 2019; Konopka *et al.*, 2017; Kroulik *et al.* 2016; Malyuta, 1989. The study was subjected to working bodies – vertical conical and

cylindrical, as with the installation in the main drum of additional drums with plates, immersed in a layer of seed mixture and with the additional effect on a layer of seed by vibrating force, installation on the inner surface of the intensifier, accelerating the stratification process, and jet effect on a layer of mixture by air flow. The aerodynamic properties of seeds of agricultural plants under conditions of pneumatic action have been studied in detail (Zewdu, 2007; Kroulik *et al.*, 2016).

Using advantages and disadvantages of the investigated pneumatic vibration centrifuge (Prilutsky, 2004), taking into account influence of constructive and kinematic parameters on the process of separating the seed mixture by density of its components, the improved kinematic scheme of the sieveless seed-cleaning machine (Stepanenko *et al.*, 2013) was suggested, but substantiation of its parameters requires further research.

The purpose of the work is a theoretical study of the process of sieveless separation of mixtures by pneumatic vibrocentrifugation and the substantiation of the parameters of the separating surface for separating the grain mixture similar to separation by pneumatic sorting tables.

Materials and Methods

During theoretical research methods of mathematical modeling, higher mathematics, in particular analytical geometry and the theory of differential equations, theoretical mechanics, as well as methods of programming and numerical calculations on a PC were used (Lenaerts *et al.*, 2014; Dell'aquila, 2007, Bulgakov *et al.*, 2017).

Theoretical studies concern the technological process of separation of the seed grain mixture by the sieveless pneumatic vibrationcentrifuge machine – pneumatic vibrationcentrifuge, the design and technological scheme of which basically corresponds to the schemes considered earlier in the works (Prilutsky, 2004; Prilutsky & Stepanenko, 2014; Stepanenko, Prilutsky & Shvidya, 2013). Seed mixture here means a mixture of seeds of cultivated and

weed plants, mineral and organic impurities. During the separation process, the grain pile can be separated into main crop seeds and waste.

According to the scheme of this seed cleaning machine shown in Figure 1, the separating sections 1 are fixed on the rotor frame 3, which is mounted movably in the machine housing 4 on the eccentric shaft 2, driven in the rotary motion by the pulley 6 with angular speed 1ω . The rotor itself 3, with the sections 1 attached to it, is driven in a rotary motion by pulley 5 with angular velocity 2ω . Separating sections 1, when unfolded, are a rectangular surface with a bevel at the bottom, divided into two parts: air-permeable trapezoidal shape in the form of corrugations 12 and "deaf" (i.e. not air-permeable) surface 13. In this case the air-permeable part of the surface, made in the form of grooves 12, is protected by rims 7, 8, 9, 10 and in the lower part has a discharge edge 11, which allows the seed moving along the trajectory 15 to distribute the seed into I, II and III fractions, namely: light particles (I), medium particles (II) and heavy particles (III), i.e. seeds with the highest density. The predicted values of the parameters of the fractions are as follows: I – fraction, light particles; (for example wheat $1.0 \dots 1.2 \text{ g}\cdot\text{cm}^{-3}$). II – fraction, seeds of medium density; (for example wheat $1.2 \dots 1.35 \text{ g}\cdot\text{cm}^{-3}$). III – fraction, heavy seeds, seeds of the highest density, which can and should be used for sowing material; (for example wheat $1.35 \dots 1.5 \text{ g}\cdot\text{cm}^{-3}$).

The seed mixture to be separated is initially directed to the initial zone 14 of the air-permeable sections 1. Under the action of centrifugal force of rotational motion, a layer of seed mixture is pressed to the surface of the grooves 12 of the separating section 1, and the forces of inertia of oscillatory motion caused by the rotation of the eccentric shaft 2, weight and pressure of the air stream contribute to the movement of particles of the seed mixture layer along certain trajectories 15, the direction of which depends on the interaction of these forces, shape, location of the separating surface in space and physical and mechanical properties of these particles.

Figure 1. Design and technological scheme of the sieveless pneumatic centrifugal seed-cleaning machine: (a) Vertical section; (b) Cross section *A-A*; (c) Diagram of the inner separating surface in unfolded form with the scheme of trajectories of the components of the seed mixture: 1 – separating section; 2 – eccentric shaft; 3 – rotor frame; 4 – machine body; 5 – rotor rotation drive; 6 – eccentric shaft rotation drive; 7, 8, 9, 10 – fencing sides; 11 – discharge edge of surface; 12 – grooves; 13 – "blind" surface; 14 – seed mixture feeding zone; 15 – trajectories of seed mixture components movement.

The studies presented (Prilutsky, 2004) found that the most stable process of relative movement of seed mixture particles on the inner surface of the separating sections 1 in the horizontal direction provides the surface, the cross-section of which by horizontal plane is made in the form of a logarithmic spiral with a constant angle φ (Figure 2 a) between the tangent at each point of the surface to the line of the normal section and the direction of the radius ρ rotation of this point. Therefore, the curvature of the separating sections in the horizontal plane section is taken similar to that presented (Prilutsky, 2004). At the same time grooves 12 have a slope of forming separating sections, the angle between which and the vertical (Figure 2 b) decreases as the distance from the feed area 14 of the seed mixture to the discharge edge 11 of the separating surface, which implies ensuring the reduction of the seed mixture layer thickness and its uniform distribution over the whole area of the separating surface when moving from top to bottom to the discharge edge 11.

To study the behavior of the material particle of the seed mixture on the working surface of the given vibrating centrifugal separator with blowing of the mixture layer by the air flow, first of all, let us build the equivalent scheme (Figure 2). For this purpose let us consider the section of separator cleaning surface as a curvilinear surface (the whole specified surface has conic shape and it is air-permeable), let us place the particle *M* of grain mixture on it in any position and show the supposed trajectory of its movement. Since the motion of the particle *M* will be complex, in order to describe it, let us set and show on this equivalent diagram all coordinate axis systems necessary for this case. Since the separating surface rotates around the rotor's *OZ* axis with angular velocity 2ω , and the axis itself *OZ* of the rotor rotates around a circle of radius *a* around the *O_oZ_o* axis, passing through the center of this circle, the separating surface makes a complex motion, and it is obvious that the motion of the rotor, and therefore the specified separating surface, on a circle of radius *a* will be progressive. Therefore, each point of the rotor, including

those belonging to the separating surface, in the specified motion will move equally, i.e. having the same trajectory, speed and acceleration, coinciding with the trajectory, speed and acceleration of point *O* (axis *OZ*). To describe the motion of the rotor on a circle of radius *a*, let us choose an absolute stationary coordinate system *O_oX_oY_oZ_o*, the axis which passes through the center of the circle (point *O_o*). Let us point the coordinate axis *O_oX_o* horizontally to the right, perpendicular to the axis, and the axis *O_oY_o* – perpendicular to the plane *Z_oO_oX_o* (Figure 2).

Figure 2. Equivalent scheme of the motion of the material particle *M* of the seed mixture on the separating surface of the pneumatic vibration centerless sieve cleaning machine.

Let us also relate the Cartesian coordinate system $OXYZ$ to the point O of the rotor, the origin of which is located at the point O . The coordinate axes of this system will be parallel to the corresponding coordinate axes of the system $O_oX_oY_oZ_o$, that is $OZ \parallel O_oZ_o$, $OX \parallel O_oX_o$ and $OY \parallel O_oY_o$. Since the rotor moves translationally on a circle of radius a , the corresponding coordinate axes of the $OXYZ$ system remain parallel to the axes of the coordinate system at all times. And this means that the coordinate systems and $OXYZ$ differ only in the fact that in the first coordinate system the point O_o (origin) is stationary, and in the second, the point O moves on a circle of radius h around the point O_o . Therefore, it can be argued in advance that the equations of motion of a material point M in the $O_oX_oY_oZ_o$ and $OXYZ$ coordinate systems will differ only in the presence of centrifugal force of inertia in the equations of motion in the $OXYZ$ coordinate system (correction for non-inertiality of this system). All other forces (centrifugal force of inertia of rotor rotation around its own axis, Coriolis force of inertia, airflow force, friction force, normal coupling reaction) will have the same expressions for their determination and the same values in both coordinate systems. Further, since we consider the rotational motion of the rotor around its own axis OZ , the most appropriate to describe the motion of the seed mixture particle is to use the cylindrical coordinate system, in which the equations of motion of the particle M will have a simpler and easier to solve form than in the Cartesian coordinate system $OXYZ$. So, we will consider the motion of the separating surface itself and the particles M of the seed mixture in a cylindrical coordinate system $OZ\rho\alpha$, OZ axis of which points vertically upwards and coincides with the rotor's axis of rotation (common axis with Cartesian coordinate system $OXYZ$), $O\rho$ axis is located in horizontal XOY plane, oriented in radial direction from point O and deviated from horizontal axis OX by angle α , that is, in the OXY plane, the parameters ρ and form a polar coordinate system $O\rho\alpha$ and are the coordinates of the particle M in the horizontal plane OXY . The direction of change of angle α in Fig. 2 is shown as an axis $M\alpha'$, perpendicular to the $O\rho$ axis. In space, in the cylindrical coordinate system $OZ\rho\alpha$, the particle has coordinates $M(Z, \rho, \alpha)$ should be noted that the coordinate system $OZ\rho\alpha$, as well as the coordinate system $OXYZ$, will move on a circle of radius a around the point O_o progressively. Thus, the motion of the seed mixture particle M in the cylindrical coordinate system $OZ\rho\alpha$, taking into account the above correction for non-inertiality, can be considered as a motion in the absolute coordinate system.

On a material particle M of mass m in its relative motion, considered in the coordinate system the following forces act:

$G = m \cdot g$ – particle weight, N;

where m – particle mass, kg;

g – acceleration of gravity, $m \cdot s^{-2}$;

N – normal response of the conical surface, N;

$F_m = fN$ – force of friction, N;

F_b – power of the air flow, N;

$P = m h \omega_1^2$ – the force of the air flow;

$F_{ce} = m \rho \omega_2^2$ – the centrifugal force of inertia of the particle's transfer motion;

$F_{cr} = m \frac{V_v^2}{\rho_k}$ – the centrifugal force of inertia of relative

motion of the particle, resulting from the curvature of the trajectory of relative motion;

$F_k = 2m\omega_2 V_r \sin(\bar{\omega}_2, \bar{V}_r)$ – Coriolis force of inertia.

In this case, the symbols included in the expressions for determining the above forces mean the following:

f – coefficient of friction;

h – amplitude of oscillatory motion, m;

ω_1 – angular velocity of the eccentric shaft, rad^{-1} ;

ω_2 – rotor angular velocity, rad^{-1} ;

V_r – velocity of the relative motion of the particle, $m \cdot s^{-1}$;

ρ – radius of curvature of the transport trajectory of the particle, m;

ρ_k – radius of curvature of trajectory of relative motion of the particle, m;

$(\bar{\omega}_2, \bar{V}_r)$ – the angle between vector $\bar{\omega}_2$ the angular velocity

of the rotor and the vector $\bar{V}$ relative velocity of the particle, rad;

By projecting the above forces onto the normal of the tapered surface, we obtain an expression for determining the normal reaction of the tapered surface:

$$N = F_{ce} \cdot \sin\varphi \cdot \cos\gamma + P \cdot \sin(\omega_1 t - \alpha + \varphi) \cdot \cos\gamma - F_b \cdot \sin(\beta + \varphi) + F_{cr} \cdot \cos(\bar{n}, \bar{\lambda}) \cdot \cos\gamma + F_k \cdot \cos\varphi + G \cdot \sin\gamma, \quad (1)$$

where φ – angle between the radial coordinate ρ of the material particle M and the tangent τ to the surface at the location of this particle; γ – angle between the vertical and the formative of the conical surface; $t_1 \omega$ – angle of rotation of the eccentric shaft at an arbitrary moment of time; α – angular coordinate (angle of deviation of radial coordinate from the axis OX); β – angle between the radial coordinate and the vector F_b of airflow force; $(\bar{n}, \bar{\lambda})$ – is the angle between the direction of the normal to the conical surface and the direction of the normal to the trajectory S_r of the relative motion of the material particle M on the surface.

Let us further express the terms in expression (1) through the kinematic parameters of the process under study and the cylindrical coordinates ρ , α and α' . Thus, it is known from differential geometry that the following equality can be written for a cylindrical surface:

$$m \frac{V_r^2}{\rho_k} \cdot \cos(\bar{n}, \bar{\lambda}) = m \frac{V_{r\rho\alpha}^2}{\rho_n}, \quad (2)$$

where ρ_n – radius of curvature of the normal section of the separating surface, the value of which will be equal:

$$\rho_n = \frac{\rho}{\sin\varphi}, \quad (3)$$

V_{rpa} – the horizontal component of the relative velocity of a material particle M , $m \cdot s^{-1}$.

Since the relative velocity in the cylindrical coordinate system $OZ\rho\alpha$ is found from the following expression:

$$V_r = \sqrt{(\dot{\rho})^2 + (\omega_2 - \dot{\alpha})^2 \cdot (\rho)^2 + (\dot{Z})^2}, \quad (4)$$

then its horizontal component V_{rpa} will be equal to:

$$V_{rpa} = \sqrt{(\dot{\rho})^2 + (\omega_2 - \dot{\alpha})^2 \cdot (\rho)^2}. \quad (5)$$

It can also be expressed in terms of the tangential component of the relative velocity of the particle and the angle of φ , namely:

$$V_{rpa} = \frac{(\omega_2 - \dot{\alpha}) \cdot \rho}{\sin \varphi}. \quad (6)$$

Then, taking into account (3) and (6), expression (2) can be written in the following form:

$$m \frac{V_r^2}{\rho_k} \cdot \cos(\bar{n}, \bar{\lambda}) = m \frac{(\omega_2 - \dot{\alpha})^2 \cdot \rho}{\sin \varphi}, \quad (7)$$

or

$$F_{cr} \cdot \cos(\bar{n}, \bar{\lambda}) = m \frac{(\omega_2 - \dot{\alpha})^2 \cdot \rho}{\sin \varphi}. \quad (8)$$

Since the following expression takes place:

$$\sin(\bar{\omega}_2, \bar{V}) = \frac{V_{rpa}}{V_r}, \quad (9)$$

then, taking into account (6), we obtain the expression for determining the Coriolis force of inertia:

$$F_k = 2m\omega_2 \frac{(\omega_2 - \dot{\alpha}) \cdot \rho}{\sin \varphi}. \quad (10)$$

Substituting values for centrifugal forces into expression (1) F_{ce} and P , as well as taking into account expressions (8) and (10), we obtain an analytical dependence for determining the normal reaction N of the separating surface of the following form:

$$\begin{aligned} N = & m \rho \omega_2^2 \cdot \sin \varphi \cdot \cos \gamma + m h \omega_1^2 \cdot \sin(\omega_1 t - \alpha + \varphi) \cdot \cos(\gamma) - \\ & - F_b \cdot \sin(\beta + \varphi) + m \frac{(\omega_2 - \dot{\alpha})^2 \cdot \rho}{\sin \varphi} \cdot \cos \gamma + \\ & + 2m\omega_2 \frac{(\omega_2 - \dot{\alpha}) \cdot \rho}{\sin \varphi} \cdot \cos \varphi + mg \cdot \sin \gamma. \end{aligned} \quad (11)$$

Results and Discussion

The material particles M of the seed mixture during pneumatic vibration centrifugation are characterized by three main modes of motion relative to the separating surface of the section: with sliding on the surface, with a stop on the surface and with a breakaway from it.

To study the motion of a material particle M , we apply the basic law of dynamics of a material point. Taking into account the equivalent scheme shown in Fig. 2, the equation of its motion (without taking into account the centrifugal force of inertia of transfer motion and the Coriolis force of inertia) in vector form will have the following form:

$$m\bar{a} = \bar{N} + \bar{F}_m + \bar{P} + \bar{F}_b \quad (12)$$

where $\bar{a}$ – acceleration of a material particle M .

In projections on the axes of the absolute cylindrical coordinate system $OZ\rho\alpha$ equation (12) will be written as the following system of differential equations:

$$\left. \begin{aligned} m(\ddot{\rho} - \rho(\dot{\alpha})^2) &= -N \sin \varphi \cos \gamma - \\ &- F_m \frac{\dot{\rho}}{V_r} + P \cos(\omega_1 t - \alpha) - F_b \cdot \cos \beta, \\ m(2\dot{\rho}\dot{\alpha} + \rho\ddot{\alpha}) &= -N \cos \varphi \cos \gamma - \\ &- F_m \frac{(\omega_2 - \dot{\alpha}) \cdot \rho}{V_r} + P \sin(\omega_1 t - \alpha) - \\ &- F_b \cdot \sin \beta m(\ddot{Z}) = G - F_m \frac{\dot{Z}}{V_r} - N \sin \gamma, \end{aligned} \right\} \quad (13)$$

where Z , ρ , α ; $\dot{Z}$, $\dot{\rho}$, $\dot{\alpha}$ and $\ddot{Z}$, $\ddot{\rho}$, $\ddot{\alpha}$ – respectively, the projections of displacement, velocity and acceleration of a material particle M on the axes of the adopted cylindrical coordinate system $OZ\rho\alpha$;

t – time of motion of a material particle.

As can be seen, the system (13) included the basic physical and mechanical properties of seeds in the form of F_b – the force of the air flow, which includes the midsection of the seeds, the coefficient of soaring and the density of seeds (specific gravity).

When the value of the relative velocity is reached $V_r = 0$ material particle M moves in the mode with relative stopping as long as:

$$F_m > R, \quad (14)$$

where R – is the net result of all forces except for the friction force F_m , acting on the material particle M in the tangential plane to the separating surface, in which this particle is located.

In this case, its kinematic parameters in the relative stop mode will be equal:

$$\left. \begin{aligned} \ddot{\rho} &= 0, \quad \ddot{\alpha} = 0, \quad \ddot{Z} = 0, \\ \dot{\rho} &= 0, \quad \dot{\alpha} = 0, \quad \dot{Z} = 0, \\ \rho &= \text{const}, \quad \alpha = \text{const}, \quad Z = \text{const}. \end{aligned} \right\} \quad (15)$$

If condition (14) is violated, the material particle M begins relative motion. With decreasing magnitude of pressing of material particle M to surface, especially if normal reaction reaches value $N = 0$, its detachment from separating surface starts, and process of particle motion in accepted coordinate system is modeled by system of differential equations, which follows from system of differential equations (13) at condition when $N = 0$, and thus $F_m = f \cdot N = 0$, i.e. will have such form:

$$\left. \begin{aligned} m(\ddot{\rho} - \rho(\dot{\alpha})^2) &= P \cos(\omega_1 t - \alpha) - F_b \cdot \cos \beta, \\ m(2\rho\dot{\alpha} + \rho\ddot{\alpha}) &= P \sin(\omega_1 t - \alpha) - F_b \cdot \sin \beta, \\ m(\ddot{Z}) &= G. \end{aligned} \right\} \quad (16)$$

The motion of the material particle M with relative detachment occurs as long as its coordinate ρ is less than the coordinate ρ_n of the separating surface point, the coordinate Z is less than the coordinate Z_n of the separating surface point, lying on the coordinate axes in the plane $OZ\rho$. In the adopted coordinate system $OZ\rho\alpha$ and taking into account the parameters of relative motion of the particle M on the separating surface, the surface of the separating section of the pneumovibrocentrifuge has the form:

$$\rho_n = (\rho_0 - Z_n \cdot \tan \gamma) \cdot e^{\cot \varphi (\omega_2 t - \alpha)} \quad (17)$$

where ρ_0 – is the radius of the logarithmic spiral corresponding to the radial coordinate of the particle M at the initial moment of time t of its motion along the separating surface;

e – the base of natural logarithms.

Thus, a mathematical model of the movement of seed mixture particles, modeling the movement of particles on the separating surface with relative slip (13), with a stop on the separating surface (15) and with a break from it (16), as well as the boundary conditions of particle motion transition from one mode to another, was obtained. Analysis of the system of equations (13) with consideration of V_r and N shows that, other things being equal, the character of movement of seed mixture particles depends on their frictional properties, mass, aerodynamic properties (influence of air flow), as well as the curvature of surface (angle φ) and inclination of the wedge-shaped grooves (angle γ), which provides movement of the lower layer of particles mainly along horizontal trajectories, along the wedge-shaped grooves, and the upper layer of particles mainly above the grooves. When particles move with a relative stop, their absolute motion occurs depending on the direction of rotation ω_1 and ω_2 : if the directions coincide, the particles move along epicycloids, otherwise they move along hypocycloids. The mode of movement of particles of the separated mixture with a relative stop on the separating surface is known to be unfavorable for the segregation process, since it does not provide layer opening; and therefore the conditions for intra-layer movement of particles. In the mode of movement of particles with

separation from the separating surface, as follows from equations (12), the main influence on the nature of their movement has the air flow pressure and weight, which by analogy with the movement on the deck of pneumatic sorting tables creates a "fluidization" of the seed mixture layer, intensifying the process of redistribution of particles by layer thickness by the complex of physical and mechanical properties of particles.

Due to the difference in physical and mechanical properties of the particles, and primarily their density, their intra-layer movement is achieved, in which larger and lighter particles "float" to the layer surface in the zone of less influence of centrifugal forces, due to increased "fluidity" move on the layer surface in the direction of increasing ρ_n , while the denser ones go deeper into the mixture layer, are subjected to more centrifugal forces and forces of oscillatory motion, which ensure their transport across the surface in the downward direction ρ_n . Thus, the "front" distribution of particles with different physical and mechanical properties extends along the discharge edge 11 (Figure 1, c), which provides their sorting into fractions, similar to the process of separation of seeds by pneumatic sorting tables. We carried out numerical calculations on a PC, which allowed us to construct graphs of the trajectories of the movement of seeds on the separating surface (Figure 3). The received graphs show that during movement of particle M on separating surface radial and vertical components of its velocity change periodically with frequency equal to their difference at coincidence of directions of rotor and eccentric shaft rotation speeds, and at noncoincidence of directions – their sum. With increase of acceleration of separating surface the process of particles movement on it proceeds more intensively. By changing the geometric shape and kinematic mode of motion of the separating surface to the particles of the grain mixture can provide a relative movement on this surface both with their distance and with their approach to the center of rotation of the surface. Grain mixture particles with different frictional properties move along certain trajectories, their movement with periodic detachment from the surface achieves the most precise distribution of them, depending on these properties, along the perimeter of the section (Figure 3). Despite the fact that the particles of the grain mixture are placed on the separating surface of the pneumatic vibration centrifuge according to the thickness of the layer, depending on their physical and mechanical properties, the "upper", lighter particles in the "fluidization" state have more "fluidity", due to which it is supposed to achieve their distribution depending on these properties over the entire separating surface, as on the deck of pneumatic sorting tables.

Given the effect of "restraining" the movement of particles in the vertical direction due to the stepped shape of the separating surface, it is expected to achieve a clearer distribution of particles of the grain mixture along the discharge edge of the separating surface than to increase the efficiency of particle distribution of the grain mixture on the set of physical and mechanical properties, and in pre-cleaning by air flow and sorting by size – density.

Figure 3. Dependence of vertical displacement on radial displacement for particles of grain mixture at $f = 0.4$;
 $\varphi = 1.465$ rad;

$h = 0.006$ m; $\omega_1 = 110$ rad·s⁻¹; $\omega_2 = 13$ rad·s⁻¹ for
different acceleration ω_a airflow:
1 – $\omega_a = 0$ m·s⁻²; 2 – $\omega_a = 8$ m·s⁻²

Figure 4. Dependence of vertical displacement on radial displacement for particles of grain mixture at
 $f = 0.3$; $\varphi = 1.465$ rad; $h = 0.006$ m; ω_1

$= 110$ rad·s⁻¹; $\omega_2 = 13$ rad·s⁻¹ for different
acceleration ω_a airflow:
1 – $\omega_a = 0$ m·s⁻²; 2 – $\omega_a = 8$ m·s⁻²

Figure 5. Dependence of vertical displacement on radial displacement for particles of grain mixture at $f = 0.2$;

$\varphi = 1.465$ rad; $h = 0.006$ m; $\omega_1 = 110$ rad·s⁻¹; $\omega_2 = 13$ rad·s⁻¹ for different acceleration ω_a airflow: 1 –
 $\omega_a = 0$ m·s⁻²; 2 – $\omega_a = 8$ m·s⁻²

As the graphs shown in Figure 3 – Figure 5 show, the increase in acceleration of air flow contributes to the increase in vertical movement of the material particle. Moreover, the smaller is the friction coefficient f of the particle, the more significant is this effect. However, it should also be noted that increasing the frictional properties of the particle contributes to its greatest radial movement, which means that the separation of particle trajectories is more effective when these properties are increased.

On the basis of studies it was found that the rational parameters of the separating working body, its kinematic mode and geometric dimensions it is advisable to take the following: – take the initial radius at the point of grain mixture feeding on the separating surface equal to 0.3 m; the height of the separating surface – 0.6 m; angular velocity of rotation of the rotor $2\omega = 13 \text{ s}^{-1}$; angular velocity of oscillatory motion $1\omega = 110 \text{ s}^{-1}$; the air mode is provided regulated at full air pressure $H_a = 200...300 \text{ Pa}$; angle $\varphi = 1.4...1.57 \text{ rad}$; the shape of the separating surface to be trapezoidal.

Conclusions

1. Theoretical studies of the movement of grain seed mixture particles on the sieveless separating surface under the influence of vibration and centrifugal forces with its simultaneous blowing by an air stream were carried out.

2. A mechanical-mathematical model of the movement of seed mixture particles over the separating surface, the solution and analysis of which allows us to study the process of separation and separation of the grain mixture into fractions, was built. It has been established that the range of seed separation in the vertical plane will vary from 0.12 m to 0.33 m, and in the radial plane from 0.01 m to 0.2 m, depending on the density of the seeds. That is, seeds with a lower density will travel a shorter distance (trajectories of their movement) than seeds with a higher density but with the same geometric parameters of the seed.

3. Changing the geometric dimensions and kinematic modes of motion of the separating surface of the new design can provide different trajectories of movement of grain mixture particles with different physical and mechanical properties. It was found that the rational parameters of the separating working body are as follows: take the initial radius at the point of grain mixture feeding on the separating surface equal to 0.3 m; the height of the separating surface – 0.6 m; angular velocity of rotation of the rotor $= 13 \text{ s}^{-1}$; angular velocity of oscillatory motion $= 110 \text{ s}^{-1}$; the air mode is provided regulated at full air pressure $H_a = 200...300 \text{ Pa}$; angle $\varphi = 1.4...1.57 \text{ rad}$; the shape of the separating surface to be trapezoidal.

4. Separation of grain mixture particles according to the complex of physical and mechanical properties is provided not only by layer thickness, but also on the entire separating surface.

5. The greatest stratification of grain mixture particles by the complex of their physical and mechanical properties is achieved with the same direction of oscillatory motion speed and rotation of the separating surface, which rotates in the direction from large radius to the smaller radius of the surface, in the mode of "fluidization" with simultaneous blowing of the layer by an air stream.

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