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MATHEMATICAL MODELING OF THE VIBRO-CENTRIFUGAL PROCESS OF GRAIN SEPARATION

This article addresses an important scientific and practical problem in agricultural engineering: the intensification of grain cleaning and sorting processes through the use of vibrating centrifugal force fields. It has been established that traditional separation methods often fail to meet the necessary quality standards due to slight differences in the physical and mechanical properties of the components of the grain mixture. The study demonstrates that combining centrifugal fields with axial oscillations of the working surface effectively amplifies differences in particle density and aerodynamic properties, leading to more accurate separation.

The study presents an improved mathematical model of the mechanics of a single particle on the inner surface of a conical rotor performing both rotational and oscillatory motion. A comprehensive force analysis was conducted, taking into account the centrifugal inertial force, the oscillatory inertial force, the gravitational force, the normal reaction of the rotor surface, and the friction force between the particle and the material. Based on an analysis of dynamic equilibrium and the conditions of continuous contact motion, a differential equation for the particle's displacement to the end of the rotor's expansion was derived.

Analytical expressions were derived for determining the instantaneous and average velocities of grain material as functions of the oscillation phase. The study identified the critical conditions necessary to ensure a steady-state motion regime with periodic stops, which is optimal for high-quality separation. The quantitative influence of key kinematic parameters, in particular specifically, the amplitude and frequency of oscillations, the angular velocity of the rotor, the taper angle, and the friction coefficient, on process performance was established. The formulated recommendations provide a rigorous scientific basis for the design and modernization of high-performance vibrocentrifugal machines for grain cleaning, aimed at improving seed quality while simultaneously reducing energy consumption during post-harvest processing stages.

Keywords: *vibrocentrifugal separator, grain material, mathematical modeling, differential equation of motion, conical rotor, kinematic parameters, continuous contact motion, displacement velocity, grain cleaning.*

Formulation of the problem. The cleaning of grain materials is one of the key stages of post-harvest processing, significantly affecting the quality of the final product, the energy efficiency of technological processes, and the minimization of grain losses. Various separation principles are used in the design of grain cleaning machines, among which vibrocentrifugal and pneumatic centrifugal separators stand out for their ability to intensify the separation of grain mixtures based on the physical and mechanical properties of their components. However, existing designs of such separators often fail to ensure the desired separation quality due to insufficient theoretical justification of the kinematic parameters of grain material movement across the working surface and the interaction of particles with the working surfaces under the action of combined forces. In classical approaches, many studies focus on the empirical determination of relationships between productivity and process parameters, whereas modern mathematical and mechanical-mathematical models of grain movement in separators still require more in-depth scientific investigation.

In particular, improved mechanical-mathematical models of pneumatic centrifugal separators have demonstrated a critical dependence of separation efficiency on the rotational parameters and vibrational characteristics of the working surface, as well as on the interaction between the grain mixture and the air flow; however, these models require further development to account for complex kinematic processes under real operating conditions [1]. An analysis of existing theoretical works confirms that the motion trajectories of grain material, the velocity of movement, and the influence of the vibration parameters and geometry of the separator's working surface remain insufficiently studied in the context of their impact on separation quality [2]. The mechanisms of interaction between grain particles and the walls and force fields under combined vibrational and pneumatic influences are also insufficiently studied, which limits the ability to accurately predict separation results and optimally design machine working parts.

Thus, there is a pressing need to develop and refine theoretical models of grain motion in vibrocentrifugal and pneumatic centrifugal separators, taking into account the influence of kinematic parameters (vibration frequency and amplitude, angular velocities, surface geometry, friction forces, and aerodynamic forces) on the efficiency of the separation process. Improving such models will contribute to increasing the productivity and quality of grain cleaning machines through the well-founded selection of optimal design and operating parameters and their influence on the motion of particles in the grain medium.

Analysis of the latest research and publications. In recent scientific literature, the issue of intensifying grain cleaning processes using force fields generated by vibrating and air separators is regarded as an important scientific and practical challenge. In particular, significant attention is paid to the development and refinement of mathematical-mechanical models of grain flow in separators to improve separation quality, as well as to the development of optimal kinematic parameters and aerodynamic characteristics of working surfaces.

Studies by other researchers have shown that grains with a higher specific gravity are biologically more mature. When such seeds are sown, yields increase by 2–5 centners per hectare. Therefore, it is clearly advisable to develop new technological processes and machine designs in which the grain mixture would be separated based on specific gravity. However, since the differences in grain specific gravity are relatively small (1.2 to 1.5 g/cm³ for wheat, and 1.2 to 1.4 g/cm³ for barley and oats), to amplify these differences, the grains must be placed in a centrifugal field. This can be achieved using centrifuges.

One of the main areas of focus is the refinement of mechanical-mathematical models for the pneumatic vibrating-centrifugal separation of grain material by density, which allows for the interaction between the phases of the grain mixture and the air flow to be taken into account, as well as for the determination of optimal operating parameters for the separator to improve separation efficiency [1].

The research also covers theoretical models of grain mixture flow on working surfaces without screens, incorporating a detailed hydrodynamic model of particle motion, which allows for the prediction of trajectories and the distribution of components in separators with combined forces. This makes it possible to determine the optimal design and operating parameters that affect separation efficiency and quality [3].

Some studies are aimed at analyzing kinematic parameters and optimizing the working bodies of the separator, in particular, mathematical modeling of the motion of grain mixtures on vertical mesh surfaces of vibrocentrifugal separators [4].

Numerous publications have examined the energy and design aspects of separators, particularly methods for improving drive efficiency and reducing operating costs through the use of new drive mechanisms, including linear electric motors in the drive system of a vibrating centrifugal separator [5].

Another area of research focuses on optimizing the aerodynamic elements of grain separation in pneumatic separation channels, taking into account the shape and geometry of the channels, which affect the productivity and quality of mixture separation [6, 7, 8].

Also important are studies devoted to the analysis of particle motion parameters under combined vibrational and aerodynamic conditions, in which the authors examine the factors determining particle trajectories and their interaction with the force fields of working surfaces [9, 10, 11].

The general conclusion of current research indicates the need for further development of mathematical models that account for the actual kinematic, aerodynamic, and physical-mechanical parameters of grain mixtures, which will improve the accuracy of modeling particle motion effects and the influence of external forces on the separation process.

The purpose of the study.The aim of this article is to investigate the influence of kinematic parameters on the motion of grain material in vibrating centrifugal separators and to develop improved mathematical-mechanical models for predicting particle trajectories and optimizing the separation process based on grain density. The study aims to determine optimal operational and design parameters for the separator that enhance the efficiency, quality, and productivity of the separation process.

***The main results of the study*.** The kinematic parameters of a vibrating centrifugal separator include the amplitude A and frequency Ω of the vibrations, the angular velocity ω of the working element, the taper angle α of the rotor, and the coefficient of friction f between the material and the working surface.

Literature sources [4] indicate that kinematic parameters determine the nature and speed of material movement across the working surface of grain cleaning machines.

In turn, the nature of the movement and the average speed of material displacement determine the technological process of grain cleaning machines.

The maximum initial load in a vibrocentrifugal separator for the given values of kinematic parameters and the state of the grain material is determined by the expression:

$$Q_0 = 3600 \cdot \pi \cdot D_{IN} \cdot \Delta \cdot V_{avg} \cdot \gamma, \qquad (1)$$

where D_{IN} – diameter of the circle at the entrance to the gap between the conical surfaces, m; Δ – average cross-sectional dimension of the seed, m; V_{avg} – average velocity of the seed at the entrance to the working body, m/s; γ – bulk density of the seed, kg/m³.

Equation (1) shows that the initial load (for given values of the other terms in the equation) depends on the average flow velocity of the grain material. Changes in the initial load affect the efficiency of grain cleaning machines [4].

Thus, the average material flow velocity is a determining factor that links the effects of most parameters influencing the efficiency of grain cleaning machines. Therefore, to understand the operational process of a vibrating centrifugal separator and control this process, it is necessary to know the material flow velocity under any specific conditions and the effect of flow velocity on the efficiency of the separation process.

During the rotation and vibration of the working element of the vibrocentrifugal separator in the axial direction, the following forces act on a particle located on the surface of the rotor (Fig. 1):

– centrifugal force of inertia $C = m\omega^2 R_x$;

– the inertial force due to vibrational motion, $I = mA\Omega^2 \sin\theta$, which depends on the phase of the vibrations $\theta = \Omega t$ and changes in magnitude and direction: when the rotor is above the mean position, it is directed upward and assists the particle's movement in the positive direction, and in the opposite case, it is directed downward and opposes the upward movement

– gravitational force $\mathrm{P} = mg$;

– wall reaction force N;

– friction force of the particle against the working surface F_f;

– Coriolis inertial force, which is negligible compared to the other acting forces.

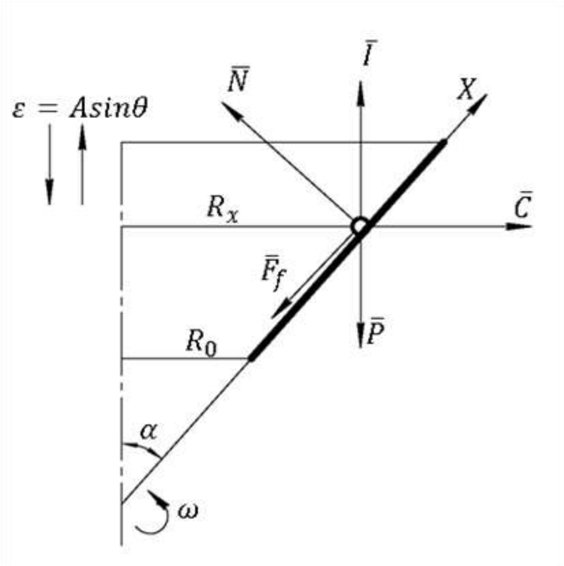

Fig. 1 Diagram of the forces acting on a particle in the rotor of a vibrating centrifugal separator

The particle velocity is determined under the condition of continuous contact between the particle and the working surface. The condition for continuous contact of the particle in a conical rotor is determined as follows. For this, the wall reaction force N must be greater than zero:

$$N = mg\sin\alpha + m\omega^2 R_x \cos\alpha - mA\Omega^2 \sin\theta \cdot \sin\alpha > 0 \qquad (2)$$

Transforming expression (2), we obtain: $Z_0 = \frac{R_x\omega^2 ctg\alpha + g}{A\Omega^2 \sin\theta} > 1$.

If the expression $I = A\Omega^2 \sin\theta$ reaches its maximum value when $\sin\theta = 1$ and condition (2) holds for the radius $R_x = R_0$, then

$$Z_0 = \frac{1}{A\Omega^2}(R_0\omega^2 ctg\alpha + g) > 1 \qquad (3)$$

Considering the condition of dynamic equilibrium, we obtain a differential equation without discontinuous motion of particles in the direction of the rotor's expansion:

$$m\frac{d^2 \cdot X}{dt^2} = mR_x\omega^2 \sin\alpha - mg\cos\alpha + mA\Omega^2 \sin\theta \cdot \sin\alpha - f(mR_x\omega^2 \cos\alpha + mg\sin\alpha - mA\Omega^2 \sin\theta \cdot \sin\alpha) \quad (4)$$

After the appropriate transformations, differential equation (4) will take the form:

$$\frac{d^2X}{d\theta^2} - \frac{X\sin\alpha\cdot\sin(\alpha-\varphi)}{\cos\varphi}\cdot\frac{\omega^2}{\Omega^2} = -\frac{A\cos(\alpha-\varphi)}{\cos\varphi}\cdot\left\{\frac{1}{A\Omega^2}\cdot[-R_0\omega^2 tg(\alpha-\varphi)+g]-\sin\theta\right\} \qquad (5)$$

where X – displacement of a particle on the surface of a conical rotor: $X=\frac{R_x-R_0}{\sin\alpha}$; R_x – distance from the axis of rotation to the particle located on the rotor surface; R_0 – initial coordinate of the particle; $\varphi=\text{arctg}f$ – the angle of friction between the material and the rotor wall (φ is less than the conicity angle of the rotor of the centrifugal separator).

Let us derive the notation: $k_+=\frac{\omega}{\Omega}\cdot\sqrt{\frac{\sin\alpha\cdot\sin(\alpha-\varphi)}{\cos\varphi}}$; $k_-=\frac{\omega}{\Omega}\cdot\sqrt{\frac{\sin\alpha\cdot\sin(\alpha+\varphi)}{\cos\varphi}}$; $Z_+=\frac{1}{A\Omega^2}\cdot[-R_0\omega^2 tg(\alpha-\varphi)+g]$; $Z_-=\frac{1}{A\Omega^2}\cdot[-R_0\omega^2 tg(\alpha+\varphi)+g]$; $\sigma=\frac{A\cdot\cos(\alpha-\varphi)}{\cos\varphi}$,

where Z_+, k_+ – parameters characterizing the motion of the material in the desired direction; Z_-, k_- – parameters characterizing the motion of the material toward the narrowing end of the conical rotor (this motion is not considered here).

Then, finally, we have:

$$\frac{d^2X}{d\theta^2}-k_+^2X=-\sigma[Z_+-\sin\theta] \qquad (6)$$

Among the wide variety of possible motion patterns of granular material on the surface of a conical rotor, the predominant mode is one in which the particles move toward the widening end with temporary pauses.

Analysis of the differential equation (6) shows that particle motion toward the expansion end with temporary stops is possible if the parameter Z_+ is a fractional value and the following conditions are satisfied:

$$0<Z_+<1;\ -\sim<Z_-<-1.$$

Therefore, the condition that the kinematic parameters must satisfy for motion in the positive direction with temporary stops is expressed by the inequality:

$$g-R_0\omega^2 tg(\alpha-\varphi)<A\Omega^2<R_0\omega^2 tg(\alpha+\varphi)-g \qquad (7)$$

By solving the differential equation (6) governing the motion of a particle in a vibrating centrifugal separator, we obtain expressions for displacement and velocity as functions of the vibration phase θ.

These expressions are as follows:

$$X=C_1e^{k_+\theta}+C_2e^{k_+\theta}-\frac{\sigma\sin\theta}{1+k_+^2}+\frac{\sigma Z_+}{k_+^2} \qquad (8)$$

$$V=C_1k_+e^{k_+\theta}-C_2k_+e^{k_+\theta}-\frac{\sigma\cos\theta}{1+k_+^2} \qquad (9)$$

The coefficients C_1 and C_2 are determined from the initial conditions: $x=0$, $x=0$; at $\theta=\theta_0$; where θ_0 is the initial phase of motion, which is determined from the expression $Z_+-\sin\theta=0$ and is equal to $\theta_0=\arcsin Z_+$.

Using the initial conditions $x=0$, $x=0$ and assuming the velocity is again zero, one can find the phase increments $\Delta\theta$ between two adjacent stops.

$$\frac{\sigma\cos\theta}{1+k_+^2}=\frac{\sigma\sin\theta_0}{2(1+k_+^2)}\left[e^{k_+(\theta-\theta_0)}+e^{k_+(\theta_0-\theta)}\right]+\left[\frac{\sigma\sin\theta_0k_+}{2(1+k_+^2)}-\frac{\sigma Z_+}{2k_+}\right]\left[e^{k_+(\theta-\theta_0)}-e^{k_+(\theta_0-\theta)}\right] \qquad (10)$$

where $\theta=\theta_0+\Delta\theta$, which corresponds to the particle coming to a stop.

Substituting $\theta=\theta_0+\Delta\theta$ into equation (10), we obtain:

$$2cos(\theta_0+\Delta\theta)=\sin\theta_0\cdot\left[e^{k_+\Delta\theta}+e^{-k_+\Delta\theta}\right]+\left[k_+\sin\theta_0-\frac{1+k_+^2}{k_+}\cdot Z_+\right]\cdot\left[\mathrm{e}^{\mathrm{k}_+\Delta\theta}-\mathrm{e}^{-\mathrm{k}_+\Delta\theta}\right] \qquad (11)$$

If we take the limit as $k_+\to0$, we obtain the following expression for $\Delta\theta$:

$$\cos(\theta_0+\Delta\theta)=\sin\theta_0-Z_+\Delta\theta \qquad (12)$$

From this, the relationship between $\Delta\theta$ and Z_+, shown in Fig. 2, can be determined graphically.

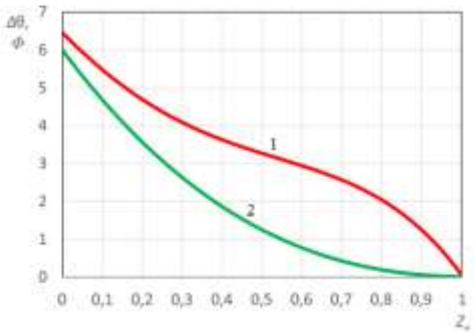

Fig. 2 The dependencies of $\Delta\theta$ (line 1) and Φ (line 2) on Z_+

Given $\Delta\theta$, the particle's displacement Δl during the time between two stops can be calculated using the following formula:

$$\Delta l=\frac{\sigma\cos\theta_0}{2_{k+}(1+k_+^2)}\left[e^{\kappa+\Delta\theta}-e^{-\kappa+\Delta\theta}\right]+$$
$$+\left[\frac{\sigma\cos\theta_0}{2(1+k_+^2)}-\frac{\sigma Z_+}{2k_+^2}\right]\times$$
$$\times\left[e^{\kappa+\Delta\theta}+e^{-\kappa+\Delta\theta}\right]\frac{\sigma\cos(\theta_0+\Delta\theta)}{1+k_+^2}-\frac{\sigma Z_+}{k_+^2} \qquad (13)$$

When $K_+\to0$, equation (13) becomes:

$$\Delta l=\sigma\cdot\Phi(Z_+) \qquad (14)$$

where:

$$\Phi(Z_+) = \Delta\theta\cos\theta_0 + \sin\theta_0 - \frac{(\Delta\theta)^2 Z_+}{2} - \sin(\theta_0 + \Delta\theta) \quad (15)$$

The right-hand side is a function of Z_+, since θ_0 and $\Delta\theta$ depend only on Z_+.

The graph of the dependence of $\Phi(Z_+)$ on Z_+ is also shown in Fig. 2

The average particle velocity V_{avg} is the ratio of the displacement Δl over one period of oscillatory motion to the value $2\pi/\Omega$ of that period. Thus, after moving $\cos\varphi$ to the left, we obtain:

$$V_{avg}\cdot\cos\varphi = \frac{1}{2\pi}A\Omega\cos(\alpha-\varphi)\cdot\Phi(Z_+) \qquad (16)$$

This equation shows the effect of kinematic parameters on the particle velocity. The average particle velocity increases with increasing amplitude and frequency of vibration. It also increases as the angular velocity of the rotor increases. An increase in the angle of friction between the material and the rotor wall while maintaining the difference $\alpha-\varphi$, i.e., an increase in the angle of taper, reduces $\cos\alpha$, while the right-hand side of equation (16) remains unchanged. Thus, despite the increase in friction, the velocity of the granular material increases. A decrease in the friction angle while maintaining the difference $\alpha-\varphi$, i.e., a decrease in the angle of conicity, reduces the velocity of the particles.

The dependence of the influence of kinematic parameters on the velocity of particle motion is shown in Fig. 3.

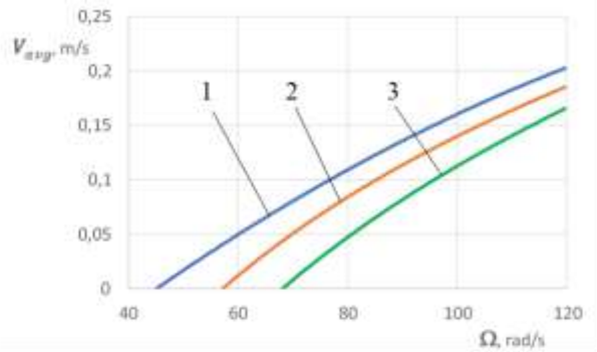

Fig. 3 The effect of kinematic parameters on particle velocity: 1 – $\omega = 12$ rad/s; 2 – $\omega = 16$ rad/s; 3 – $\omega = 20$ rad/s

Conclusions. Based on an analysis of the forces acting on a grain particle on the surface of a conical rotor (centrifugal, inertial, gravitational, and friction forces), an improved mathematical model of its motion has been developed. The resulting differential equation allows describing the trajectory and velocity of particle movement under combined vibrational and centrifugal fields.

Mathematical conditions for the non-detachable motion of grain particles along the working surface have been established. It was found that the most efficient mode for high-quality separation is the movement of particles in the direction of the conical rotor's expansion with periodic stops, which is ensured by the appropriate ratio of kinematic parameters (amplitude, vibration frequency, and angular velocity).

It has been analytically proven that the average velocity of grain material movement is directly proportional to the amplitude and frequency of vibrations, as well as to the angular velocity of the rotor. It has been established that increasing the rotor's taper angle contributes to an increase in flow velocity, especially at high friction coefficients, which is a key factor in improving the separator's productivity.

The derived mathematical relationships and graphical interpretations allow for the justification of the design parameters of vibrating centrifugal separators during the design phase. This ensures the intensification of the process of separating grain mixtures by density, contributing to the production of biologically valuable seed material.

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МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ ВІБРОВІДЦЕНТРОВОГО ПРОЦЕСУ СЕПАРАЦІЇ ЗЕРНА

Стаття присвячена актуальній науковій проблемі інтенсифікації процесів очищення та сортування зернових матеріалів шляхом використання вібровідцентрових полів. Традиційні методи сепарації часто не забезпечують належної якості розділення зернових сумішей через незначну різницю у фізико-механічних властивостях компонентів. Встановлено, що застосування відцентрових сил у поєднанні з осьовими вібраційними коливаннями робочої поверхні дозволяє штучно посилити різницю між частинками за їхньою питомою вагою.

У роботі представлено вдосконалену математичну модель руху одиничної частинки зернового матеріалу по внутрішній поверхні конічного ротора, що здійснює одночасний обертальний та коливальний рухи. Проведено аналіз силової схеми взаємодії, що включає відцентрову силу інерції, силу інерції від вібраційного руху, силу тяжіння, нормальну реакцію стінки ротора та силу тертя. На основі аналізу умов динамічної рівноваги та забезпечення безвідривного переміщення матеріалу отримано диференціальне рівняння руху частинки в напрямку розширення конуса.

Отримано аналітичні залежності для визначення миттєвої та середньої швидкості переміщення зерна залежно від фази вібрації. Визначено критичні умови, за яких забезпечується сталий режим руху з періодичними зупинками, що є оптимальним для процесу сепарації. Встановлено кількісний вплив основних кінематичних параметрів – амплітуди і частоти вібрацій, кутової швидкості ротора, кута конусності та коефіцієнта тертя на продуктивність процесу. Сформульовані рекомендації можуть бути використані при проєктуванні та модернізації високопродуктивних вібровідцентрових зерноочисних машин, що дозволить підвищити якість насіння та знизити енерговитрати на післязбиральну обробку врожаю.

Ключові слова: *вібровідцентровий сепаратор, зерновий матеріал, математичне моделювання, диференціальне рівняння руху, конічний ротор, кінематичні параметри, безвідривний рух, швидкість переміщення, очищення зерна.*

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