

## SUBSTANTIATION OF A NEW METHOD FOR SEPARATION OF BULK MATERIALS ON A VIBRO-FRICTION SEPARATOR

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**Abstract.** The processes of separating bulk materials are an important component of processing, food, chemical, pharmaceutical industries, and agricultural production. This ensures the separation of components based on various characteristics, which is crucial for operations such as cleaning, sorting, or calibrating bulk materials. A new method for separating components of bulk materials based on a set of characteristics has been proposed and comprehensively substantiated. An analytical-experimental methodology was used for the research. A mathematical model of plane-parallel vibrational non-detached movement of components on an inclined non-perforated frictional vibrating plane was developed. In this model, the cross-section of particles is approximated by a figure representing a point mass, from which rays of finite length emanate uniformly in all directions. Based on the conducted studies of the vibrational movement of components, using the example of a bulk material of sugar beet seed mixture, the fundamental possibility of their separation was established. Significant factors of the process of separating bulk materials on a vibro-friction separator were analytically and experimentally determined: amplitude and frequency of oscillations, direction angle of oscillations, longitudinal and transverse tilt angles of the working body. The result of the research was the rational ranges of these separator parameters for the studied material, which produced high-quality fractions of bulk material. The efficiency of the proposed separator was: for seed material – an increase in conditioned seeds with high sowing properties. The proposed technical solution, developed calculation methodology, and rational parameters will allow intensifying the processes of separating bulk materials and increasing the efficiency of various technologies.

**Keywords:** separation, bulk materials, vibro-friction separator, parameters, substantiation, dynamics

### UZASADNIENIE NOWEJ METODY ROZDZIELANIA MATERIAŁÓW SYPKICH NA SEPARATORZE WIBRO-TARCZOWYM

**Streszczenie.** Procesy separacji materiałów sypkich stanowią istotny element przemysłu przetwórczego, spożywczego, chemicznego, farmaceutycznego oraz produkcji rolnej. Zapewniają one rozdzielenie składników na podstawie różnych cech, co ma kluczowe znaczenie dla takich operacji, jak czyszczenie, sortowanie czy kalibracja materiałów sypkich. Zaproponowano i kompleksowo uzasadniono nową metodę separacji składników materiałów sypkich w oparciu o zestaw cech. W badaniach zastosowano metodologię analityczno-eksperymentalną. Opracowano model matematyczny płaszczyznowo-równoległego ruchu drgającego bez odrywania się składników na nachylonej, nieperforowanej płaszczyźnie drgającej o charakterze tarcowym. W modelu tym przekrój poprzeczny cząstek jest aproksymowany przez figurę reprezentującą masę punktową, z której promienie o skończonej długości rozchodzą się równomiernie we wszystkich kierunkach. Na podstawie przeprowadzonych badań ruchów drgających elementów, na przykładzie materiału sypkiego w postaci mieszanki nasion buraków cukrowych, ustalono zasadniczą możliwość ich separacji. Analitycznie i eksperymentalnie określono istotne czynniki procesu separacji materiałów sypkich na separatorze wibro-tarczowym: amplitudę i częstotliwość drgań, kąt kierunku drgań oraz podłużne i poprzeczne kąty nachylenia korpusu roboczego. Wynikiem badań było określenie racjonalnych zakresów tych parametrów separatora dla badanego materiału, co pozwoliło uzyskać wysokiej jakości frakcje materiału sypkiego. Skuteczność proponowanego separatora polegała na: w przypadku materiału siewnego – zwiększeniu ilości nasion kondycjonowanych o wysokich właściwościach siewnych. Proponowane rozwiązanie techniczne, opracowana metodologia obliczeniowa oraz racjonalne parametry pozwolą na intensyfikację procesów separacji materiałów sypkich oraz zwiększenie wydajności różnych technologii.

**Słowa kluczowe:** separacja, materiały sypkie, separator wibro-tarczowy, parametry, uzasadnienie, dynamika

### Introduction

The processes of separating bulk materials are a significant component of processing, food, chemical, pharmaceutical industries, and agricultural production [12, 18, 20]. The task of separation is to divide the components of bulk materials based on various indicators [2, 3, 19, 25]: size, density, aerodynamic properties, shape, surface condition, colour, electromagnetic properties.

A common separation of bulk materials involves dividing components on general-purpose machines with air, sieve, and trieur working bodies [14, 17, 29]. These machines separate the components of bulk materials based on aerodynamic properties (pneumatic separation channels), size (perforated sieving surfaces – sieves), and shape (trieurs). Cleaning and sorting bulk materials (grain or seeds of agricultural crops, mineral fertilizers, building materials, granules, etc.) on these machines is associated with significant difficulties. For example, the lack of difference in the separation characteristics of impurity and main components leads to a significant loss of separation quality. "Problematic" impurity components have the same size, aerodynamic indicators, density, and shape as the main components. This leads to a decrease in the specific productivity of machines and a reduction in the completeness of component separation [16, 32]. Multiple passes of material through machines result in material damage and loss of the main component, increased energy consumption, and loss of profitability [7, 11, 21].

Additionally, the problem is posed by the complex shapes of bulk material components, as well as the presence of protrusions and depressions.

Preliminary separation of bulk material components on pneumatic and sieve machines improves the quality of separation and the efficiency of machine operation [4, 15, 16]. Preliminary technological separation of part of the light and large components increases the flowability of materials, facilitates their movement in equipment, and creates conditions for the effective separation of main components.

Promising solutions for intensifying the processes of separating bulk materials in pneumatic separation channels include the preliminary preparation of the mixture by stratification [23]. Despite the increase in the efficiency of component separation based on aerodynamic properties by 30-35%, the separation by size and specific weight remains unresolved.

A promising solution for increasing the efficiency of component separation by size is the use of perforated sieving surfaces with complex geometry holes [5, 26]. Such sieves improve the quality of size separation by additionally orienting the components to the hole, levelling deviations in their shape. However, this solution cannot ensure separation based on other characteristics besides size.

A significant drawback of existing machines that separate bulk material components is the low quality of separation, insufficient productivity, significant energy losses, and loss of the main component of the material. The low technological



efficiency of existing machines is due to the fact that the principle of separation is based on considering only individual characteristics of the separation of bulk material components.

The lack of technical means that would perform the separation of components based on a set of characteristics determines the need for relevant research and the development of methodologies. The requirements for such machines should be: high technological indicators of productivity and separation quality, low energy consumption, expanded functional use for bulk materials with different properties, and simple service.

## 1. Analysis of literature sources and problem statement

The separation of problematic components from bulk materials, which have similar characteristics to the main ones, requires the development of new methods and technical means for implementation.

Among the known methods and equipment, the use of special machines that separate based on characteristics such as density, shape, surface condition, etc., should be noted [1, 8, 15, 28]. However, these machines are mainly capable of separating based on a single characteristic, and their combination in a line leads to significant energy costs and reduced profitability of technologies.

To ensure the effective separation of bulk materials with problematic components, a method for separating bulk materials based on a set of physical and mechanical properties and a technical means in the form of a vibro-friction separator with non-perforated frictional working surfaces (Fig. 1) has been developed [8, 18, 30]. The novelty of these machines lies in their ability to separate components of bulk materials based on a set of physical and mechanical properties: elasticity, frictional properties, and shape.

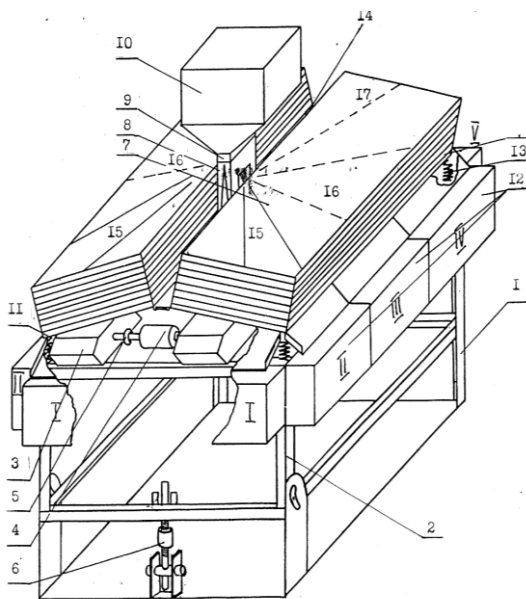


Fig. 1. Diagram of the vibro-friction separator: 1, 2 – main and intermediate frame; 3 – vibrators; 4 – intermediate transmission; 5 – flexible couplings; 6 – mechanism for adjusting the longitudinal tilt angle of the working surfaces to the horizon; 7 – non-perforated frictional surfaces; 8 – feeding devices; 9 – transition pipes; 10 – hopper; 11 – vibrating tables; 12 – component receivers; 13 – springs; 14 – mechanism for adjusting the transverse tilt angle of the working surfaces to the horizon; 15, 16, 17 – seed movement trajectories [24]

The working bodies of the machine are frictional non-perforated separating surfaces (two sets of fifteen each), installed with a longitudinal-transverse tilt angle to the horizon. Depending on the type of bulk material and the mechanical-technological properties of the components, the surface of the working body can be lined with different frictional materials: technical plywood, abrasive cloth, rubber, canvas, and other materials. The longitudinal and transverse tilt angles of the working surfaces are adjusted by mechanisms 14 and 6, respectively. The separating surfaces

are attached to vibrating tables 11, which are mounted on springs 13. The springs are symmetrically placed on the frame 2.

Feeding devices 8, which direct a certain volume of bulk material to each working plane, are installed on the vibrating part of the machine.

Two-shaft unbalanced vibrators 3 of directed action are attached to the vibrating tables so that the line of action of the forced forces forms an acute angle with the direction of the increase in the angle of ascent of the working surface. The vibrators are driven by an AC motor through a belt drive via an intermediate transmission 4 and flexible couplings 5. There are receivers for the separated components 12 to collect the separation products.

The aim of the research is to increase the efficiency of separating bulk materials by substantiating a new method for separating components and the parameters of vibro-friction separators that implement it.

To achieve this goal, the following tasks are addressed:

- Analytically determine the dynamic indicators of bulk material components depending on their properties and the kinematic parameters of the separator.
- Perform experimental identification of the frictional properties of bulk material components and the efficiency indicators of their separation process.
- Determine the rational parameters of the separator and substantiate recommendations for its application to the specified bulk material.

## 2. Research methods and materials

The research was conducted according to the following algorithm: analytical studies of the dynamics of bulk material components on a vibrating plane → experimental determination of the properties of bulk materials → refinement of analytical expressions → experimental verification and determination of model adequacy → determination of rational parameters of the separator → determination of the efficiency of using the separator on the specified bulk material.

The bulk material chosen for the research was a mixture of sugar beet seeds of the Bilotserkivsky single-seed 45 variety and impurities.

The research used the standards of Ukraine DSTU 3226-95, DSTU 2292-93 [6, 10, 13, 24], the requirements and rules of the International Seed Testing Association (ISTA), and the Seed Schemes of the Organization for Economic Cooperation and Development (OECD). According to these standards, sugar beet seeds should have the following sowing indicators: content of the main crop seeds 98.0%, including seeds of other cultivated plants 0.2%, weed seeds 0.1%, seed germination (non-pelleted) 80.0%, single-seediness 85.0%, uniformity 85%, moisture content 14.5%.

For the research, an artificially created non-standard seed mixture with the following indicators was used: content of the main crop seeds 91.0% (germination 78.0%, single-seediness 79.0%, uniformity 81.0%) and 9% impurity components. A characteristic and difficult-to-separate impurity component of sugar beet seeds is wild radish seeds [9]. This impurity has similar parameters to beet seeds: size, density, and aerodynamic properties. As a result, separating this impurity is difficult on typical seed cleaning machines, leading to the intensive accumulation of this crop in the fields and deterioration of seed material quality. Additionally, mineral impurities in the form of parts of crushed beet stems, which also have similar parameters, pose a problem and are difficult to separate.

For the research, a laboratory vibro-friction separator (Fig. 2, Table 1) was created with the following operating principle. Under the influence of vibrations, the input material from the hopper through flexible pipes and feeding devices falls onto the working surfaces. On these surfaces, the components move along different trajectories depending on their physical and mechanical characteristics and are separated into fractions.

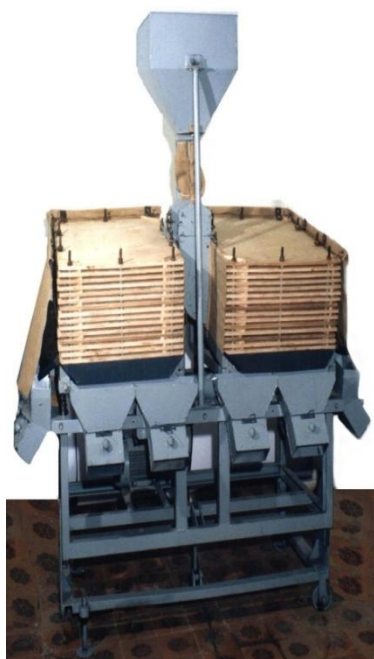


Fig. 2. General view of the vibro-friction separator

Thus, along trajectories 15 (Fig. 1), more rounded, elastic components (main) move and roll into the lower receivers of the separation products.

Flat, rough, less elastic components (impurities) move along trajectories 17 into the upper receivers.

Components with intermediate values of these properties fall along trajectories 16 into the side receivers.

The seed material is fed onto the working surfaces in such a way that single-layer movement of the seeds occurs on the working body.

Table 1. Technical characteristics of the vibro-friction machine

Indicator name	Value
Electric motor power, kW	1.2
Overall dimensions, mm: length / width / height	1350 / 970 / 1850
Total weight, kg	960.0
Type of vibrator	two-shaft unbalanced directed action
Frequency of working body oscillations, Hz	30.0-41.7
Oscillation amplitude, mm	0.8-2.5
Oscillation direction angle, degrees	22.0-48.0
Type of working body	non-perforated frictional surface-canvas
Working body dimensions, mm: length / width	700 / 500
Number of fractions	5

Considering the characteristics of bulk material separation, additional experiments were conducted. To determine the possibility of separating components based on surface condition and to determine the friction coefficients, a device was used (Fig. 3) [8].

The working surface was lined with canvas, selected on the basis of preliminary comparative tests of frictional materials and the requirements for practical manufacturing of separator working bodies. Canvas was chosen because it provides an intermediate and sufficiently stable friction level for sugar beet seeds, wild radish seeds, and crushed stem particles. Compared with smoother surfaces such as technical plywood or wood, canvas increases frictional interaction and improves the differentiation of particle trajectories. Compared with rubber, it avoids excessive adhesion, local damping, and unstable particle sticking, which may negatively affect rolling-sliding motion on the vibrating surface. Therefore, canvas ensures favourable conditions for the formation of different motion trajectories of the separated components.

The wear resistance of the canvas coating was also considered important for the stability of the experimental results. During the laboratory tests, no visible local damage or significant change in surface roughness was observed, which ensured repeatability of the measured friction coefficients and separation-quality indicators. Nevertheless, for long-term industrial operation, periodic inspection of the frictional coating is required, since excessive wear may change the coefficient of friction and, consequently, affect the stability of the separation process.

The tilt angle of surface 1 was set to be less than the static friction angle of the bulk material. Components of the bulk material were placed on each section of the surface, and the adjustment mechanism handle 3 was rotated until the components began to move down the frictional surface.

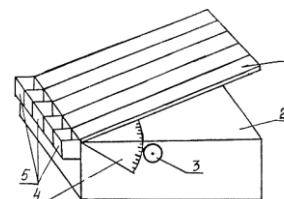


Fig. 3. Diagram of the device for determining the friction coefficients of bulk material components: 1 – inclined plane, 2 – base, 3 – mechanism for adjusting the tilt angle, 4 – scale, 5 – component receivers

The angle at which the component starts to move is taken as the friction angle  $\phi$ . The static friction coefficient of bulk material components is determined by the formula [8, 13, 15, 27]:

$$f_{CK} = \tan \phi \tag{1}$$

Using seeds with high sowing qualities is one of the important factors affecting yield. The main task in obtaining sugar beet seeds with high sowing conditions is to increase their germination, energy of germination, single-seediness, uniformity, and the weight of 1000 seeds by discarding substandard seeds of the main crop.

The determination of the sowing properties of sugar beet seeds obtained after separation on the proposed separator was carried out according to standard methods.

Experiments on the efficiency of separation and sowing properties were conducted at the final stage. Rational scientifically substantiated kinematic parameters were established, and the technological process of separating bulk material was carried out, dividing it into 5 fractions. Then, the contents of the respective trays were analysed, the quality of separation was determined, and the sowing properties of each fraction were identified.

### 3. Analytical studies of the dynamics of bulk material components on a vibrating plane

The movement of an arbitrary point of a body performing plane-parallel movement is determined by the movement of the body's pole and the rotation of the body around this pole. Possible movements of the component include sliding on the surface, rolling, and simultaneous rolling with sliding. These possible movements can be expressed in generalized coordinates. The number of generalized coordinates corresponds to the number of degrees of freedom, which is two.

For modelling, the following parameters of the working vibrating surface were used (Fig. 4): kinematic parameters  $A$  and  $\omega$ , where  $A$  is the oscillation amplitude and  $\omega$  is the angular frequency of oscillations; and structural parameters  $\alpha$  and  $\beta$ , which are the longitudinal and transverse inclination angles of the working surface to the horizon, respectively. To facilitate comparison with industrial vibrating equipment, angular frequency values were additionally converted into vibration frequency  $f$  in Hertz and equivalent rotational speed  $n$  in revolutions per minute according to:

$$f = \frac{\omega}{2\pi}, \quad n = 60f = \frac{60\omega}{2\pi}$$

The first generalized coordinate of relative movement is taken as  $X_{CK}$  – the movement of the pole parallel to the vibrating surface. The second generalized coordinate of relative movement is chosen as the change in the angle  $\theta$  of the body's rotation relative to the pole  $O_K$ .

To determine the generalized coordinates of the system as functions of time, the corresponding differential equations of motion are needed. The cross-section of the component is approximated by a figure representing a point mass, from which rays of finite length emanate uniformly in all directions. When rolling, the center of mass of the component moves in the direction of both coordinate axes  $O_K X_K Y_K$  (Fig. 4).

In deriving and simplifying the equations of motion, several assumptions were introduced to define the physical limits of the model. The particle was considered as a rigid body performing non-detached plane-parallel motion on the inclined non-perforated vibrating frictional surface. Air resistance was neglected because of the relatively small particle size, low motion velocity, and the dominant influence of gravitational, inertial, and frictional forces under the investigated operating conditions. Inter-particle collisions were not considered, since the material was supplied to the working surface in a single layer. Particle deformation, rolling resistance caused by local deformation of the contact zone, stochastic fluctuations of the feed rate, and possible changes in the coefficient of friction during motion were also assumed to be negligible. The coefficient of sliding friction was taken as experimentally determined for the corresponding material component and working-surface coating. Therefore, the proposed model is applicable mainly to single-layer particle motion with continuous contact between the component and the vibrating surface.

The absolute movement of the center of mass of the component in the coordinate axes  $O_a X_a Y_a$  can be represented as:

$$\begin{aligned} X_a &= X_p + X_{CK} + X_K \\ Y_a &= Y_p + Y_K \end{aligned} \quad (2)$$

where  $X_p, Y_p$  are the coordinates of the vibrational translational movement of the surface;  $X_{CK}$  is the sliding coordinate;  $X_K, Y_K$  – are the coordinates of the rolling component.

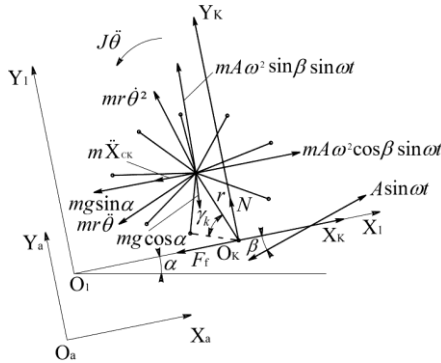


Fig. 4. Diagram of the application of forces to the bulk material component on the separator's working surface

After transformations and simplifications, the system of differential equations of motion for generalized coordinates in the case of sliding of the component and rotation at a constant rolling radius towards the upper edge of the vibrating surface is as follows:

$$\begin{aligned} \ddot{X}_{CK} + r_i \ddot{\theta} [\sin(\gamma_k + \theta) \pm f_{CK} \cos(\gamma_k + \theta)] + \\ + r_i \ddot{\theta}^2 [\cos(\gamma_k + \theta) \pm f_{CK} \sin(\gamma_k + \theta)] = \\ = A\omega^2 \sin \omega t [\cos \beta \pm f_{CK} \sin \beta] - \\ - g(\sin \alpha \pm f_{CK} \cos \alpha) \cdot \\ \cdot (\rho^2 + r_i^2) \ddot{\theta} + X_{CK} r_i \sin(\gamma_k + \theta) = \\ = (A\omega^2 \sin \omega t \cos \beta - g \sin \alpha) r_i \sin(\gamma_k + \theta) + \\ + (A\omega^2 \sin \omega t \sin \beta - g \cos \alpha) r_i \cos(\gamma_k + \theta) \end{aligned} \quad (3)$$

where  $\alpha$  is the longitudinal tilt angle of the working surface to the horizon;  $f_{CK}$  – is the sliding friction coefficient;  $r_i, \rho$  – are the rolling radius and density of the component;

$g$  – is the acceleration due to gravity;  $\theta$  is the rotation angle of the component relative to the pole  $O_K$ ;  $\gamma_k$  – is the oscillation direction angle.

However, there is a possible case of the component rolling on the vibrating surface without sliding. In this case, the equation describing such movement of the component can be obtained by simplifying the system of differential equations (3). For this, it is necessary to set  $\dot{X}_{CK} = 0$  in the second differential equation of the specified system. The first equation should not be considered, as the possible movement  $\dot{X}_{CK}$  is absent. After setting  $\dot{X}_{CK} = 0$  in the second equation of the specified system, we obtain the equation of the sum of the works of only those forces that occur during rolling without sliding.

The differential equation describing the rolling of the component at a constant rolling radius is as follows:

when rolling towards the upper edge of the vibrating surface:

$$\begin{aligned} (\rho^2 + r^2) \ddot{\theta} = (A\omega^2 \sin \omega t \cos \beta - g \sin \alpha) r \sin(\gamma_k + \theta) + \\ + (A\omega^2 \sin \omega t \sin \beta - g \cos \alpha) r \sin(\gamma_k + \theta) \end{aligned} \quad (4)$$

when rolling towards the lower edge of the vibrating surface:

$$\begin{aligned} (\rho^2 + r^2) \ddot{\theta} = (A\omega^2 \sin \omega t \cos \beta - g \sin \alpha) r \sin(\gamma_k + \theta) + \\ + (g \cos \alpha - A\omega^2 \sin \omega t \sin \beta) r \cos(\gamma_k + \theta) \end{aligned} \quad (5)$$

Additionally, theoretically, particles can slide at the end of one of the radii on the vibrating surface without rolling.

In this case, the differential equation describing this movement can also be obtained based on the system of differential equations (3) that describe the complex movement of particles. For this, it is necessary to set  $\dot{\theta} = \theta = 0$  in the first equation of the specified system.

As a result, the differential equation of vibrational movement during sliding is obtained as follows:

$$\begin{aligned} \ddot{X}_{CK} = A\omega^2 \sin \omega t \cos \beta - g \sin \alpha - \\ - f_{CK} (g \cos \alpha - A\omega^2 \sin \omega t \sin \beta) \text{sign}(\dot{X}_{CK}) \end{aligned} \quad (6)$$

Let's consider the condition for the presence of non-detached movement of the particle on the vibrating surface. The necessary condition for stopping the non-detached movement of the component is the condition of the negativity of the normal pressure force (N).

This condition can be written as:

$$\begin{aligned} g \cos \alpha + r \ddot{\theta} \cos(\gamma_k + \theta) > A\omega^2 \sin \omega t \sin \beta + \\ + r \ddot{\theta}^2 \sin(\gamma_k + \theta) \end{aligned} \quad (7)$$

To perform numerical calculations of the obtained equations, it is necessary to experimentally determine the significant parameter of the sliding friction coefficient of particles on the working surface according to the methodology in section 3.

## 4. Research results

### 4.1. Determined properties of bulk materials

Figure 5 shows the variation curves of the sliding friction coefficients of bulk material components on an inclined surface covered with canvas, obtained using the methodology described in section 3. The changes in the friction coefficients of the components were studied for: sugar beet seeds separated by the proposed separator; seeds after typical (air-sieve) primary cleaning; crushed stem particles; and wild radish impurity seeds.

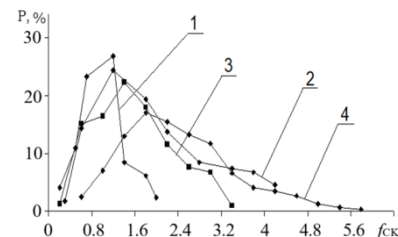


Fig. 5. Variation curves of sliding friction coefficients of bulk material components: 1 – sugar beet seeds (calibrated on the proposed separator), 2 – sugar beet seeds (after typical primary cleaning), 3 – wild radish impurity seeds, 4 – mineral impurity – stem parts

The analysis of the variation curves of the sliding friction coefficients shows the possibility of separating these components due to the differences in their frictional properties. It was found possible to separate up to 16.0% of wild radish seeds and about 39% of crushed stems from the full-fledged beet seeds. Using the proposed separator allows obtaining full-fledged seeds, which differ from the beet seeds obtained by typical primary cleaning. This allows additionally separating up to 9.0% of wild radish seeds and about 14.0% of crushed stems without losing the main crop seeds.

The rational range of variation of the sliding friction coefficients of the components was:

$f_{CK} = 0.7-1.3$  – for beet seeds obtained on the proposed separator;

$f_{CK} = 0.7-2$  – for beet seeds obtained after typical cleaning;

$f_{CK} = 0.7-1.9$  – for wild radish impurity seeds;

$f_{CK} = 1.4-3.1$  – for mineral impurity – stem parts.

## 4.2. Results of modelling the dynamics of bulk particles on a vibrating surface

The modes, settings, and kinematic parameters of the separator's working body movement, at which the separation of sugar beet seeds, weeds, and impurities occurs on the non-perforated vibrating surface, were determined by numerical integration of differential equations. Additionally, experimental studies were conducted on the laboratory setup (Fig. 2) to confirm and refine the data.

To ensure maximum productivity of the seed mixture component separation, it is necessary to find the parameter range in which the particle movement speed on the vibrating plane is maximal.

Analytical studies (section 4) established that the non-detached movement mode of the particle involves the sequential alternation of body rolling and rolling with simultaneous sliding (87.2% of the longitudinal coordinate change is the rolling with simultaneous sliding mode). The final task of analytical modelling is to determine the change in the component's movement speed values depending on the significant kinematic parameters of the separator: oscillation amplitude ( $A$ ), oscillation frequency ( $\omega$ ), longitudinal tilt angle of the working surface ( $\alpha$ ), and oscillation direction angle ( $\gamma_k$ ).

Figure 6 shows the dependence of the average particle movement speed on the oscillation amplitude of the separator's working surface.

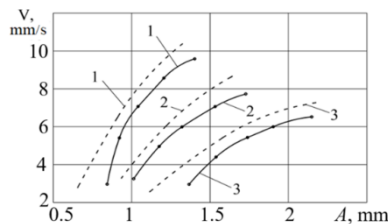


Fig. 6. Dependence of the change in average speed ( $V$ ) of component movement on the working surface on the amplitude of its oscillations ( $A$ ), at angular frequency of oscillations ( $\omega$ ): 1 –  $\omega = 110 \text{ rad s}^{-1}$  ( $f = 17.5 \text{ Hz}$ ;  $n \approx 1050 \text{ rpm}$ ); 2 –  $\omega = 100 \text{ rad s}^{-1}$  ( $f = 15.9 \text{ Hz}$ ;  $n \approx 955 \text{ rpm}$ ); 3 –  $\omega = 90 \text{ rad s}^{-1}$  ( $f = 14.3 \text{ Hz}$ ;  $n \approx 860 \text{ rpm}$ ) and tilt angle ( $\alpha = 7.8 \text{ degrees}$ ); - - - - analytical results; — - experimental results

The analysis of the dependencies (Fig. 6) shows that at high oscillation frequencies ( $110.0 \text{ s}^{-1}$ ), the detachment mode begins at an amplitude of 1.27 mm. However, the calculated movement speed of the component at this oscillation frequency is the highest and amounts to 10.4 mm/s. At lower oscillation frequencies of the working surface, the value of the maximum calculated speed in the non-detachment movement mode becomes lower. The detachment mode also begins later, i.e., at a higher amplitude of surface oscillations.

Numerical calculations of the obtained equations (section 4) yielded the dependence of the change in the average movement speed of the component (particle) on the oscillation frequency of the vibro-friction separator's working surface (Fig. 7).

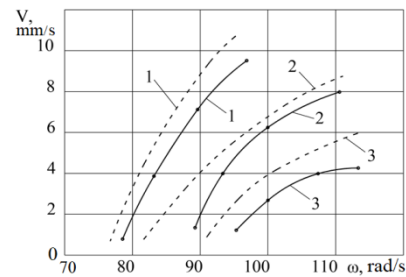


Fig. 7. Dependence of the change in average speed ( $V$ ) of bulk material component movement on the working surface on the angular frequency of oscillations ( $\omega$ ), with corresponding values expressed in Hz and rpm for comparison with industrial vibrating equipment, at oscillation amplitude ( $A$ ): 1 –  $A = 1.8 \text{ mm}$ ; 2 –  $A = 1.4 \text{ mm}$ ; 3 –  $A = 1.0 \text{ mm}$ ; tilt angle ( $\alpha = 7.8 \text{ degrees}$ ); - - - - analytical results; — - experimental results

The analysis of the dependencies (Fig. 7) shows that with an increase in the oscillation amplitude of the working surface, the average movement speed increases. Moreover, the larger the oscillation amplitude, the greater the increase in the component's movement speed. At higher amplitude values, the detachment mode begins at lower oscillation frequencies of the separator's working body.

Additionally, the research task included determining the dependence of the average movement speed of the component on the longitudinal tilt angle ( $\alpha$ ) of the working plane (Fig. 8) and on the oscillation direction angle ( $\gamma_k$ ) (Fig. 9) at different oscillation frequencies.

When changing the longitudinal tilt angle ( $\alpha$ ) of the working surface, the center of mass, according to the diagram (Fig. 3), can move in different directions. At a longitudinal tilt angle ( $0 < \alpha < 7.8 \text{ degrees}$ ), the component under study can move towards the upper edge of the working vibrating surface (Fig. 8). If  $\alpha$  is greater than 7.8 degrees, the body shifts towards the lower edge of the working surface of the vibro-friction separator.

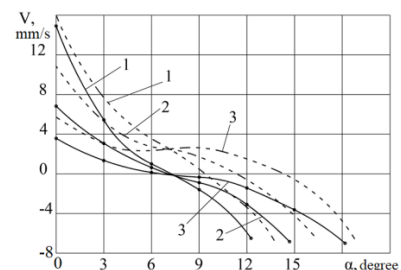


Fig. 8. Dependence of the change in average speed ( $V$ ) of component movement on the working vibrating surface on the longitudinal tilt angle ( $\alpha$ ), at angular frequency of oscillations ( $\omega$ ): 1 –  $\omega = 120 \text{ rad s}^{-1}$  ( $f = 19.1 \text{ Hz}$ ;  $n \approx 1146 \text{ rpm}$ ); 2 –  $\omega = 100 \text{ rad s}^{-1}$  ( $f = 15.9 \text{ Hz}$ ;  $n \approx 955 \text{ rpm}$ ); 3 –  $\omega = 80 \text{ rad s}^{-1}$  ( $f = 12.7 \text{ Hz}$ ;  $n \approx 764 \text{ rpm}$ ); oscillation amplitude  $A = 1.4 \text{ mm}$ ; - - - - analytical results; — - experimental results

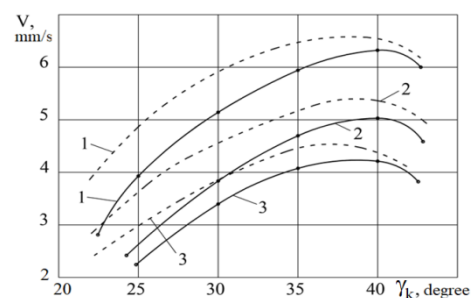


Fig. 9. Dependence of the change in average speed ( $V$ ) of bulk material component movement on the working vibrating surface on the oscillation direction angle ( $\gamma_k$ ), at angular frequency of oscillations ( $\omega$ ): 1 –  $\omega = 120 \text{ rad s}^{-1}$  ( $f = 19.1 \text{ Hz}$ ;  $n \approx 1146 \text{ rpm}$ ); 2 –  $\omega = 100 \text{ rad s}^{-1}$  ( $f = 15.9 \text{ Hz}$ ;  $n \approx 955 \text{ rpm}$ ); 3 –  $\omega = 80 \text{ rad s}^{-1}$  ( $f = 12.7 \text{ Hz}$ ;  $n \approx 764 \text{ rpm}$ ); tilt angle  $\alpha = 7.8 \text{ degrees}$ ; - - - - analytical results; — - experimental results

The dependence of the average component velocity on the oscillation direction angle has a pronounced maximum. For the investigated sugar beet seed components, the maximum

velocity was observed within the range  $\gamma_k = 37 \dots 39$  degrees. A further increase in the oscillation direction angle reduced the average velocity of component motion along the vibrating frictional surface.

The obtained modelling results made it possible to identify the main tendencies in particle motion depending on the separator operating parameters. An increase in oscillation amplitude and angular frequency generally increased the average velocity of component motion until the onset of the detachment mode. The longitudinal inclination angle determined the direction and intensity of particle displacement along the working surface, whereas the oscillation direction angle influenced the formation of stable rolling-sliding trajectories.

The conducted studies allow establishing the range of settings and kinematic parameters for the operation of the vibro-friction separator when sorting bulk materials, using the example of sugar beet seeds.

### 4.3. Comparative analysis of analytical and experimental studies

A comparative analysis of the analytical and experimental results was carried out to assess the adequacy of the proposed mathematical model. These ranges of factor levels were determined as follows: oscillation amplitude  $1.0 \text{ mm} < A < 2.0 \text{ mm}$ , angular frequency of oscillations  $80.0 < \omega < 190.0 \text{ rad s}^{-1}$ , which corresponds to  $12.7 < f < 30.2 \text{ Hz}$  or approximately  $764 < n < 1814 \text{ rpm}$ , longitudinal tilt angle of the working body  $0 < \alpha < 18$  degrees, oscillation direction angle  $20 < \gamma_k < 45$  degrees.

The influence of the vibration parameters of the working surface on the average vibration movement speed of sugar beet seeds is shown in the graphs (Figs. 6–9). Thus, with an increase in the amplitude and frequency of the separator's working surface oscillations, the vibration movement speed of the bulk material component increases.

The influence of the longitudinal tilt angle ( $\alpha$ ) of the working body on the average vibration movement speed of the bulk material component is graphically shown in Figure 8. At a longitudinal tilt angle ( $\alpha = 0$ ) degrees, the vibration movement speed of the bulk material component is maximal in the direction of the vibration. As the angle ( $\alpha$ ) increases, the transportation speed of the component upwards along the working vibrating surface decreases. The tilt angle ( $\alpha$ ), at which the vibration movement speed equals zero for the component (sugar beet seeds), is 7.2 degrees. To separate impurity components (weed seeds and stem particles) from full-fledged sugar beet seeds, the tilt angle of the frictional surface should be chosen so that the movement directions of these components are opposite.

With an increase in the oscillation direction angle  $\gamma_k$  (Fig. 9), the component's movement speed initially increases, reaching a maximum in the range of oscillation direction angles  $\gamma_k = 37 \dots 42$  degrees. With a further increase in the direction angle, the vibration movement speed decreases.

The observed deviations between the analytical and experimental data can be explained by the natural heterogeneity of the investigated seed material and by the simplifications adopted in the mathematical model. In particular, the moisture content of individual seeds may vary slightly, affecting their mass, elasticity, surface condition, and coefficient of friction. In addition, the micro-relief and roughness of the seed surface, local protrusions and depressions, and deviations of the real particle shape from the equivalent geometric representation used in the model influence the rolling-sliding interaction with the canvas-coated working surface. Other possible sources of discrepancy include random particle orientation, small fluctuations in the feeding rate, local variation in contact conditions, and minor changes in frictional interaction during motion. These factors are difficult to fully account for in a deterministic analytical model; however, the maximum discrepancy of 5.2%

indicates satisfactory agreement between theoretical and experimental results.

Thus, the analysis of the graphs of the average movement speed change of the component shows that the vibration parameter ranges and the longitudinal tilt angle ( $\alpha$ ) of the working body, obtained based on the analytical model, and those obtained experimentally, practically coincide (up to 2.4%). The values of the average vibration movement speed of the components, the critical lift angles, and the nature of the dependencies of the vibration movement speed on the influence of various factors satisfactorily coincide.

### 4.4. Sowing properties of bulk material components

For each fraction and the initial seeds, an analysis of the sowing qualities of the seeds (germination, energy of germination, single-seediness, weight of 1000 seeds) was conducted.

The results of sorting sugar beet seeds on the vibrating machine are presented in Table 2.

Table 2. Results of experimental sorting of sugar beet seeds on the proposed separator

Indicator name	Initial material	Receiver number				
		I	II	III	IV	V
Component distribution, %	100	8.7	24.3	37.6	19.8	9.6
Cumulative component distribution, %	100	8.7	33	70.6	90.4	100
Germination, %	78	89	88	92	92	68
Energy of germination, %	75	86	80	88	87	63
Single-seediness, %	79	62	93	97	96	92
Uniformity, %	81	77	91	96	98	89
Weight of 1000 seeds, g	11.5	14.2	14	13.9	12.8	10.2
Main component content, %	91	83	98	98	98	71

The initial bulk material was obtained after passing through a typical line using an air-sieve separator and had the following indicators: germination – 78%, single-seediness – 79%, and weight of 1000 seeds – 11.5 g; main component content 91%, 8.7% of the initial material went to the first receiver, of which 83% was full-fledged seeds. This material has a germination rate that increased by 11% compared to the initial material. The weight of 1000 seeds in this receiver increased by 2.7 g. However, the single-seediness significantly decreased to 62%, which does not meet International Rules for Seed Testing of ISTA and the OECD Seed Schemes requirements [5, 10, 22] for single-seediness. The germination rate of the seeds in the V receiver also does not meet the standard requirements.

Therefore, the material collected in receivers I and V should not be directly used as standard sowing material. The fraction from receiver I is characterized by relatively high germination and increased 1000-seed weight; however, its single-seediness is insufficient to meet the standard requirements. For this reason, this fraction may be directed to additional calibration or re-separation in order to recover viable seeds that can potentially be included in the standard seed fraction after further processing.

The material from receiver V represents the lowest-quality fraction, with reduced germination and a higher content of non-standard components. Depending on its composition and the economic feasibility of additional processing, this fraction may either be subjected to repeated separation or removed from the seed material flow and used for non-seed purposes.

The germination, single-seediness, and weight of 1000 seeds in the second receiver increased by 10%, 14%, and 2.5 g, respectively.

The third receiver received sugar beet seeds that exceeded the initial material in germination by 14% and in single-seediness by 18%.

The single-seediness of the seeds in the fourth and fifth receivers exceeded the control by 17% and 13%, respectively.

Combining the second and third receivers (arithmetic mean) gives 61.9% of the initial material, with a main component content of sugar beet seeds at 98%. The combined material from these receivers has increased germination by 12% and single-seediness by 6% compared to the initial material.

Combining the third and fourth receivers allows obtaining 57.4% of the initial material, of which 98% are full-fledged seeds, exceeding the initial material in germination by 14%, in single-seediness by 17.5%, and in the weight of 1000 seeds by 1.85 g. Thus, under the selected operating conditions, receivers III and IV form the main standard seed fraction. Receivers II–IV may also be considered as a technologically valuable seed stream, depending on the required balance between seed yield and quality. In contrast, receivers I and V are return or reject fractions and require additional technological decisions before further use. These indicators of the selected 57.4% bulk material meet the standard norms (germination, single-seediness) for seed quality and can be classified as full-fledged sugar beet seed material.

Thus, the use of the proposed vibrating machine for seed material separation allows improving its sowing qualities, reducing the seeding rate, which in turn increases yield and production profitability.

## 5. Discussion of results

The research established that the main parameters significantly affecting the technological process of separating bulk material components on the vibro-friction separator are as follows: oscillation amplitude and frequency, oscillation direction angle, and the longitudinal and transverse tilt angles of the working body.

Studies of the separation process of bulk materials, performed using sugar beet seeds as an example, showed that to increase efficiency and prepare high-quality seed material, the oscillation amplitude of the vibro-friction separator's working body should be  $A = 1.9$  mm, angular frequency of oscillations  $\omega = 177.0$  rad  $s^{-1}$ , which corresponds to  $f = 28.2$  Hz or approximately  $n = 1690$  rpm, the oscillation direction angle  $\gamma_k = 37$  degrees, the longitudinal tilt angle of the working body  $\alpha = 7.6$  degrees, and the transverse tilt angle of the working body 2.3 degrees.

The experimental verification confirmed the adequacy of the analytical model and demonstrated the practical efficiency of the proposed separator. Using the proposed separator with substantiated parameters allowed obtaining 57.4% of full-fledged seed material (receivers III+IV) from a non-standard sugar beet mixture. The selected seed material showed improved sowing properties compared with the initial material obtained after conventional air-sieve separation: germination by 4.0–14%, energy of germination by 5–12%, single-seediness by 3–18%, and the weight of 1000 seeds by 1.3–2.7 g, compared to typical (air-sieve) separation methods.

These results indicate that the proposed vibro-friction separation method is especially promising for mixtures containing components with similar size, density, and aerodynamic characteristics but different frictional, elastic, and shape-related properties. In this case, separation is achieved due to differences in the dynamic response of particles to the vibrating frictional surface rather than due to only one conventional separation feature.

It should be noted that the rational parameters obtained in this study were substantiated for a specific bulk material, namely a sugar beet seed mixture containing wild radish seeds and crushed stem particles as hard-to-separate impurities. The experiments were carried out using a canvas-coated non-perforated working surface. Therefore, when applying the proposed method to other seed mixtures, granular materials, or industrial products, additional identification of frictional properties and adjustment of separator parameters are required. Further research should focus on validating the proposed approach for other bulk materials, different frictional coatings, higher throughputs, and continuous industrial operating conditions.

## 6. Conclusions

A method and methodology for substantiating the parameters of a separator for separating bulk material components based on a set of distinctive properties have been proposed.

Analytical studies were conducted, and a model of plane-parallel vibrational non-detached movement of components on an inclined non-perforated frictional vibrating plane was obtained. The influence of setting and kinematic parameters on the dynamics of the components was studied using the obtained equations.

Based on the conducted analytical and experimental studies, the fundamental possibility of separating hard-to-separate impurity components (weed seeds and stem particles) from the main crop seeds was proven using a sugar beet seed mixture as an example.

The rational operating parameters of the vibro-friction separator for separating the investigated sugar beet seed mixture were established as follows: oscillation amplitude of the working body  $A = 1.9$  mm, angular frequency of oscillations  $\omega = 177.0$  rad  $s^{-1}$ , corresponding to  $f = 28.2$  Hz or approximately  $n = 1690$  rpm, oscillation direction angle  $\gamma_k = 37$  degrees, longitudinal inclination angle of the working body  $\alpha = 7.6$  degrees, and transverse inclination angle of the working body 2.3 degrees.

Using the separator with scientifically substantiated parameters allowed obtaining 57.4% of standard seed material from a non-standard mixture of sugar beet seeds. Fractions collected in receivers III and IV were identified as the main standard seed material, whereas fractions from receivers I and V require additional calibration, re-separation, or removal from the sowing-material flow depending on their quality indicators and economic feasibility. An increase in sowing properties of the seeds was also established: germination by 4.0–14%, energy of germination by 5–12%, single-seediness by 3–18%, and the weight of 1000 seeds by 1.3–2.7 g, compared to typical (air-sieve) separation methods.

As a result of the research, further development of the direction of improving machines for separating bulk materials, based on the comprehensive consideration of properties, was achieved, allowing the separation of hard-to-separate impurity components. The obtained results can be used in research, design, and adjustment of separators for separating bulk material components in the processing, food, chemical, and pharmaceutical industries.

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