Optimization of separation of two-component mixtures of seeds under horizontal vibration

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Abstract. The paper presents data on the separation of two-component mixtures of agricultural seeds by means of low-frequency horizontal vibration. Experiments were carried out with beans, peas and sunflower seeds. Modelling of the separation process of mixtures by the method studied in this work shows that the trajectory of a particle is a vortex along an ascending or descending line, depending on the combination of the properties of the components and operating parameters. The studies have shown that the minimum time for complete separation of the mixture into components is achieved when the container inclination angle is approximately equal to the repose angle of mixture components. The separation process is carried out only at amplitudes smaller than the particle size of the mixture.

1. Introduction
Separation of bulk mixtures is an essential part of various technological processes including the processing of preparation of seed material and plant row materials [1, 2]. In the separation of seeds, the possibilities of using both wet separation and flotation, which are widely used in the chemical and construction industries, are limited. In this regard, the problem of increasing the efficiency and optimization of methods of vibration separation of seed material remains topical [3].

Optimization of the separation process can be carried out by a combination of vibration and additional factors, such as ascending air flow [4] and electrification of the sorted particles [5], which, however, entails the complication of technology and equipment. Since the mechanical (vibrational) component in the total energy consumption for the separation of mixtures is predominant, it seems more preferable to determine the optimal conditions for the vibrational action, such as the direction, frequency and amplitude of vibrations of the vibrator, depending on the characteristics of the sorted material.

This paper deals with aspects of the behavior of bulk material during horizontal low-frequency vibration at various angles of vibrator inclination.

2. Materials and methods
Mixtures of beans and sunflower seeds as well as peas and sunflower seeds were selected to study experimentally the optimal separation conditions. To a greater extent, this choice is due to the clarity of the separation process, due to the good color distinction of the seeds. In addition, the large size of the seeds makes it possible to neglect the effect of electrostatic forces arising from the charging of particles of the mixture during vibration. The characteristics of the components of the studied mixtures are presented in Table 1.
The mixtures under study were placed in a cylindrical vibrator made of transparent material with an adjustable angle of inclination. The selected mixtures, under appropriate conditions, can behave like both solid and fluid media [6, 7]. The oscillatory energy of the container is transferred to the individual particles of the mixture. As a result, under certain vibration modes, a "phase" transition occurs and the entire volume of granular material begins to move, begins to "flow" like a liquid. However, in contrast to a liquid, during the interaction between the particles of the mixture, friction occurs, collisions are not always elastic, and there are no forces of attraction. This leads to instability with respect to clustering: if the "neighbor" of a particle is a particle of a different kind, then the resulting forces acting on them are different. When a particle is surrounded by particles similar to itself, the relative motion of the particles becomes minimal and, as a result, the particles unite into a cluster.

| Material          | Angle of repose, ° | Density, kg/m³ |
|-------------------|--------------------|----------------|
| Pea seeds         | 22.1               | 820            |
| Bean seeds        | 31.0               | 740            |
| Sunflower seeds   | 28.4               | 350            |

We consider a particle on a surface with an angle of inclination $\alpha$ to the horizon, such that $\mu = \tan \alpha$, where $\mu$ is the coefficient of friction between the material of the particle and the surface (Figure 1). A particle of bulk material in a mixture is acted upon by the force of gravity, the force of inertia, the force of reaction from the particles surrounding it, and the force of friction. In the first approximation, the effects of electric charging of particles due to friction can be neglected.

![Figure 1. Quasi-static equilibrium of a particle.](image)

Let $\hat{i}$, $\hat{j}$ and $\hat{k}$ be unit vectors specifying the direction of the greatest descent (gradient), the direction of the tangent to the trajectory of the particle and the direction of some averaged force $F$ acting from the surrounding particles, respectively. The condition of quasi-static equilibrium, when the particle practically does not move, is expressed by the equation:

$$F + mg \cdot \sin \alpha \cdot \hat{i} + F_f = 0,$$

where $F_f$ is force of friction.

Since $F_f = -\mu mg \cdot \cos \alpha \cdot \hat{j}$ and $\mu = \tan \alpha$, equation (1) takes the form:

$$F + mg \cdot \sin \alpha \cdot \hat{i} = \tan \alpha \cdot mg \cdot \cos \alpha \cdot \hat{j}.$$  

(2)

Let us square both sides of equation (2) and simplify the expression (denoting $\cos \delta = \langle \hat{k}, \hat{i} \rangle$):

$$F^2 + m^2 g^2 \cdot \sin^2 \alpha + 2F \cdot mg \cdot \sin \alpha \cdot \cos \delta = m^2 g^2 \cdot \sin^2 \alpha$$

or
\[ F(F + 2mg \cdot \sin \alpha \cdot \cos \delta) = 0. \]  

From the equation (3) it follows that \( F = -2mg \cdot \sin \alpha \cdot \cos \delta > 0 \) when \( 90 \leq \delta \leq 180 \). If \( \delta \) takes values from the range \( 0 \leq \delta < 90 \), then it follows from (3) that \( F = 0 \). The particle trajectory is determined by the resulting force:

\[ \ddot{R} = \ddot{F} + mg \cdot \sin \alpha \cdot \hat{i} = mg \cdot \sin \alpha \left( \hat{i} - 2\cos \delta \cdot \hat{k} \right) = \]
\[ = mg \cdot \sin \alpha \left[ \hat{i} + 2\cos \delta \left( \sin \delta \cdot \hat{i} - \cos \delta \cdot \hat{j} \right) \right] = \]
\[ = mg \cdot \sin \alpha \cdot 2\delta \left( \tan 2\delta \cdot \hat{i} - \hat{j} \right). \] (4)

where \( \hat{i} \) is the unit vector in the direction of the \( Oy \) axis.

An analysis of equation (4) shows that, depending on the conditions, the particle moves, sliding down or rising up along the vector \( \hat{i} \), which agrees with the results given in [8]. For example, for the condition \( 90 \leq \delta \leq 180 \) from equation (4) it follows that the trajectory of the particle is described by the equation:

\[ \frac{dy}{dx} = -\tan 2\delta = -\frac{2\sin \delta \cdot \cos \delta}{\cos^2 \delta - \sin^2 \delta} = \frac{2xy}{x^2 - y^2}, \]

that is, the particle moves along a trajectory, the tangent to which coincides with the tangent to the arc of the circle.

Since the efficiency of the separation process depends on the value of the angle of natural friction, we consider a two-component mixture of flour and millet seeds. When pouring such a mixture, a complex cone is formed, consisting of a cone located on another, truncated cone. The different values of the angles between the generatrices and the bases of the cones are due to different angles of repose for each of the components of the mixture. The more the angles of repose differ, the more expressed the effect. The cone shape and fracture depend on the ratio of the content of the components. Table 2 shows the dynamics of the angle between the base and the generatrix of the cones, depending on the proportion \( (\nu) \) of the components that make up the mixture. For pure flour, the angle is 51.72° and for millet seeds 31.42°. Analysis of the data in Table 2 shows that it is the most statistically significant for describing the dependence is \( f(\nu) = 7.254 \ln(\nu) + 51.196 \), that is, as the proportion of flour in the mixture increases, the angle corresponding to the upper cone increases according to the logarithmic law from 34.43° to 49.72°.

### Table 2. The value of the cone inclination angle depending on the composition of the flour – millet seeds mixture.

| The proportion of flour in the mixture (\( \nu \)) | Upper cone, ° | Lower cone, ° |
|-------------------------------------------------|---------------|---------------|
| 0.125                                           | 34.43         | 33.02         |
| 0.250                                           | 43.53         | 31.42         |
| 0.375                                           | 45.00         | 30.96         |
| 0.500                                           | 45.60         | 26.57         |
| 0.625                                           | 47.23         | 28.61         |
| 0.875                                           | 49.72         | 45.00         |

For an experimental study of the features of separation of a two-component mixture of bulk materials, the installation shown in Figure 2 was used. The installation consisted of a cylindrical container, the angle of inclination of the axis of which to the horizontal can be changed using a rotary mechanism. The cylinder was fixed to a platform that oscillated in a horizontal plane with an adjustable frequency.
The directions of all forces, except gravity and inertia, are constantly changing due to the chaotic movement of particles relative to each other due to vibration. The resulting gravity and inertia forces are constant at a given oscillation frequency. Under certain conditions in an oscillatory system, the resulting force allows heavy particles to reduce their potential energy by moving down relative to light particles.

3. Results

Figure 3 shows the sequential development of the separation process of a mixture of beans and sunflower seeds over time with horizontal vibration with a vibration frequency of 5 Hz. Since the density of sunflower seeds is less than that of beans, sunflower seeds "float" out of the mixture when vibrated. Visualization shows that with low-frequency horizontal vibration, the separation effect is noticeable at the very beginning of the process. It takes a large proportion of the time to bring the mixture to complete separation.
Figure 4 shows the dependence of the time of complete separation of the mixture on the angle of inclination of the container to the horizon with a vibration frequency of 5 Hz. At the same angle, measurements were carried out many times and the graph was plotted according to the averaged values. The maximum deviation of the measurement results relative to the average values did not exceed 8%. For all mixtures and separation modes used, the extremum of the function is found, namely – the minimum time for complete separation of the mixture. This time is achieved when the container inclination angle is approximately equal to the repose angle of mixture components. The experiments also revealed insignificant variations in the optimal angle of the container inclination depending on the vibration frequency.

The amplitude of oscillations also have a certain effect on the time of complete separation of the mixture. The separation process is carried out at amplitudes smaller than the particle size of the mixture. When the vibration amplitude of vibrator is significantly exceeded the particle size in the mixture, intensive mixing of the mixture components occurs.

4. Conclusion
Low-frequency horizontal vibration of bulk mixtures, taking into account the angle of repose of their components, is a simple and quite effective method for separating mixtures, easily implemented in agricultural production. Modeling of the separation process of mixtures by the method studied in this work shows that the trajectory of a particle is a vortex along an ascending or descending line, depending on the combination of the properties of the components and operating parameters.

For all used mixtures and operating modes, the minimum time for complete separation of the mixture into components is achieved when the container inclination angle is approximately equal to the repose angle of mixture components. The separation process is carried out at amplitudes smaller than the particle size of the mixture.

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