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REGRESSION MODELS FOR ASSESSING THE EFFICIENCY OF VIBRATORY SEPARATION OF PARSNIP SEEDS TAKING INTO ACCOUNT AIR DYNAMICS BASED ON NUMERICAL SIMULATION AND FIELD EXPERIMENT

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To reduce the complexity of research into designing promising vibratory machines while minimizing the harmful effect of the aerodynamic factor, it is convenient to use regression models. With their help, a quantitative assessment of the effectiveness of separation (cleaning) of seed mixtures is carried out, depending on the design parameters and the mode of operation of vibratory machines.

This paper reports the results of research on the construction of regression models for parsnip seeds based on numerical modeling and full-scale experiment. Based on numerical modeling, a four-factor regression model of the second order was built, which takes into account the geometric characteristics of the aerodynamic screen, the design of the set of working surfaces, and the oscillation amplitude of a vibratory machine. Based on a full-scale experiment, a three-factor regression model of the second order was constructed for a constant gap between the working surfaces.

A comparative analysis of the resulting regression models suggests that numerical modeling provides satisfactory accuracy in assessing the influence of the aerodynamic factor. This estimate, when using a regression model based on a numerical experiment, exaggerates the estimate determined by the full-scale experiment by 5–15 % (depending on the regressate variation area localization).

Hence, the numerical model of the process of vibrational motion of light-weight seeds, taking into account the action of aerodynamic forces and moments, used to build a regression model of separation of parsnip seeds, can be considered adequate. Regression models (for parsnips and other plant crops), which are built on the basis of numerical modeling, should be used to solve problems of optimizing the parameters of vibratory machines according to the criterion of reducing the harmful effect of the aerodynamic factor

Keywords: aerodynamic screen, vibratory movement, light-weight seed, linear regression, seed separation

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1. Introduction

The task to find optimal or rational values of parameters for the working process of vibratory separation is associated with a large number of full-scale tests and calculations. It is impossible to carry out such a search in the form of solving some extreme problem. Hence, a relevant task is to construct a variety of regression models for the processes of vibratory separation (cleaning) of small-seeded mixtures. Based on the use of such models, it would be possible to write algorithms for optimizing the design parameters and operating modes of vibratory machines according to the criterion of minimizing the harmful effect of the aerodynamic factor (reducing the quality of vibratory separation of seeds that are sensitive to air movement, due to the impact on the vibratory movement of seeds of aerodynamic forces and moments). This would significantly reduce the complexity of designing new vibratory machines and adjusting them for seed treatment of new plant crops.

But the task of conducting research in order to build the required regression models is also quite difficult if you solve it on the basis of using the results of a full-scale experiment. For example, the construction of a three-factor regression model of the second order at three levels according to a full-factor plan of the corresponding order requires $3^3=27$ experiments. For each experiment, it is necessary to perform about 15–20 launches of the vibratory machine, followed by an analysis of seeds in the resulting fractions of the mixture. The four-factor model, respectively, would require 81 experiments, according to a similar plan, with a similar number of machine launches for each experiment. It needs quite a long time, given that regression models are needed not for one but for several plant crops.

It is more convenient to build regression models based on numerical modeling. If you carry out a cyclical launch of the model where the parameters-regressates change according to the established plan of the experiment and the initial conditions of vibrational motion are determined using a quasi-probabilistic generator, you can form a table of observations for a relatively short period of time. But, at the same time, the question of the adequacy of the numerical model used is critical. It is necessary to assess: what error is introduced into the regression models if they are built on the basis of a numerical experiment?

2. Literature review and problem statement

The harmful effect of the aerodynamic factor on the process of vibrational separation of seed fractions was investigated in [1–11].

In [1], the influence of aerodynamic drag force on the movement of seeds in a channel with constant parameters of air flow is investigated. Analytical expressions for calculating the values of the aerodynamic force of seed resistance are proposed. But the lateral aerodynamic forces and aerodynamic moments arising from the uneven distribution of pressure along the surface of the seed during its air flow are not taken into account.

The importance of taking into account the aerodynamic factor in the treatment of seed material is indicated in [2]. But numerical metrics for measuring these properties are not formulated.

In [3], an overview of the mechanism of interaction of the working bodies of the separator with air is carried out. But numerical mathematical models are not presented for the implementation of parametric studies of promising machines.

In [4], a numerical model of the flow of gas and particles inside cyclone separators was developed. But outside the study were the processes of interaction with the air of modified working bodies with devices to reduce the harmful effects of the aerodynamic factor.

In [5], the interaction of air with wide-angle diffusers was investigated. However, the nature of the interaction of air with devices such as an aerodynamic screen, the effectiveness of their use is not considered.

In [6], a mathematical model of the vibrational motion of seeds of an ellipsoidal shape along a tilted rough surface is proposed. But the action of aerodynamic forces and moments is not taken into account. In addition, the approximation of seeds in the form of a body of rotation makes it impossible to take into account the aerodynamic characteristics of the seed.

In [7], the processes of interaction of seeds with working surfaces, taking into account air fluctuations based on analytical flat gasdynamic models, are investigated. According to the results of the study, regularities of distribution of air velocities along the height of interplane space in established cross-sections were established. An assessment of the influence of the aerodynamic factor on the vibrational movement of seeds due to their attribution by the air flow during the rebound from the working surface was made.

In [8], a method of increasing the efficiency of the process of separating sunflower seeds from impurities is considered by selecting the parameters of the vibratory machine according to the criterion of minimizing the effects of air. Studies have shown that the selection of angles of inclination, the amplitude and oscillation frequency of working surfaces can reduce the harmful effects of air during the separation of oil crops. However, for small-seeded light-weight crops, this technique would not give satisfactory results because the seeds do not differ from impurities in terms of their parameters and aerodynamic properties.

Paper [9] proposed a method for calculating the field of velocities and air pressures between the planar space of the package of an oscillating vibratory machine for a three-dimensional case. Patterns of change in air dynamics in different phase positions of the working bodies of the vibratory machine, under different modes of its operation, are obtained. The operability of the method is shown on the condition of using modern computing technology. However, the model does not have a mechanism for the influence of air dynamics on the kinematic parameters of the vibratory movement of seeds on the working surface of the machine.

In [10], a numerical model of seed vibrational motion is presented, which is sensitive to air movement, taking into account aerodynamic drag forces, lateral aerodynamic forces and moments. However, the proposed model is quite laborious if it is used in the design of promising samples of vibratory machines. The reported model needs to be simplified by replacing it with a regression model.

In [11], the results of the construction of four-factor regression models of the second order to assess the indicator of the effectiveness of the separation of seed mixtures of parsnip, fragrant dill, and leaf lettuce, taking into account the dynamics of air between the working surfaces of the vibratory machine unit, are presented. Regressions are built on the basis of numerical modeling of the vibrational movement of seeds during their interaction with the air moving due to the operation of the vibratory machine. But the accuracy of regression equations depends entirely on the degree of adequacy of the mathematical model used. There is no comparative assessment of the results obtained with the results of a full-scale experiment.

Thus, the above review allows us to assert the following:

– the constructed numerical models of seed vibratoty motion when cleaning (sorting) seed mixtures using vibratory machines take into account the dynamics of air in the space inside the blocks of working surfaces. The possibility of numerical modeling of working processes of vibratory machines with measures to eliminate the aerodynamic factor for light seed mixtures is provided;

– to reduce the complexity of parametric studies into the construction of promising samples of vibratory machines, on the basis of numerical modeling, regression equations for assessing the effectiveness of separation (cleaning) of some small-seed crops were built. The regression models include parameters for the design of the working unit, the aerodynamic screen, and the amplitude of oscillations of the working surfaces of the vibratory machine;

– there is no comparative evaluation of regression models for assessing the effectiveness of vibrational separation of light seeds, which are built on the basis of numerical modeling, with regression models built on the basis of a full-scale experiment.

Therefore, there is a task to conduct a comparative assessment of the accuracy of regression models for assessing the effectiveness of separation (cleaning) of light seed mixtures built on the basis of numerical modeling and regression models derived from the results of a full-scale experiment.

3. The aim and objectives of the study

The aim of this study is to construct a regression model for assessing the effectiveness of vibrational separation of parsnip seeds on the basis of a full-scale experiment, comparing the resulting performance estimates with the estimates determined using a similar regression model based on numerical modeling. This would make it possible to determine the assessment of the correctness of the replacement of the physical model of the vibratory machine with a numerical model of vibrational motion of light seeds, taking into account the dynamics of air. Building regression models based on a numerical experiment would provide significant savings in labor costs and resources, in contrast to full-scale modeling. Based on numerical modeling, a system of regression equations could be built to design promising vibratory machines effective for processing any small crops sensitive to air movement.

To accomplish the aim, the following tasks have been set:

– to build a regression equation of dependence of the indicator of the harmful effect of air dynamics on the efficiency of vibrational separation of parsnip seeds depending on the design parameters of the aerodynamic screen and the amplitude of vibrations of the vibratory machine based on the data from the full-scale experiment;

– to compare the resulting regression model with the regression model, which was derived from the data of a numerical experiment and evaluate the correctness of the use of a numerical model of vibrational motion of seeds replacing a physical sample of a vibratory machine.

4. Materials and research methods

4. 1. The object and hypothesis of research

The object of our study is the impact on the process of vibratory separation of light seed mixtures that are sensitive to air dynamics exerted by such parameters as a vertical gap between the working surfaces in the block; the size of the vertical wall of the aerodynamic screen and its distance from the end of the block; the amplitude of oscillations of the vibratory machine.

When conducting the study, a hypothesis is accepted about the correctness of using a regression model for assessing the indicator of the harmful effect of air dynamics on the quality of vibrational separation of seed mixtures, depending on the specified parameters, which is built on the results of numerical modeling, instead of a similar regression model, which is constructed from the results of a full-scale experiment.

The following assumptions are accepted in the work:

– limited range of variation of factors taken into account. The range of oscillation amplitude (from 0.3 mm to 3 mm) corresponds to the non-detachable modes of vibratory movement of seeds. The vertical gap between the working surfaces (from 6 mm to 15 mm) is for blocks of vibratory machines used for processing small-seeded mixtures;

– the surface of the seed, when calculating aerodynamic forces and moments, was taken in an arbitrary shape, which was set using discrete triangles. When modeling the interaction of seeds with a rough vibrating surface, the shape of the seed in the form of an ellipsoid was adopted;

– the model of vibrational motion took into account only the non-detachable mode with the rolling and sliding of seeds;

– as a criterion for the correctness of replacing a physical sample of a vibratory machine with a numerical model, the criterion is taken not to exaggerate more than the maximum permissible value of the difference in estimates of the indicator of the harmful effect of the aerodynamic factor obtained on regression models based on full-scale experiment and numerical modeling;

– the maximum permissible value of the relative difference in estimates of two regression models was taken as 10 %, which satisfies the requirements for the accuracy of engineering calculations.

To simplify the conduct of full-scale tests, instead of four factors, only three were considered. The vertical gap between the working surfaces of the block, which was constant and equal to 10 mm, was excluded from our consideration.

4. 2. Multiple linear regression method

When conducting research, the method of multiple linear regression was used [12] with the selection of the form of regression equations according to the criteria:

– testing the hypothesis of zero values of regression coefficients for regression factors. The test was carried out using Student's *t*-criterion;

– checking the condition of statistical significance of the resulting regression equation using the Fisher criterion;

– maximization of the correlation index (coefficient of determination) of the regression equation built.

The response vector for the matrix of observations was determined on the basis of a full-scale experiment on the vibrational separation of parsnip seeds, depending on the geometric characteristics of the screen, the amplitude of oscillations, with a certain vertical gap between the working surfaces.

4. 3. Regression equations obtained on the basis of a numerical experiment

For the implementation of comparative analysis, we used the results of research reported in [11].

To simulate the vibrational motion of seeds, the geometric shape and physical and mechanical properties of the seeds of the studied plant species were set.

The physical and mechanical properties of seeds were measured using the following characteristics:

– seed mass;

– sliding friction coefficient;

– the moments of inertia of seeds around their main axes.

These characteristics differed in types and fractions of seeds. For each type of seed, four fractions of the seed mixture were considered. The fourth fraction is the impurity fraction (particles of seeds and dry stem).

The geometric shape of the seed was given by representing its surface as a set of discrete elements (triangles). Fig. 1 shows an example of the breakdown of the surface of parsnip seeds into discrete triangles.

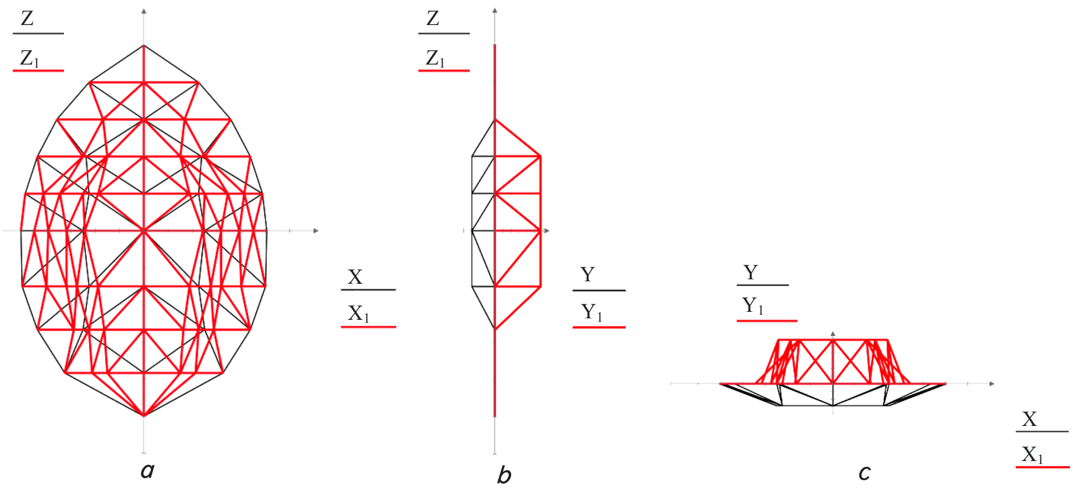


Fig. 1. Representation of the surface of parsnip seeds in the form of a set of discrete triangles:
a — view from above; *b* — side view; *c* — rear view

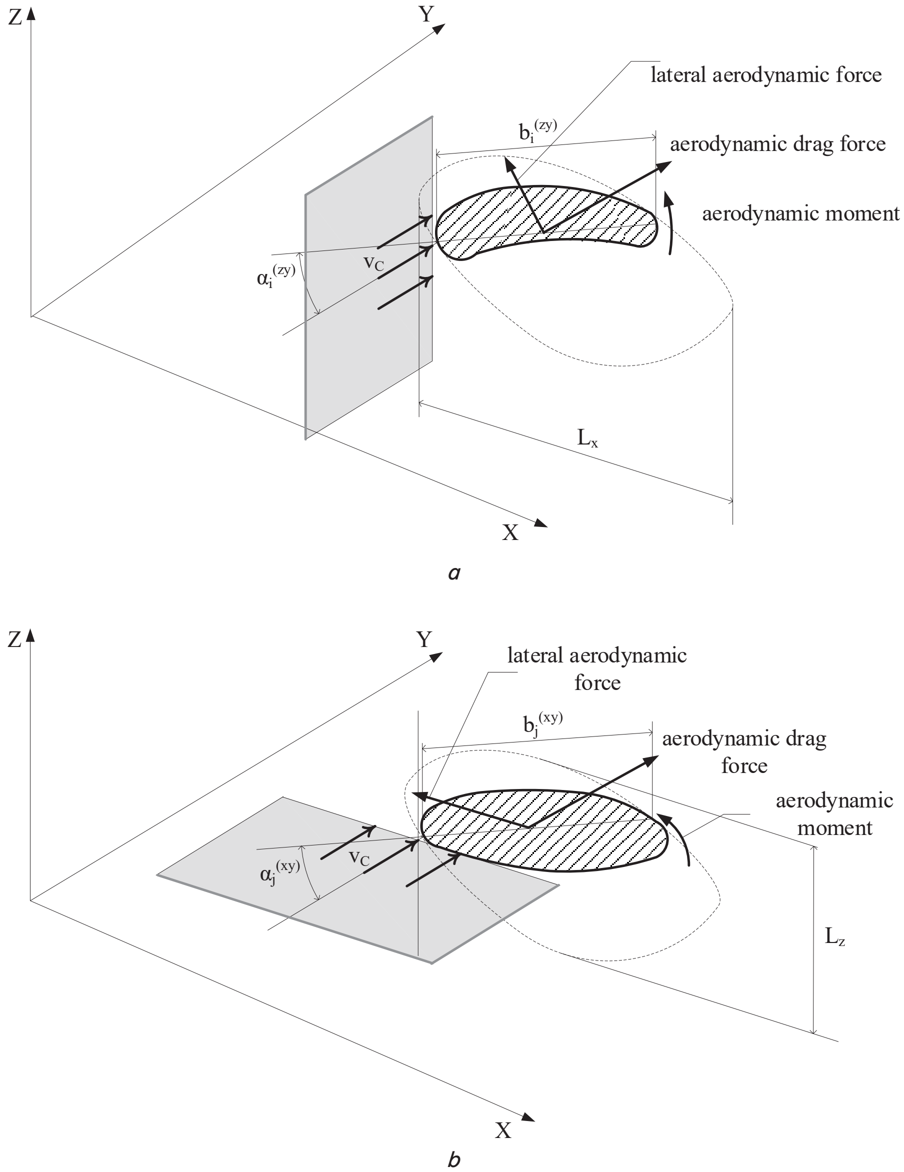


Fig. 2. Calculation of aerodynamic forces and moments for projections of air velocity in the coordinate system of the working surface: *a* — velocity projection in the *ZOY* plane; *b* — velocity projection in the *XOY* plane

To calculate the aerodynamic forces and moments acting on the seeds in the air flow, the procedure of summing up the resistance forces, lateral forces, as well as cranking aerodynamic moments calculated for flat cross-sections of seeds is used [16].

The calculation of aerodynamic characteristics is carried out separately for each projection of the air flow velocity vector at the point of location of the center of gravity of the corresponding cross-section of seeds.

For each projection of the air velocity vector at the point of the working space under consideration, the division of seeds into parallel flat cross-sections is carried out in two perpendicular planes (Fig. 2).

The field of velocities depending on the time for the volume of air located between two parallel working planes of the vibratory machine, synchronously oscillating, is calculated by solving the boundary problem by the numerical method of three-dimensional run [9]. To simulate the dynamics of the air environment inside the block of the vibratory machine, a system of Euler differential equations and an inseparability equation (excluding viscosity, ideal gas) were used.

The form of the calculated field of velocities and air pressure formed during oscillations of working surfaces is shown in Fig. 3, 4 for different values of the vertical gap between surfaces and the amplitude of their oscillations. The results correspond to the oscillation phase: the beginning of the downward movement.

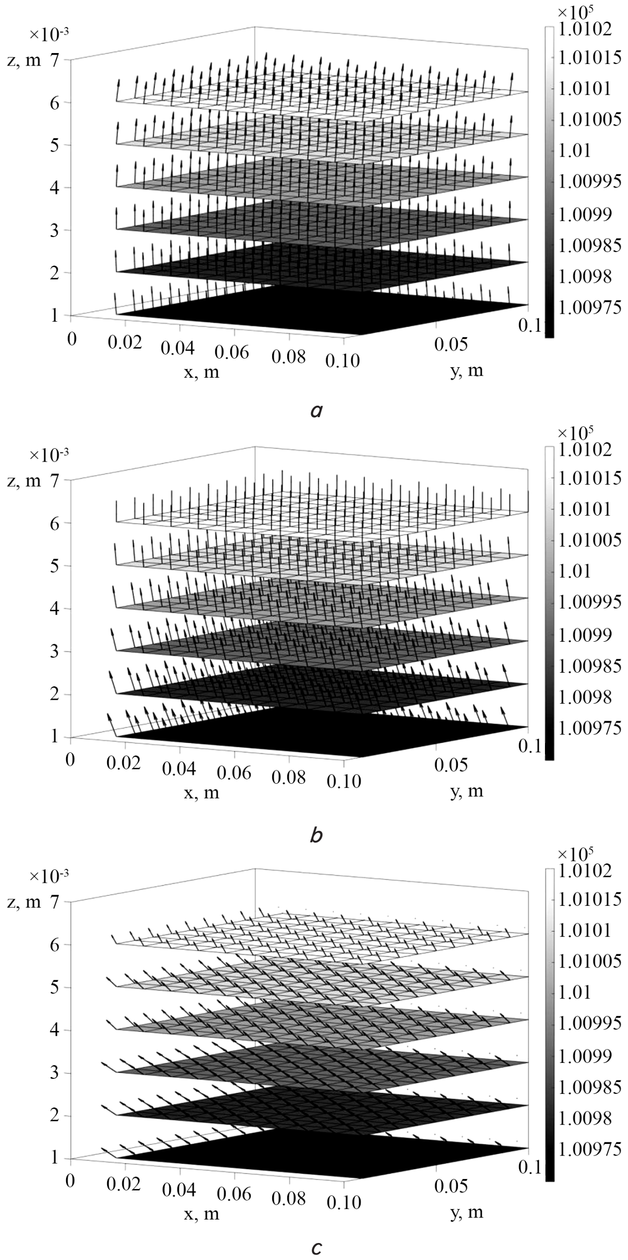


Fig. 3. The field of velocity and pressure at the distance between the working planes: *a* — 4 mm; *b* — 8 mm; *c* — 16 mm

The velocity field is displayed using oriented arrows that come out of the breakdown grid nodes of the working airspace and have a length that is proportional to the magnitude of the air velocity at that point. The pressure field is depicted using parallel planes inside the working space of different colors, the thicket of which is proportional to the amount of pressure. On the side axis on the right, numerical pressure values are given.

To simulate the vibrational motion of seeds, a model of non-stop movement of an ellipsoidal solid with rolling and slipping was used [8]. The movement occurs under the action of gravity, vibration (harmonic push), transmitted to the body from the working surface, as well as aerodynamic forces and moments arising from the movement of air relative to the oscillating working surface. The kinematic parameters of the motion of a body (the vector of the speed of movement of the center of gravity of a body and the vector of its angular velocity of rotation) are determined by solving a system of equations:

$$\begin{cases} \dfrac{d\mathbf{L}_i}{dt} = \mathbf{F}, \\ \dfrac{d\mathbf{H}_i}{dt} = \mathbf{M}_i, \end{cases} \tag{1}$$

where $\mathbf{L}_i$ is the amount of body movement in the accepted inertial coordinate system; $\mathbf{H}_i$ – moment of the amount of body movement in the inertial coordinate system; $\mathbf{F}$ – equivalent to the external forces applied to a given body; $\mathbf{M}_i$ is an equivalent moment from the external forces applied to the body, which is calculated relative to the origin of the inertial coordinate system.

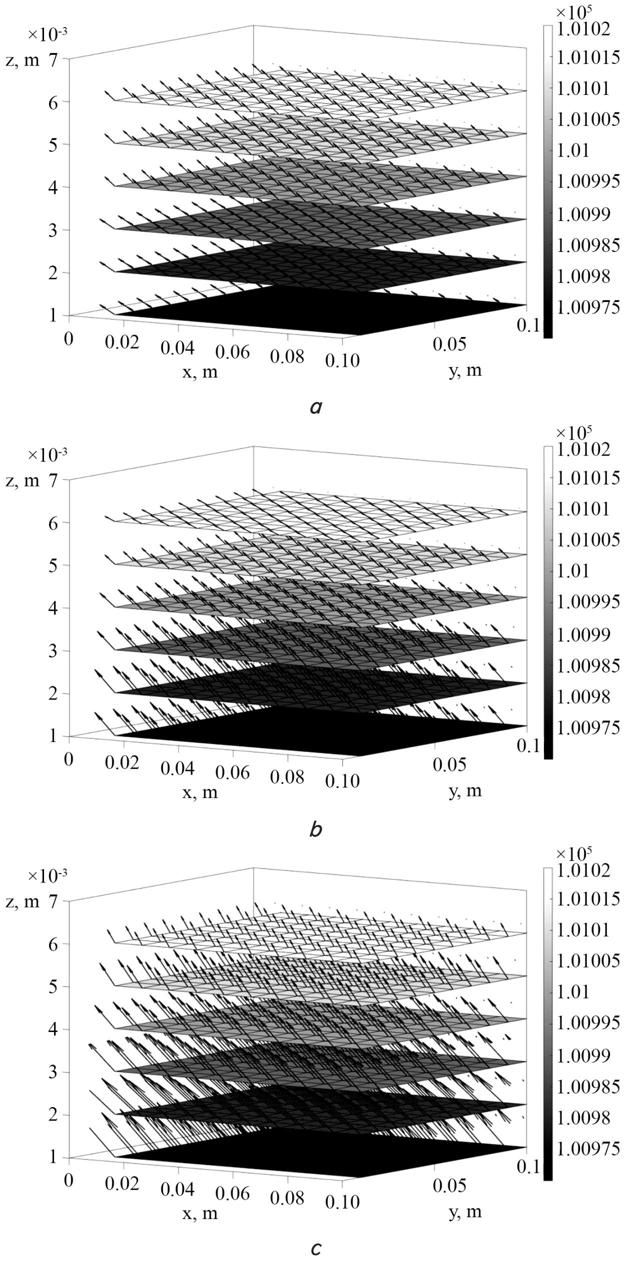


Fig. 4. Field of velocities and pressure at oscillation amplitude: *a* — 1 mm; *b* — 1.5 mm; *c* — 3 mm

The system of equations (1) is solved by their numerical integration by the Euler method with advancement along the axis of time with a constant step. The result of integration (1) looks like moving the center of mass of an individual seed when it rolls and slides relative to the working surface. Fig. 5 shows the calculated trace of the movement of the center of mass of the seed without taking into account and taking into account the action of aerodynamic forces and moments.

Exposure to air makes it difficult for the seeds to move relative to the working surface under the action of vibration pulses. If, when modeling vibrational motion, the aerodynamic forces and moments acting on the seed differ from zero, then the trajectory of the seed consists of a noticeably larger number of steps-movements. This is a trajectory that is indicated by the letter «b». Each such step, obtained under the influence of the impulse of movement of the working surface, has a shorter length. There is also a greater deviation of the approximating axis towards the slope. The angle of direction of movement of the seed with respect to the Y axis is less acute.

This leads to a decrease in the productivity of the vibratory machine and a deterioration in the quality of separation of seed crops with pronounced aerodynamic properties. Quantitatively, such a deterioration is characterized by an indicator for assessing the harmful effect of the aerodynamic factor (Fig. 6):

$$K=\frac{\sum_{i=1}^{N^{fr}}\delta_i^a+\sum_{i=1}^{\left(N^{fr}-1\right)}\varphi_i^a}{\sum_{i=1}^{N^{fr}}\delta_i+\sum_{i=1}^{\left(N^{fr}-1\right)}\varphi_i},\qquad(2)$$

where φ_i^a, φ_i are the angles of overlapping of sectors of possible trajectories of motion of seeds of the i-th and $(i+1)$-th fractions, which are obtained from the results of modeling vibrational motion, taking into account and without taking into account aerodynamic forces and moments, respectively; δ_i^a, δ_i – angles of sectors of possible trajectories of seeds of the i-th fraction, taking into account and without taking into account the aerodynamics.

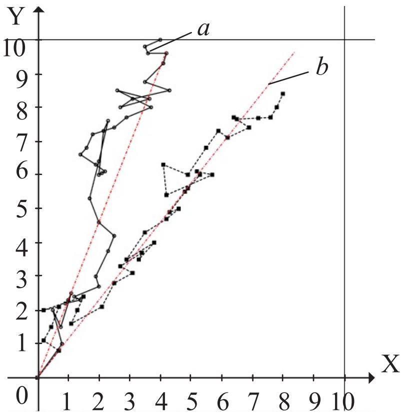


Fig. 5. Results of simulation of vibrational movement of seeds: *a* — without consideration; *b* — taking into account aerodynamic forces and moments

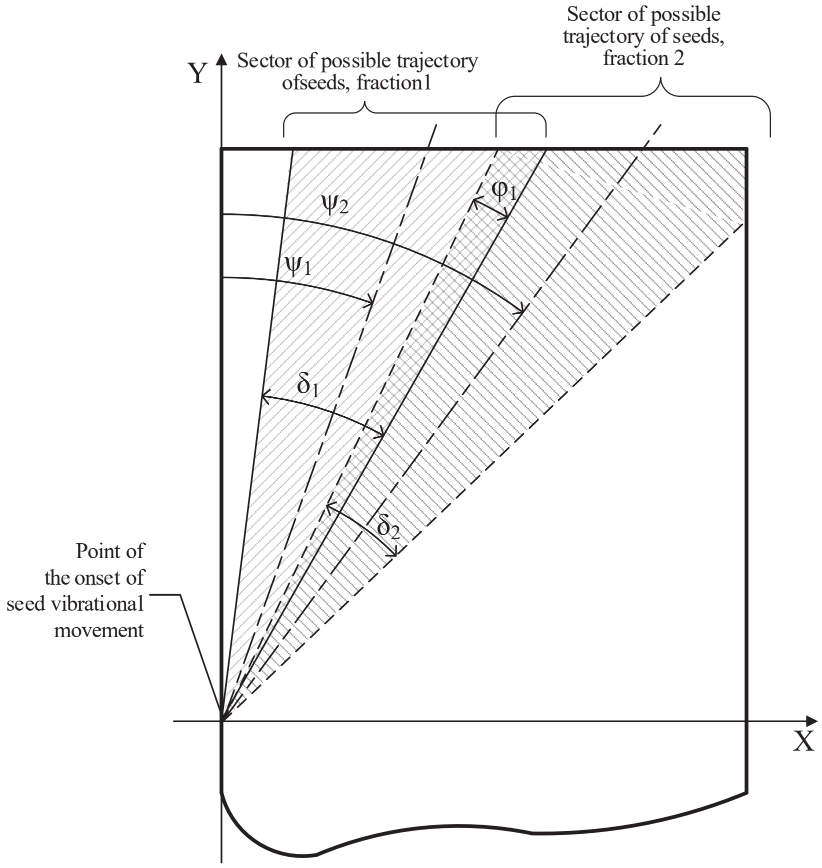


Fig. 6. Sectors of possible seed trajectories for two fractions of the seed mixture

Fig. 6 shows two sectors of possible trajectories of seeds of two fractions without taking into account the aerodynamic factor. Taking into account aerodynamic forces and moments, the sectors and angles of their intersection would increase.

The indicator of the harmful effect of the aerodynamic factor varies in the range from 1 to $+\infty$. If there is no action of aerodynamic forces and moments, then $K=1$. If the kinematic parameters of vibrational motion are affected by the force of aerodynamic drag, lateral force, aerodynamic moment arising from the discrepancy between the center of pressure and the center of mass of the seed, then $K>1$.

When conducting numerical experiments for each observation, the average values of the angles of inclination of the bisectors of possible trajectories for different fractions of seed mixtures were determined. A total of 20 iterations were carried out for each observation for each plant crop. The angles of sectors of possible trajectories were defined as a double probable deviation from the middle angle of inclination of the bisector of the corresponding trajectory sector. The probable deviation was defined as a triple standard deviation from the mean value of the corresponding angle. Average quadratic deviations were calculated using known statistical methods for processing probabilistic data.

Based on numerical modeling, studies were conducted to clarify the nature of the impact on the indicator of the harmful effect of the aerodynamic factor of such characteristics of the design of the working unit and the mode of operation of the vibratory machine as:

– a relative distance of the aerodynamic screen from the end of the working unit, z/H;

– a height of the vertical wall of the screen in relation to the vertical gap between the two working surfaces of the vibratory machine block, d/H;

– a vertical gap between the two working surfaces of the working unit, H;

– the amplitude of oscillations, A.

Modeling and filling the matrix of observations based on its results were carried out according to a full-factor three-level plan [17].

For parsnip seeds, the following regression equation was built depending on the indicator of the harmful effect of the aerodynamic factor on the mentioned parameters:

$$\begin{aligned} K &= 1.109 - 0.046x_1 - 0.123x_2 + \\ &+ 0.127x_3 + 0.135x_4 + 0.134x_1x_2 + \\ &+ 0.027x_1x_3 - 0.046x_2x_3 - \\ &- 0.122x_2x_4 + 0.04x_3x_4 + 0.035x_1^2 - 0.067x_3^2, \end{aligned} \quad (3)$$

where

$$x_1 = \frac{X_1 - X_1^{\min}}{X_1^{\max} - X_1^{\min}}, \quad X_1 = \frac{z}{H},$$

$$X_1^{\min} = 0.3, \quad X_1^{\max} = 1, \quad (4)$$

$$x_2 = \frac{X_2 - X_2^{\min}}{X_2^{\max} - X_2^{\min}}, \quad X_2 = \frac{d}{H},$$

$$X_2^{\min} = 0, \quad X_2^{\max} = 1.2, \quad (5)$$

$$x_3 = \frac{X_3 - X_3^{\min}}{X_3^{\max} - X_3^{\min}}, \quad X_3 = H,$$

$$X_3^{\min} = 6 \text{ mm}, \quad X_3^{\max} = 15 \text{ mm}, \quad (6)$$

$$x_4 = \frac{X_4 - X_4^{\min}}{X_4^{\max} - X_4^{\min}}, \quad X_4 = A,$$

$$X_4^{\min} = 0.5 \text{ mm}, \quad X_4^{\max} = 3 \text{ mm}, \quad (7)$$

where z/H is the relative distance of the aerodynamic screen from the end of the working unit; d/H – the height of the vertical wall of the screen in relation to the vertical gap between the two working surfaces of the vibratory machine block; H – the vertical gap between the two working surfaces of the working unit; A – the amplitude of oscillations; K is the indicator of the harmful effect of aerodynamic factor (2).

4. 4. Procedure for conducting a full-scale experiment

The full-scale experiment was carried out on a vibratory machine equipped with an adjustable aerodynamic screen [14]. A three-factor experiment was conducted with a variation of parameters in three levels. The following parameters varied:

– a height of the vertical wall of the screen, d (normalized parameter x_2 (5));

– the distance of the vertical wall from the end of the block of working surfaces, z (normalized parameter x_1 (4));

– an oscillation amplitude, A (normalized parameter x_4 (7)).

The intervals for changing the varied parameters were taken at similar intervals of variation, which were established during the numerical experiment. So:

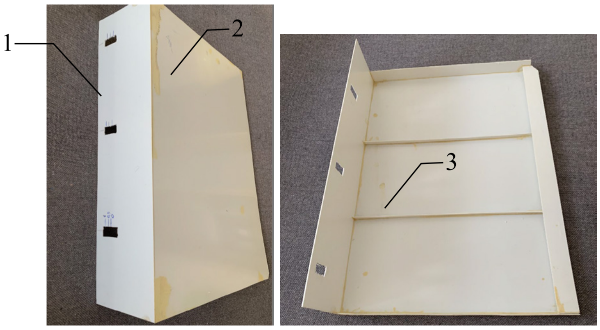
$$\frac{z}{H} \in [0.3; 1], \quad \frac{d}{H} \in [0; 1.2], \quad A = [0.5; 3], \text{ mm}.$$

The vertical gap between the working surfaces in the block did not vary and was set to equal 10 mm. That is:

$$H = 10 \text{ mm}, \quad x_3 = \frac{H - X_3^{\min}}{X_3^{\max} - X_3^{\min}} = \frac{10 - 6}{15 - 6} = 0.44.$$

The experiment was conducted according to a three-level plan for three factors [17].

The aerodynamic screen for the block of working surfaces was formed using a structural element, the general view of which is shown in Fig. 7.



a *b*

Fig. 7. General view of the aerodynamic screen: *a* – view from the outside; *b* – view from the inside; 1 – horizontal shelf with adjustable holes; 2 – vertical wall; 3 – stiffeners that regulate the distance of the screen from the end of the working unit

To adjust the distance of the vertical wall of the screen, special adjustment punctures were used to attach the horizontal shelf of the screen (Fig. 7, *a*, position 1) and stiffeners on the vertical wall (Fig. 7, *b*, position 3).

The screen in the form of vertical walls with horizontal shelves was mounted along each side of the block of working surfaces. To increase the distance, each wall of the aerodynamic screen was moved away from the corresponding end of the working surface. To reduce it, it was decreased. To fix the required position of the screen, the fastening screws were tightened, which pressed the horizontal shelf of the screen to the upper working surface of the working block.

To adjust the height of the vertical wall of the screen, the walls were replaced. During the experiments, two sets of vertical walls with horizontal shelves were used. A set that blocked the vertical gap between the two upper working surfaces of the block by 75 %, and a set that blocked by 150 %. The experiment, which was to be carried out for the case of zero overlap by a vertical gap screen, was carried out without an aerodynamic screen.

Studies into the influence of the aerodynamic factor were carried out only for the first two working surfaces of the block. To this end, the receiver of separated seed fractions was mounted directly under the second working surface of the unit. Seeds for vibrational separation were fed only to the second surface.

The amplitude of oscillations varied in the range from 0.5 to 3 mm. To adjust the amplitude, the characteristics of the vibration exciter were changed (Fig. 8). Adjustment of the vibration exciter was carried out by replacing sets of control levers and their distance from the axis of rotation of the vibration exciter.

With an increase in weight and distance from the axis of rotation of the regulating levers, an increase in the amplitude of oscillations occurred. When reducing the weight and approaching the levers to the axis of rotation – reducing the amplitude of oscillations.

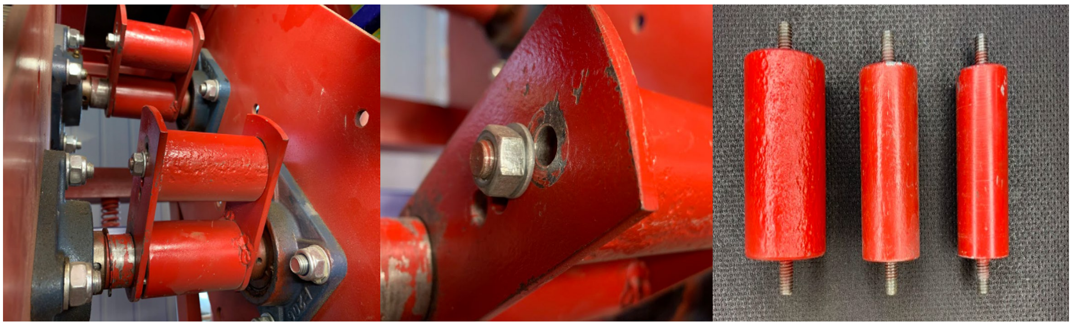

a *b* *c*

Fig. 8. Vibration exciter of the vibratory machine with the ability to adjust the amplitude of oscillations: *a* — the general general view of the vibration exciter design; *b* — adjustment of the distance of the lever from the axis of rotation; *c* — variable levers with different weights

To assess the kinematic parameters of the vibration motion of seeds, custom-made receivers of divided products were used, which were mounted on the block of separating plates of the machine. The results of the separation were collected in 10 receivers.

By statistical processing of seed material, which was formed in the installed receivers, the sectors of possible trajectories (average angles of directions of movement of seeds of different fractions (8) and angles of sectors of possible trajectories of seeds of these fractions (9)) of the mixture fractions and the indicator of the harmful effect of the aerodynamic factor (11) were determined.

In total, three fractions of the seed mixture of parsnip were considered. The first fraction is the content of foreign seeds (impurities) not exceeding 120...400 pcs/kg, the similarity is not less than 90 %. The second fraction – foreign seeds (impurities), no more than 80...280 pcs/kg; the similarity is 85 %. The third fraction is an impurity (damaged and empty seeds, dry stem, weed seeds).

The average angles of seed fractions were calculated as:

$$[\varphi_i]=\sum_{k=1}^{10}\frac{m_{ik}}{M\cdot\gamma_i}\varphi_k,\quad \sum_{k=1}^{10}\frac{m_{ik}}{M\cdot\gamma_i}=1, \tag{8}$$

where $[\varphi_i]$ is the average value of the angle of deviation of the axis of vibrational motion of seeds of i-th fractions; m_{ik} – the number of seeds of the i-th fraction that fell into the k-th section of the receiver; M – the total number of particles that makes up the seed mixture; y_i – a weight coefficient that determines the share that makes up the seeds of the i-th fraction in the mixture; φ_k – the angle of the beam connecting the point of location of the feeder of the vibratory machine with the middle of the k-th section of the seed receiver.

The sum of ratios $m_{ik}/M\cdot y_i$, taken in all ten sections of the receiver, is 1.

The half angle of the sector of possible trajectories of seeds of the i-th fraction is calculated as:

$$[\delta_i]=\frac{\left([\varphi_i]-\varphi_i^{\min}\right)+\left(\varphi_i^{\max}-[\varphi_i]\right)}{2}, \tag{9}$$

where $\varphi_i^{\min}$, $\varphi_i^{\max}$ is the minimum and maximum value of the angles that determine the corresponding seed receivers, where the number of seeds of the i-th fraction is not zero.

For the derived values $[\varphi_i]$, $[\delta_i]$, $i=1...3$ we calculate the overlapping angles of the sectors of vibrational motion of the seeds of the considered fractions:

$$\Delta_i=\begin{cases}(\varphi_i+\delta_i)-(\varphi_{i+1}+\delta_{i+1}),\\ \text{if } (\varphi_i+\delta_i)-(\varphi_{i+1}+\delta_{i+1})\geq 0,\\ 0,\\ \text{if } (\varphi_i+\delta_i)-(\varphi_{i+1}+\delta_{i+1})<0.\end{cases} \tag{10}$$

For known $[\varphi_i]$ and overlapping angles of the i-th and i+1-th fractions, Δ_i, the indicator of the harmful effect of the aerodynamic factor is calculated:

$$K=\frac{\sum_{i=1}^{2}\left(\delta_i+\Delta_i\right)}{\sum_{i=1}^{2}\left(\delta_i^*+\Delta_i^*\right)}, \tag{11}$$

where δ_i, δ_i^* is the theoretically achievable and obtained during the full-scale experiment half angles of the sectors of dispersion of the trajectories of seeds (particles) of the considered fractions; Δ_i, Δ_i^* is a theoretically achievable and experimental overlapping of sectors of seed fractions.

Theoretically achievable values of half angles of the sectors of dispersion of seed trajectories and angles of overlap of sectors of established seed fractions are determined by modeling the vibrational motion of seeds with the specified physical and geometric characteristics without taking into account the dynamics of air inside the space between the working surfaces of the vibratory machine block.

5. Results of the study on the construction of a regression model based on a full-scale experiment and its comparison with a model based on numerical modeling

5. 1. Full-scale experiment and construction of a regression model of the efficiency of separation of parsnip seeds

The full-scale experiment was conducted according to a three-level full-factor plan for three factors. The influence of the geometric characteristics of the screen and the amplitude of oscillations on the quality of separation of fractions of the parsnip seed mixture for a constantly given vertical gap between the working surfaces, which was equal to 10 mm, was evaluated.

Experimental data are given in Table 1.

Based on the data provided in Table 2, the construction of the regression model was carried out. Tables 3–5 give the steps of converting a full-factor regression model to a model with statistically insignificant regressants excluded.

Table 1

Results of the full-scale experiment

Experiment number	Fraction 1				Fraction 2				K
	Theoretically achievable values		Experimental values		Theoretically achievable values		Experimental values		
	φ_1^*, [degree]	δ_1^*, [degree]	φ_1, [degree]	δ_1, [degree]	φ_2^*, [degree]	δ_2^*, [degree]	φ_2, [degree]	δ_2, [degree]	
1	3	8	3.1	8.1	5	35	5.3	36	1.05
2	4	10	4.5	10.9	6	40	6.5	44	1.11
3	5	12	5.8	13.7	7	45	8.0	53.3	1.19
4	3	8	3.1	8.1	5	35	5.3	36	1.05
5	4	10	4.5	10.9	6	40	6.5	44	1.11
6	5	12	5.8	13.7	7	45	8.0	53.3	1.19
7	3	8	3.1	8.1	5	35	5.3	36	1.05
8	4	10	4.5	10.9	6	40	6.5	44	1.11
9	5	12	5.8	13.7	7	45	8.0	53.3	1.19
10	3	8	3.1	8.2	5	35	5.2	35	1.03
11	4	10	4.0	10.0	6	40	6.0	41.6	1.04
12	5	12	5.1	12.8	7	45	7.2	49.0	1.114
13	3	8	3.1	7.8	5	35	5.2	35.8	1.04
14	4	10	4.1	9.5	6	40	6.4	41.0	1.06
15	5	12	5.5	13.0	7	45	7.5	49	1.128
16	3	8	3.2	8.6	5	35	5.4	37.5	1.05
17	4	10	4.4	10.9	6	40	6.5	43.6	1.08
18	5	12	5.8	13.8	7	45	8.1	51.8	1.145
19	3	8	3	8	5	35	5	35.1	1.003
20	4	10	4	10	6	40	6	40.1	1.003
21	5	12	5	12.1	7	45	7	45.4	1.008
22	3	8	3.1	8.2	5	35	5.1	35.9	1.02
23	4	10	4.1	10.4	6	40	6.2	41.4	1.03
24	5	12	5.3	12.6	7	45	7.1	48.3	1.05
25	3	8	3.2	8.4	5	35	5.1	36.0	1.04
26	4	10	4.3	10.8	6	40	6.2	42	1.07
27	5	12	5.3	12.7	7	45	7.3	48.6	1.083

Table 2

Transformation of a full-factor regression model for a parsnip seed mixture

Conversion step	Regression coefficients and their *t*-criteria							
	x_0		x_1		x_2		x_4	
	a_0	t_0	a_1	t_1	a_2	t_2	a_3	t_3
0	0.2956	4.63	0.1578	2.36	–0.4283	–6.42	0.4599	6.89
1	0.2685	8.91	–0.0522	–0.66	–0.2612	–3.28	0.4698	5.9
2	0.2693	9.66	–0.0369	–0.96	–0.2897	–7.58	0.4633	6.06
3	0.2675	9.35	–0.0393	–1.02	–0.2578	–3.35	0.4677	6.08
4	0.2702	9.2	–0.0512	–0.65	–0.2892	–7.32	0.4644	5.88

Table 3

Transformation of full-factor regression model for parsnip seed mixture (continued)

Conversion step	Regression coefficients and their *t*-criteria							
	x_1x_2		x_1x_4		x_2x_4		x_1^2	
	a_4	t_4	a_5	t_5	a_6	t_6	a_7	t_7
0	–	–	–	–	–	–	–	–
1	0.3106	6.37	0.0822	1.68	0.0822	1.68	0.0124	0.18
2	0.3044	6.5	0.0794	1.7	0.0794	1.7	0	0
3	0.3072	6.52	0.0818	1.74	0.0818	1.74	0	0
4	0.3043	6.29	0.0778	1.61	0.0778	1.61	0.015	0.22

Table 4

Transformation of full-factor regression model for parsnip seed mixture (continued)

Conversion step	Regression coefficients and their *t*-criteria				Fisher's criterion	Coefficient of determination
	x_2^2		x_4^2			
	a_8	t_8	a_9	t_9		
0	–	–	–	–	31.4	0.804
1	–0.0307	–0.44	0.2492	3.61	143	0.987
2	0	0	0.2565	3.87	199	0.987
3	–0.0335	–0.5	0.2514	3.77	172	0.987
4	0	0	0.2562	3.74	163	0.986

As can be seen from the above results (Tables 2–4), the most accurate is the regression model at number 2. For it, Fisher's criterion is maximum and is 199. At the same time, the threshold value of the criterion, for the level of statistical significance 0.05, is 2.03 (the number of degrees of freedom of less variance is 19, the greater variance is 25). The resulting model provides such a variance of residues, which confirms the hypothesis of its statistical significance.

Finally, the regression model for assessing the values of the indicator of the harmful effect of aerodynamics, for parsnip seeds, is as follows:

$$K = 1.053 - 0.007x_1 - 0.054x_2 + \\ + 0.087x_4 + 0.057x_1x_2 + \\ + 0.015x_1x_4 - 0.113x_2x_4 + 0.048x_4^2. \qquad (12)$$

The regression equation has a second-order polynomial structure with the exception of the quadratic equations of the relative distance of the vertical wall of the aerodynamic screen from the end of the block $\left(x_1^2\right)$ and the relative wall height $\left(x_2^2\right)$. For these excluded equation terms, the *t*-criterion was equal to, respectively: 0.18 and 0, at its tabular value of 2.07. That is, for these terms, the hypothesis of a zero value of their regression coefficients is statistically significant.

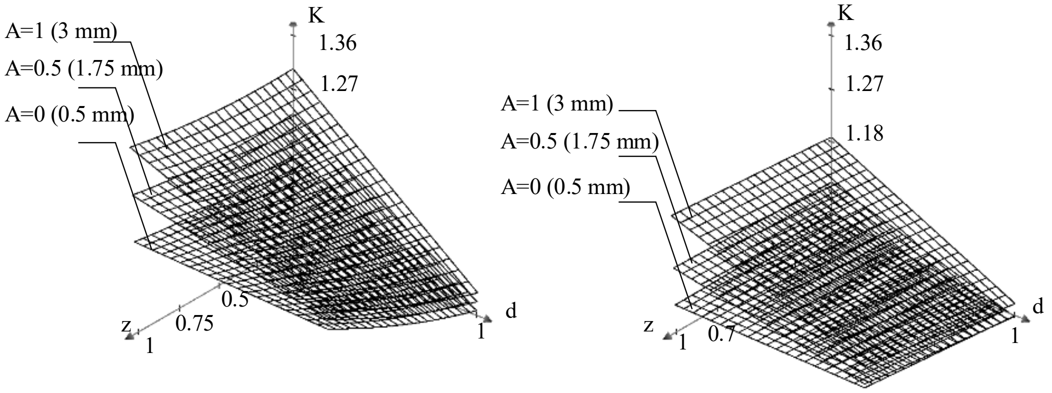
The most significant was the term, which is a multiplication of the amplitude of oscillations and the relative height of the wall of the aerodynamic screen (x_2x_4). In second place in terms of the level of influence on the indicator of the harmful effect of the aerodynamic factor is the amplitude of oscillations (x_4). Further, in order of decreasing weight according to the degree of impact on the quality of vibrational separation of seeds, the following: multiplication of the relative distance from the end of the block and the relative height of the vertical wall screen (x_1x_2); relative height of the vertical wall of the screen (x_2); square of the amplitude $\left(x_4^2\right)$; the multiplication of the relative distance of the vertical wall of the screen from the end of the block and the amplitude of oscillations (x_1x_4); the relative distance of the vertical wall of the screen from the end of the block (x_1).

The regression equation (12), based on the results of a full-scale experiment, must be compared with the regression model (3), which is built on the basis of a numerical experiment. This would make it possible to assess the correctness of the use of the vibration motion model [9, 10] instead of a physical sample of a vibratory machine.

5. 2. Comparative analysis of regression models based on the results of full-scale and numerical experiments

The regression model obtained from the results of the field experiment (12) was compared to the regression model (3), derived from the results of the numerical experiment. Fig. 4 shows dependence charts of the coefficient of harmful effect of aerodynamics on the geometric characteristics of the screen and the amplitude of oscillations, constructed using (3) (Fig. 9, *a*) and using (12) (Fig. 9, *b*). The chart, which is constructed using (2) (Fig. 9, *a*), was calculated at x_3=0.44 or H=10 mm.

As can be seen from the above charts (Fig. 9, *a*, *b*), the indicator of the harmful effect of aerodynamics, if we use the regression model obtained on the basis of a numerical experiment, exaggerates a similar estimate, which was obtained on the basis of a full-scale experiment, by 5–15 %.



a *b*

Fig. 9. Regression dependence of the coefficient of harmful influence of aerodynamic factor on the quality of vibroseparation of parsnip seeds on the geometric characteristics of the screen and the amplitude of oscillations: *a* – according to the results of a numerical experiment; *b* – based on the results of a full-scale experiment

The magnitude of the error depends on the localization of the area of varied parameters. Thus, at the maximum amplitude of oscillations (A=3 mm or x_4=1), in the absence of an aerodynamic screen (d=0 or x_2=0), the indicator of the harmful effect of aerodynamics for a full-scale experiment reaches a value of 1.19. For a numerical experiment, with similar parameters, it is equal to 1.29. With increasing value of the height of the vertical wall of the screen, the discrepancy between the results of numerical and full-scale experiments decreases and does not exceed 5 %.

If we proceed from the fact that for solving most engineering problems it is considered acceptable to ensure the accuracy of models (methods) with an error of up to 10 %, then it can be argued that the adequacy of regression equation (3) and the model from [9, 10] is satisfactory. For most of the parametric space used, the deviation from the full-scale experiment is no more than 10 %. Exceeding this threshold occurs for the case of the absence of an aerodynamic screen and at large amplitudes of oscillations. Since the model devised is intended to carry out research on the justification of the geometric characteristics of the screen (its presence is assumed) and the operating modes of the vibratory machine, when the non-detachable movement of seeds of low weight (small values of the oscillation amplitude) is realized, it can be assumed that the minimum required degree of adequacy of the model has been achieved.

6. Discussion of results of the study on the construction of regression models of the influence of the aerodynamic factor

The most significant deviation of numerical modeling results from the full-scale experiment (up to 15 %) occurs when the aerodynamic screen is absent, and the amplitude of oscillations is maximum (Fig. 9). For such initial data in the mathematical model there are maximum tangential velocities in space inside the block of working surfaces. Since the simulation does not take into account the influence of the roughness of the working surface on the pressure and the field of air velocities due to its thicket, there is some overestimation of the degree of harmful effect of the aerodynamic factor.

This result can be explained by simplifying the used model of gas-dynamic processes. The Euler and continuity (ideal gas) equation is applied. In our opinion, a model where the Navier-Stokes equations are used (viscosity is taken into account) should be more adequate. However, solving such a system of differential equations would require significantly increasing the computational complexity of the algorithm. Despite the fact that the accuracy achieved on the basis of the model used is satisfactory for the design of promising vibratory machines.

The resulting regression equation is a second-order equation with a weakly expressed nonlinear nature of dependence on variable parameters. The formed surface has no optimum. There is no change in the sign of the first derivatives. Therefore, the optimal parameters should be found on the boundaries of the established area of existence of the function under study. This conclusion is confirmed by similar results, which are reported in [15].

Therefore, the statement of the problem on optimizing the design and mode of operation of the vibratory machine according to the criterion of minimizing the harmful effect of aerodynamics should be built taking into account this feature.

As a disadvantage, it should be noted that the range of change in the amplitude of oscillations is limited to 3 mm. Although vibratory machines can also work with larger oscillation amplitudes. In this case, there is a mode of vibratory movement with a break. However, the kinematics model used does not consider the case of seed rebound from the working surface. To take into account all modes of operation of vibratory machines, it is necessary to use a model of vibration motion with a rebound.

Based on the proven adequacy of the used model of vibration motion, it is advisable to form a library of regression models for assessing the effectiveness of vibrational separation of light-weight seed mixtures of various plant crops under the conditions of the emergence of air dynamics inside the block of working surfaces.

7. Conclusions

1. According to the results of the field experiment, a regression equation was built to assess the indicator of the harmful effect of air dynamics on the efficiency of vibrational separation of parsnip seeds, depending on the geometric characteristics of the aerodynamic screen and the amplitude of oscillations. The equation has a polynomial structure. The most influential were such terms as the multiplication of the amplitude of oscillations and the relative height of the wall of the aerodynamic screen; the amplitude of oscillations. The squares of the relative distance of the vertical wall from the end of the block and the relative height of the wall turned out to be those for which, according to the t-criterion, the hypothesis of zero values of their regression coefficients was confirmed. The indicator of the harmful effect of the aerodynamic factor increases if the amplitude of oscillations and the distance of the screen from the end of the block increase; the height of the vertical wall of the screen decreases.

2. Based on the results of comparative analysis of regression models obtained from full-scale and computational experiments, it was found that numerical modeling exaggerates the harmful effect of aerodynamics by 5–15 % in relation to a full-scale experiment. The model error increases with a decrease in the vertical wall of the screen and an increase in the amplitude of oscillations. But for the design of vibratory machines with the implementation of measures to eliminate the harmful effect of air dynamics on the process of separation of light seed mixtures, when small values of the amplitude of oscillations are used and an aerodynamic screen is present, the magnitude of the deviation of experimental results from the simulation results is acceptable for engineering calculations. This provides for the correctness of replacing the physical sample of a vibratory machine with a numerical model of seed vibrational motion, taking into account the aerodynamic forces and moments.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The manuscript has related data in a data repository.

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