

When separating (cleaning) lightweight seed mixtures with the help of vibratory machines, there is an issue related to the harmful effect of air movement in the gaps between parallel working surfaces of vibratory machine units. This factor is particularly harmful to seed material, which is sensitive to air movement (some medicinal and vegetable crops). To address this issue, the design of vibratory machines is changed while their operational regimes are configured accordingly. This requires many full-scale experiments and (or) time-consuming personal computer-based simulation of the working processes of the vibrational motion of such seed mixtures.

This paper proposes several regression models that make it possible to replace time-consuming numerical modeling with simple analytical expressions (regression equations). These equations are used for a quantitative assessment of the degree of influence of aerodynamics on the kinematic parameters of the vibrational motion of particles of seed mixtures. The assessment is derived depending on the geometric characteristics of the aerodynamic screen, the design of the unit, and the amplitude of oscillations of the working surfaces of a vibratory machine. The models take the form of equations of multiple linear regression of the second order, obtained on the basis of a series of numerical experiments. The processes of vibration movement of the seed material of parsnips, lettuce, and fragrant dill were investigated. The coefficient of determination equaled 0.956...0.967.

The results reported here are useful for the construction of algorithms to optimize the design and adjust the operating modes of vibratory separators according to the criterion of minimizing the harmful effects of the aerodynamic factor

Keywords: aerodynamic factor, aerodynamic screen, vibratory machine, vibration motion, multiple linear regression

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CONSTRUCTION OF A REGRESSION MODEL FOR ASSESSING THE EFFICIENCY OF SEPARATION OF LIGHTWEIGHT SEEDS ON VIBRATORY MACHINES INVOLVING MEASURES TO REDUCE THE HARMFUL INFLUENCE OF THE AERODYNAMIC FACTOR

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1. Introduction

The design of vibratory machines, which are typically used for separating and cleaning fine-seed mixtures, is cha-

racterized by the use of units of working surfaces. This improves the productivity of the machine but predetermines the emergence of an aerodynamic factor [1]. Flat channels are formed between the working planes, inside which (during

vibration) there is a field of speed and air pressure. That, for seeds with pronounced aerodynamic properties, increases the influence of aerodynamic forces and moments, which is commensurate with the action of friction forces, vibration pulses, and gravity forces.

The aerodynamic factor significantly impairs the efficiency of the use of vibratory machines in the processing of fine-seed mixtures sensitive to air movement. A vibratory machine does not make it possible to separate elite fractions and debris particles effectively enough. Thus, there is a task to improve (by changing the design and (or) operating modes) existing vibratory machines in order to enhance the treatment efficiency of seeds with pronounced aerodynamic properties.

The task to find the optimal or rational values for the parameters of the working process of vibration separation is associated with a large number of full-time or numerical tests. It is impossible to carry out such a search in the form of a solution to some extreme problem. Given this, it is a relevant task to build various regression models of processes of vibration separation (purification) of fine-seed lightweight mixtures. Based on the use of such models, it would be possible to construct algorithms for optimizing the parameters of the design and modes of operation of vibratory machines according to the criterion of minimizing the harmful effects of the aerodynamic factor. This could significantly reduce the complexity of the structure of new vibratory machines and their adjustment to the processing of seeds of new plant crops.

2. Literature review and problem statement

The harmful effect of the aerodynamic factor on the process of vibration separation of seed fractions has been investigated by many authors. In [1], the influence of aerodynamic resistance force on the movement of seeds in the channel with constant parameters of airflow was investigated. Analytical expressions for the calculation of values of aerodynamic strength of seed resistance were proposed. However, the side aerodynamic forces and aerodynamic moments arising from the uneven distribution of pressure along the surface of the seed when it is flowed by air were not taken into consideration.

The importance of taking into consideration the aerodynamic factor in the processing of seed material is indicated in [2]. However, numerical metrics for measuring these properties were not formulated.

In [3], the mechanism of interaction between the working bodies of the separator and the air was investigated. However, there are no numerical mathematical models for the implementation of parametric studies of promising machines.

In [4], a numerical model of the movement of particles of the seed mixture was built when they interact with the working bodies of the cleaning machine. With the help of that model, the mode of operation of the machine was optimized. At the same time, only two factors were included in the parametric optimization space. Further increase in the dimensionality of the parametric space is limited by the very large complexity of optimization once use the constructed numerical model is applied.

To overcome the dimensionality crisis, work [5] proposed replacing the numerical modeling of the workflow with the «response surface». Such a surface is understood as some approximation or regression model of the behavior of the object, depending on the studied parameters of the workflow (ope-

rating conditions). This approach is quite promising in terms of reducing the complexity of the tasks of optimizing the parameters of working processes and (or) designing promising seed processing machines. As in [6], it is also possible to reduce the complexity of the tasks of parametric analysis of the processes of vibration purification (separation) of seed mixtures of medicinal and some vegetable crops.

In [7], a mathematical model of the vibrational motion of ellipsoidal seeds on a tilted rough surface was proposed. However, the effect of aerodynamic forces and moments was not taken into consideration. In addition, the approximation of seeds in the form of a rotation body makes it impossible to take into consideration the aerodynamic features of the seeds.

In [8], the processes of interaction of seeds with working surfaces were investigated, taking into consideration air fluctuations based on analytical flat gas-dynamic models. Based on the study results, the regularities of the distribution of airspeeds along the height of the interplane space in the established intersections were defined. The effect of the aerodynamic factor on the vibration movement of seeds due to their displacement by airflow during the rebound from the working surface was estimated.

In [9], a technique to improve the efficiency of the process of separating sunflower seeds from debris particles by selecting the parameters of the vibratory machine by the criterion of minimizing the effects of air action was considered. As shown by studies, the selection of angles of inclination, amplitude, and frequency of oscillations of working surfaces could reduce the harmful effects of air in the separation of oil crops. However, for lightweight fine-seed crops, that method would not give satisfactory results since, by their parameters and aerodynamic properties, the seeds do not differ from debris particles.

Paper [10] suggested a procedure for calculating the field of speeds and air pressures within the plane space of the oscillating vibratory machine package for a three-dimensional case. In [11], the authors established the regularities of changing the dynamics of air in different phase positions of the working bodies of the vibratory machine under different modes of its operation. The efficiency of the method subject to using modern computer technology was shown. However, the proposed model is quite laborious if it is used in the design of promising samples of vibratory machines. The reported model needs simplification by replacing it with a regression model.

Therefore:

- the applied models of vibration motion of seeds when cleaning (sorting) seed mixtures using vibratory machines do not fully take into consideration the harmful effects of the aerodynamic factor. Only the influence of design parameters and modes of operation of vibratory machines is investigated. The possibility of eliminating the harmful effects of the aerodynamic factor by using the screen has not been considered [1–3];
- the constructed numerical models of vibration motion are quite laborious for parametric research [7–11];
- the problems of optimizing the parameters of the working processes of seed processing based on the use of numerical models of these processes can be solved for the parametric space of small dimensionality [4];
- to reduce the complexity of such optimization problems, it is useful to replace the numerical model of the process with some approximation surface (regression model) [5].

Given this, there is a task to replace the numerical model of vibration motion of seeds, taking into consideration aero-

dynamic forces and moments, with a regression model. The parametric space of the regression model to be constructed should take into consideration the design parameters of the aerodynamic screen and the working units of the vibratory machine. It is advisable to build new regression models based on numerical experiments.

3. The aim and objectives of the study

The aim of this study is to build a regression model for assessing the effectiveness of separating lightweight seeds by vibratory machines involving measures to reduce the harmful effects of the aerodynamic factor. This would make it possible to conduct a parametric analysis of the dependence of the indicator of reducing the influence of the aerodynamic factor on the geometric characteristics of the aerodynamic screen, the height of the vertical gap between the working surfaces, and the amplitude of their oscillations. Based on the regression equations to be built, less time-consuming algorithms for optimizing the parameters of the design and modes of operation of vibratory machines could be developed, according to the criterion of minimizing the effect of the aerodynamic factor.

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

- to devise an indicator of measuring the level of harmful effects of the aerodynamic factor on the process of vibration separation of seeds;
- to determine the working range of changing regression parameters, conduct a numerical experiment to build a training sample for the regression model;
- to define the optimal form of regression equations constructed by the method of multiple linear regression by processing the results of a numerical experiment for established plant crops;
- to carry out parametric analysis on the effect exerted on the effectiveness of vibration separation of seeds of certain crops by measures to eliminate the harmful effects of the aerodynamic factor.

4. The study materials and methods

During the research, we employed the method of multiple linear regression [12] involving the selection of the form of regression equations according to the following criteria:

- testing the hypothesis of zero values of regression coefficients for regression factors. The test was carried out using the Student's *t*-criterion;
- verification of the condition of statistical significance of the formed regression equation using the Fisher criterion;
- maximization of the correlation index (coefficient of determination) of the formed regression equation.

The training sample was constructed using numerical modeling of the vibration motion of seeds under the influence of vibration pulses and aerodynamic forces and moments arising during the periodic movement of air between the working surfaces of a vibratory machine's unit. To implement numerical modeling, a model of the non-detachable vibration motion of seeds was used, taking into consideration the action of aerodynamic forces and moments [13, 14]. At the same time, the parameters of the field of speed and air pressure were determined depending on the geometric characteristics of the screen, the vertical gap between the

working surfaces, and the amplitude of oscillations. The model used makes it possible to determine the statistical characteristics of the kinematics of the movement of seeds of different fractions of seed mixtures depending on the geometric and mechanical characteristics of the seeds of the corresponding fractions, the geometry of the aerodynamic screen, the design of the working surface unit, and the mode of operation of the vibratory machine. A 10–15 % degree of adequacy of the simulation results is ensured, depending on the type of seed.

Based on the experimental data obtained (according to the results of the numerical experiment), by using a least-square method, we built regression equations of the dependence of the indicator of the harmful effects of aerodynamics on the efficiency of separation of fractions of seed mixtures of certain plant crops on the studied parameters. Regression equations were constructed in a linear form in the form of the second-order function:

$$k_i = a_{i,0} + a_{i,1}x_1 + \dots + a_{i,4}x_4 + a_{i,5}x_1x_2 + \dots + a_{i,7}x_1x_4 + a_{i,8}x_2x_3 + a_{i,9}x_2x_4 + a_{i,10}x_3x_4 + a_{i,11}x_1^2 + \dots + a_{i,14}x_4^2, \quad (1)$$

where k_i is an indicator of the assessment of the harmful effects of aerodynamics for the separation of fractions of seeds of the i -th type; $a_{i,m} = 0, 1, \dots, 14$ are the coefficients of a linear regression of the second order. The regression equation relative to the variable takes a linear form. As variables, the equation includes the parameters under study, their products, and second powers; $x_p, p = 1, \dots, 4$ are the normalized parameters under investigation.

The values of the regression coefficients, their corresponding Student's *t*-criteria, the Fisher's criterion (assessment of statistical significance), and the coefficient of determination for the regression equation built were determined using the MATLAB software package, developed in the USA, by applying the *fitlm* procedure [15].

To simulate the vibration motion of seeds, the geometric shape, as well as the physical and mechanical properties of the seeds of the studied plant species, were set. We examined the seeds of parsnip, lettuce, and fragrant dill.

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

- the mass of seeds;
- a sliding friction coefficient;
- the moments of seed inertia around its main axes.

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

The geometric shape of the seed was set by representing its surface in the form of a set of discrete elements (triangles). Fig. 1 shows an example of breaking the surface of fragrant dill seeds into discrete triangles.

According to the plan of our experimental studies, by using numerical modeling, we determined the mathematical expectations of the angles of inclination of the trajectories and half angles of sectors of possible seed trajectories by fractions of the studied seed mixtures.

During the single experiment, seeds from different fractions were alternately taken (the physical-mechanical and geometric characteristics changed). For each fraction, 20 runs of the mathematical model were made with the initial values of the Euler angles (spatial orientation) of the seeds at the point of the onset of the movement, determined randomly.

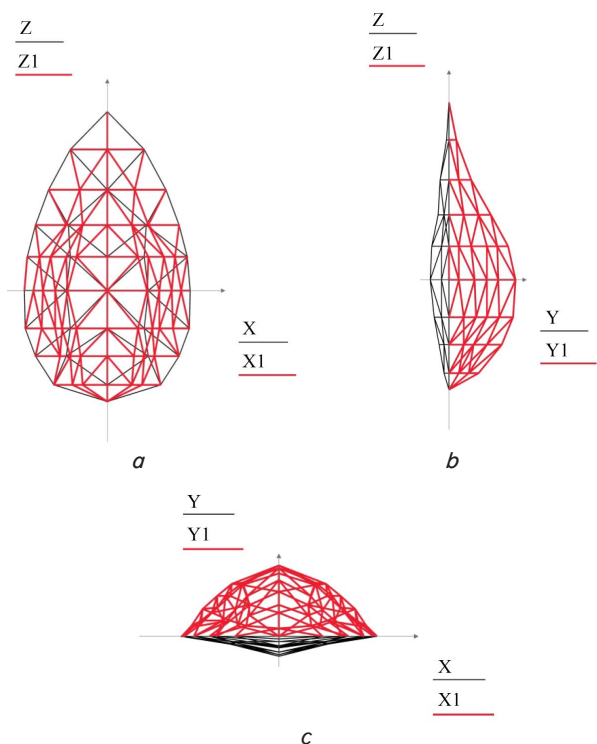


Fig. 1. Representation of the surface of fragrant dill seeds in the form of a set of discrete triangles: a – view from above; b – side view; c – rear view

Based on the derived values for the angles of inclination of trajectories and half angles of sectors of possible trajectories of seeds of different fractions, we calculated the indicator of harmful effects of the aerodynamic factor. This indicator was used as a response when filling the observation matrix.

5. Results of studying the construction of regression models of the effect of the aerodynamic factor on the parameters of seed movement

5.1. The indicator of measurement of the level of a harmful effect of the aerodynamic factor on the process of vibration separation of seeds

To determine the contribution of the action of aerodynamic forces and moments to the kinematic parameters of seed movement, the following indicator was used in the study.

A seed of a certain shape, given the established physical and mechanical characteristics, when simulating its vibrational motion, starting from the point of coordinate origin, X_0, Y_0 , taking into consideration and excluding aerodynamic forces and moments, would move along two trajectories (Fig. 2). The trajectory of the seed without taking into consideration its aerodynamics is indicated by the letter «a». Taking into consideration its aerodynamics – the letter «b».

The direction of a seed movement is fitted to a straight line (red dashed line in Fig. 2):

$$Y = a_0 + a_1 X, \tag{2}$$

where a_0, a_1 are the constant coefficients whose values are calculated using the least-square method:

$$a_1 = \frac{N \sum_{i=1}^N X_i Y_i - \sum_{i=1}^N X_i \sum_{i=1}^N Y_i}{N \sum_{i=1}^N X_i^2 - \left(\sum_{i=1}^N X_i \right)^2}, \tag{3}$$

$$a_0 = \frac{\sum_{i=1}^N Y_i - a_1 \sum_{i=1}^N X_i}{N}, \tag{4}$$

where $(X_i; Y_i)$ are the coordinates of the location of the center of mass of seeds in the coordinate system of the working plane at the i -th step of calculations; N is the number of steps of integration of the system of vibration motion equations.

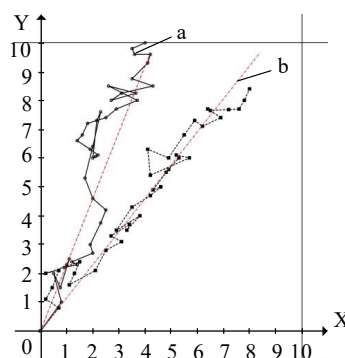


Fig. 2. Results of modeling the vibration motion of seeds: a – without taking into consideration the aerodynamic forces and moments; b – taking into consideration the aerodynamic forces and moments

The influence of air complicates the advancement of seeds relative to the working surface under the influence of vibration pulses. Once, when simulating a vibration motion, the aerodynamic forces and moments acting on seeds differ from zero, then the trajectory of the seeds consists of a noticeably greater number of displacement steps. This is a trajectory that is formed by marks in the form of black squares and is indicated by the letter «b». Each such step, due to the influence of the momentum 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 seed movement with respect to the Y axis is less acute.

That leads to a decrease in the performance of a vibratory machine and a deterioration in the quality of separation of seed crops with pronounced aerodynamic properties. Quantitatively, such deterioration is characterized by the following indicator (Fig. 3):

$$K = \frac{\sum_{i=1}^{N^r} \delta_i^a + \sum_{i=1}^{(N^r-1)} \phi_i^a}{\sum_{i=1}^{N^r} \delta_i + \sum_{i=1}^{(N^r-1)} \phi_i}, \tag{5}$$

where ϕ_i^a, ϕ_i are the overlapping angles of sectors of possible trajectories of the movement of seeds of the i -th and $(i+1)$ -th fractions, obtained according to the results of modeling of vibration motion, taking into consideration and without taking into consideration the aerodynamic forces and moments, respectively; δ_i^a, δ_i are the angles of sectors of possible trajectories of seeds of the i -th fraction, taking into consideration and excluding their aerodynamics.

Fig. 3 shows two sectors of possible trajectories of the movement of seeds of two fractions without taking

into consideration the aerodynamic factor. Taking into consideration the aerodynamic forces and moments, sectors and angles of their intersection would increase.

The overlapping angles of sectors of the possible trajectory of seeds of different fractions are calculated as:

$$\varphi_i = \begin{cases} \psi_i + \frac{1}{2}\delta_i - \psi_{i+1} - \frac{1}{2}\delta_{i+1}, & \text{if } \psi_i + \frac{1}{2}\delta_i - \\ -\psi_{i+1} - \frac{1}{2}\delta_{i+1} \geq 0, & \\ 0, & \text{if } \psi_i + \frac{1}{2}\delta_i - \psi_{i+1} - \frac{1}{2}\delta_{i+1} < 0, \end{cases} \quad (6)$$

where ψ_i is the inclination angle of the bisector of the sector of possible trajectories of the movement of seeds of the i -th fraction.

The indicator of the harmful effects of the aerodynamic factor varies at intervals from 1 to $+\infty$. If the action of aerodynamic forces and moments is absent, then $K=1$. If the kinematic parameters of vibration motion are affected by the strength of the aerodynamic resistance, lateral force, the aerodynamic moment arising from the mismatch between the pressure center and the center of mass of seeds, then $K>1$.

When conducting numerical experiments, we determined, for each observation, the mathematical expectations of the angles of inclination of the bisector sectors of possible trajectories for different fractions of seed mixtures:

$$[\varphi_{j,i}] = \frac{\sum_{n=1}^{20} \varphi_{j,i,n}}{20}, \quad (7)$$

where $\varphi_{j,i,n}$ is the value of the angle of inclination of the bisector of the sector of the possible trajectories of the i -th fraction of the seed mixture of the j -th plant crop, obtained according to the results of the n -th iteration of modeling. A total of 20 iterations were carried out for each observation of each plant crop.

The angles of the sectors of possible trajectories were defined as a double probable deviation from the angle of inclination of the bisector of the corresponding sector of possible trajectories:

$$\delta_{j,i} = 2 \cdot \left(3\sqrt{\sigma_{\varphi_{j,i}}^2} \right) = 6\sqrt{\frac{\sum_{n=1}^{20} ([\varphi_{j,i}] - \varphi_{j,i,n})^2}{20-1}}, \quad (8)$$

where $\sigma_{\varphi_{j,i}}$ is the average quadratic deviation of the angle of inclination of the bisector of the sector of the possible trajectories of the i -th fraction of the seed mixture of the j -th plant crop.

The probable deviation from the angle of inclination of the bisector is taken as a triple root-mean-square deviation from the mathematical expectation of the angle of inclination of the bisector of the sector of possible trajectories $[\varphi_{j,i}]$. Since the probable value of the angle of inclination of the bisector follows a normal probability distribution law, then all possible random values of this angle must be within the interval equal to the triple root-mean-square deviation of this value in each direction.

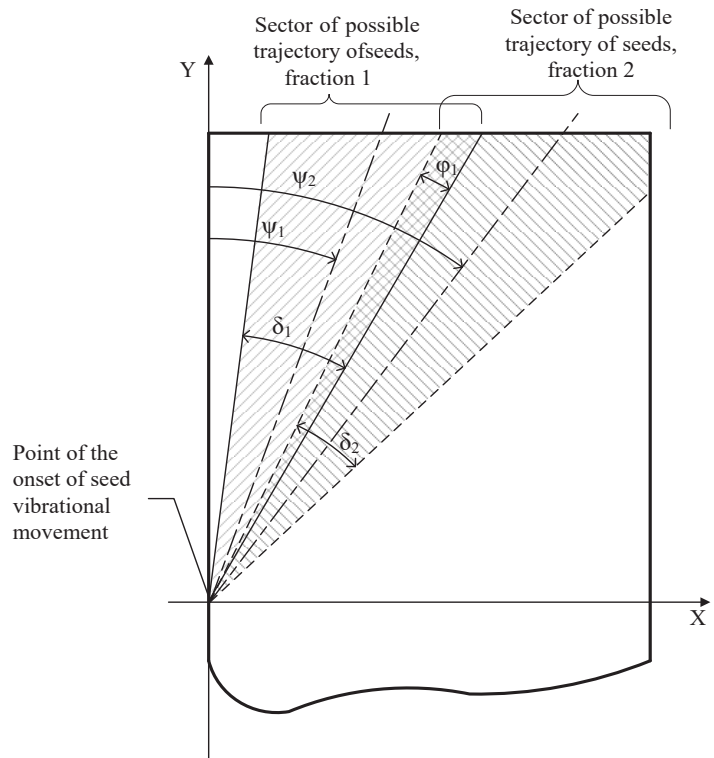


Fig. 3. Sectors of possible seed movement trajectories for two fractions of seed mixture

5. 2. Regression parameters, ranges of their change, and the plan of the experiment

We considered the following regression parameters (Fig. 4):

- the relative distance of the aerodynamic screen from the end of the working unit, z/H ;
- the height of the vertical wall of the screen with respect to the vertical gap between the two working surfaces of the vibratory machine's unit, d/H ;
- a vertical gap between two working surfaces of the working unit, H ;
- the amplitude of oscillations, A .

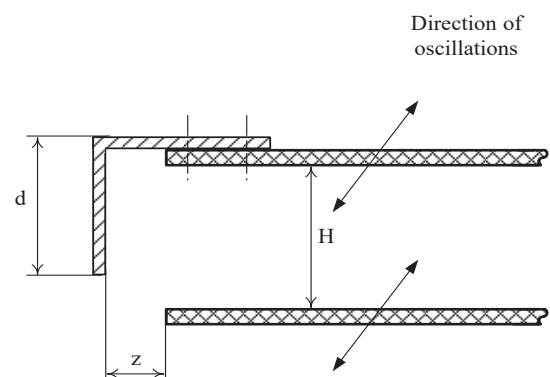


Fig. 4. Parameters that define measures to eliminate the harmful effects of the aerodynamic factor

Thus:

$$X_1 = \frac{z}{H}, X_2 = \frac{d}{H}, X_3 = H, X_4 = A.$$

For numerical modeling, the following ranges of parameters were set:

$$X_1^{\min} = 0.3, X_1^{\max} = 1,$$

$$X_2^{\min} = 0, X_2^{\max} = 1.2,$$

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

$$X_4^{\min} = 0.5 \text{ mm}, X_4^{\max} = 3 \text{ mm}.$$

To construct regression equations, the following normalized parameter values were taken:

$$x_i = \frac{X_i - X_i^{\min}}{X_i^{\max} - X_i^{\min}}, x_i \in [0;1],$$

where X_i is the irregular value of the i -th parameter; X_i^{\min}, X_i^{\max} is the minimum and maximum value of the parameter. That is,

$$x_1 = \frac{X_1 - 0.3}{1 - 0.3}; x_2 = \frac{X_2}{1.2}; x_3 = \frac{X_3 - 6}{15 - 6}; x_4 = \frac{X_4 - 0.5}{3 - 0.5}.$$

The matrix of observations was built according to a four-factor three-level plan [6].

5.3. Regression equations for assessing the effectiveness of vibrational separation of parsnip, lettuce, and fragrant dill seeds

The regression equations for assessing the indicator of harmful effects of the aerodynamic factor were constructed via a step-by-step exclusion of insignificant regressors from the full-factor regression model. Insignificant regressions were determined using the Student's t -criterion under the condition of increasing or not reducing the Fisher criterion and correlation index (coefficient of determination).

Tables 1–12 give the results on the formation of regression equations for assessing the harmful effects of aerodynamics to separate fractions of seed mixtures of parsnips, lettuce, and fragrant dill.

The regression coefficients, given in Tables 1–12, were derived for the normalized values of the indicator for measuring the effects of aerodynamics.

Table 1

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

Transformation step	Regression coefficients and their t -criteria							
	$x_0=1$		x_1		x_2		x_3	
	a_0	t_0	a_1	t_1	a_2	t_2	a_3	t_3
0	0.264	7.87	0.201	6.44	-0.377	-12.13	0.212	6.81
1	0.311	10.0	-0.155	-2.31	-0.332	-4.96	0.38	5.67
2	0.304	10.89	-0.139	-2.23	-0.37	-10.13	0.383	5.87

Table 2

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

Transformation step	Regression coefficients and their t -criteria							
	x_4		x_1x_2		x_1x_3		x_1x_4	
	a_4	t_4	a_5	t_5	a_6	t_6	a_7	t_7
0	0.314	10.09	0	0	0	0	0	0
1	0.371	5.53	0.407	10.37	0.081	2.07	0.03	0.76
2	0.408	13.09	0.405	10.62	0.081	2.12	0	0

Table 3

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

Transformation step	Regression coefficients and their t -criteria							
	x_2x_3		x_2x_4		x_3x_4		x_1^2	
	a_8	t_8	a_9	t_9	a_{10}	t_{10}	a_{11}	t_{11}
0	0	0	0	0	0	0	0	0
1	-0.136	-3.46	-0.37	-9.4	0.121	3.08	0.106	1.91
2	-0.14	-3.66	-0.368	-9.64	0.119	3.12	0.106	1.96

Table 4

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

Transformation step	Regression coefficients and their t -criteria						Fisher criterion	Coefficient of determination
	x_2^2		x_3^2		x_4^2			
	a_9	t_9	a_{10}	t_{10}	a_{11}	t_{11}		
0	0	0	0	0	0	0	84.2	0.816
1	-0.04	-0.72	-0.204	-3.67	0.022	0.39	113	0.96
2	0	0	-0.203	-3.77	0	0	153	0.96

Table 5

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

Transformation step	Regression coefficients and their <i>t</i> -criteria							
	x_1		x_2		x_3		$x_0=1$	
	a_0	t_0	a_1	t_1	a_2	t_2	a_3	t_3
0	0.223	6.66	0.18	5.83	-0.369	-11.91	0.227	7.34
1	0.235	8.28	-0.146	-2.37	-0.244	-3.98	0.348	5.67
2	0.23	8.97	-0.124	-2.17	-0.28	-8.44	0.348	5.8

Table 6

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

Transformation step	Regression coefficients and their <i>t</i> -criteria							
	x_4		x_1x_2		x_1x_3		x_1x_4	
	a_4	t_4	a_5	t_5	a_4	t_4	a_5	t_5
0	0.338	10.91	0	0	0	0	0	0
1	0.436	7.09	0.37	10.29	0.052	1.45	0.037	1.03
2	0.442	15.44	0.371	10.56	0.051	1.45	0	0

Table 7

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

Transformation step	Regression coefficients and their <i>t</i> -criteria							
	x_2x_3		x_2x_4		x_3x_4		x_1^2	
	a_8	t_8	a_9	t_9	a_8	t_8	a_9	t_9
0	0	0	0	0	0	0	0	0
1	-0.2	-5.56	-0.42	-11.62	0.147	4.09	0.109	2.14
2	-0.202	-5.75	-0.41	-11.77	0.146	4.15	0.105	2.12

Table 8

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

Transformation step	Regression coefficients and their <i>t</i> -criteria						Fisher criterion	Coefficient of determination
	x_2^2		x_3^2		x_4^2			
	a_9	t_9	a_{10}	t_{10}	a_{11}	t_{11}		
0	0	0	0	0	0	0	87.2	0.821
1	-0.04	-0.79	-0.128	-2.51	-0.011	-0.23	137	0.967
2	0	0	-0.126	-2.54	0	0	181	0.967

Table 9

Transformation of a full-factor regression model for a seed mixture of fragrant dill

Transformation step	Regression coefficients and their <i>t</i> -criteria							
	$x_0=1$		x_1		x_2		x_3	
	a_0	t_0	a_1	t_1	a_0	t_0	a_1	t_1
0	0.112	3.03	0.162	4.73	-0.308	-9.0	0.27	7.9
1	0.104	3.38	-0.067	-1.01	0.033	0.5	0.344	5.19
2	0.117	3.79	-0.02	-0.51	-0.148	-3.86	0.343	5.02

Table 10

Transformation of a full-factor regression model for a seed mixture of fragrant dill (continued)

Transformation step	Regression coefficients and their <i>t</i> -criteria							
	x_4		x_1x_2		x_1x_3		x_1x_4	
	a_4	t_4	a_5	t_5	a_6	t_6	a_7	t_7
0	0.371	10.86	0	0	0	0	0	0
1	0.314	4.73	0.298	7.67	0.055	1.41	0.053	1.38
2	0.271	3.96	0.286	7.13	0.039	0.97	0.042	1.04

Table 11

Transformation of a full-factor regression model for a seed mixture of fragrant dill (continued)

Transformation step	Regression coefficients and their t -criteria							
	x_2x_3		x_2x_4		x_3x_4		x_1^2	
	a_8	t_8	a_9	t_9	a_8	t_8	a_9	t_9
0	0	0	0	0	0	0	0	0
1	-0.235	-6.06	-0.45	-11.58	0.2	5.16	0.035	0.63
2	-0.219	-5.47	-0.423	-10.57	0.217	5.42	0	0

Table 12

Transformation of a full-factor regression model for a seed mixture of fragrant dill (continued)

Transformation step	Regression coefficients and their t -criteria						Fisher criterion	Coefficient of determination
	x_2^2		x_3^2		x_4^2			
	a_9	t_9	a_{10}	t_{10}	a_{11}	t_{11}		
0	0	0	0	0	0	0	71	0.789
1	-0.175	-3.19	-0.104	-1.89	0.137	2.5	114	0.96
2	0	0	-0.109	-1.92	0.172	3.04	122	0.956

The normalized indicator was calculated from the following expression:

$$k_{i,n} = \frac{K_{i,n} - K_i^{\min}}{K_i^{\max} - K_i^{\min}}, \quad k_{i,n} \in [0; 1], \quad (9)$$

where $k_{i,n}$ is the normalized value of the aerodynamic indicator for the i -th crop, obtained according to the results of the n -th numerical experiment; $K_{i,n}$ is the non-normalized value of an aerodynamic indicator that is calculated using (5); it varies within the interval $K_{i,n} \in [K_i^{\min}; K_i^{\max}]$.

The use of normalized response values in the construction of regression equations is more convenient for a comparative analysis of the quality of regression models built.

Finally, regression models for assessing the normalized values of the indicator of harmful effects of aerodynamics take the following form:

– parsnip seeds:

$$k_1 = 0.304 - 0.139x_1 - 0.37x_2 + 0.383x_3 + 0.408x_4 + 0.405x_1x_2 + 0.081x_1x_3 - 0.14x_2x_3 - 0.368x_2x_4 + 0.119x_3x_4 + 0.106x_1^2 - 0.203x_3^2; \quad (10)$$

– lettuce seeds:

$$k_2 = 0.23 - 0.124x_1 - 0.28x_2 + 0.348x_3 + 0.442x_4 + 0.371x_1x_2 + 0.051x_1x_3 - 0.202x_2x_3 - 0.41x_2x_4 + 0.146x_3x_4 + 0.105x_1^2 - 0.126x_3^2; \quad (11)$$

– fragrant dill seeds:

$$k_3 = 0.117 - 0.02x_1 - 0.148x_2 + 0.343x_3 + 0.271x_4 + 0.286x_1x_2 + 0.039x_1x_3 + 0.042x_1x_4 - 0.219x_2x_3 - 0.423x_2x_4 + 0.217x_3x_4 - 0.109x_3^2 + 0.172x_4^2. \quad (12)$$

To carry out parametric analysis, it is more convenient to use those regression models that produce the non-normalized values of the aerodynamic indicator.

To derive the non-normalized values for the aerodynamic indicator, it is necessary to determine new coefficients of regression equations (10), (11) using the following expressions:

$$a'_{0,i} = a_{0,i}(K_i^{\max} - K_i^{\min}) + K_i^{\min}, \quad (13)$$

$$a'_{k,i} = a_{k,i}(K_i^{\max} - K_i^{\min}), \quad k = 1, \dots, N_i^{\text{reg}}, \quad (14)$$

where $a'_{0,i}$, $a'_{k,i}$ are the adjusted free term and the regression coefficients for the i -th crop; $a_{0,i}$, $a_{k,i}$ are the coefficients of linear regression, included in (10) to (12); K_i^{\min} , K_i^{\max} are the minimum and maximum value of the non-normalized indicator of the influence of aerodynamics obtained during a numerical experiment for the i -th crop; N_i^{reg} is the number of regressors included in the regression model for assessing the harmful effects of aerodynamics on the quality of separation (cleaning) of the i -th crop.

The regression equations adjusted to determine the non-normalized aerodynamic indicators are as follows:

– parsnip seeds:

$$K_1 = 1.109 - 0.046x_1 - 0.123x_2 + 0.127x_3 + 0.135x_4 + 0.134x_1x_2 + 0.027x_1x_3 - 0.046x_2x_3 - 0.122x_2x_4 + 0.04x_3x_4 + 0.035x_1^2 - 0.067x_3^2; \quad (15)$$

– lettuce seeds:

$$K_2 = 1.066 - 0.034x_1 - 0.076x_2 + 0.094x_3 + 0.12x_4 + 0.101x_1x_2 + 0.014x_1x_3 - 0.055x_2x_3 - 0.111x_2x_4 + 0.04x_3x_4 + 0.028x_1^2 - 0.034x_3^2; \quad (16)$$

– fragrant dill seeds:

$$K_3 = 1.028 - 0.004x_1 - 0.033x_2 + 0.076x_3 + 0.06x_4 + 0.064x_1x_2 + 0.009x_1x_3 + 0.009x_1x_4 - 0.049x_2x_3 - 0.094x_2x_4 + 0.048x_3x_4 - 0.024x_3^2 + 0.038x_4^2. \quad (17)$$

The regression equations that determine the non-normalized values for the aerodynamic indicator make it possible to estimate the impact of aerodynamic forces and moments for different seed crops within a single interval of values.

5. 4. Parametric analysis on the assessment of the effectiveness of measures to eliminate the harmful effects of the aerodynamic factor

With the help of regression equations (15) to (17), the nature of the influence of the considered parameters (geometrical characteristics of the aerodynamic screen, the vertical gap between the working surfaces, and the amplitude of oscillations of units of working surfaces) on the indicator of the harmful effects of the aerodynamic factor has been analyzed.

Fig. 5 shows the charts of the function of the indicator of the harmful effects of aerodynamics depending on the geometric characteristics of the screen at the specified: the vertical gap between the work surfaces and the amplitude of oscillations for the seeds of parsnip, lettuce, and fragrant dill. As the amplitude of oscillations increases, there is a more significant harmful effect of aerodynamic forces and moments on the quality of seed fraction separation. The value of the *K* indicator reaches 1.34 (for parsnip seeds when the height of the screen *d* is zero and the vertical gap between the working surfaces is maximum). For the seeds of lettuce and fragrant dill at this point, *K* reaches the values of 1.27 and 1.22, respectively.

With an increase in the height of the screen and a decrease in its distance from the edge of the working unit, the harmful effects of aerodynamics decrease as much as possible. With an amplitude of oscillations of 0.5 mm, the value of *K* for dill and lettuce is 1 (there is no aerodynamic effect), and for parsnip – 1.05 (aerodynamic impact up to 5 %).

When varying the height of the aerodynamic screen and the vertical gap between the working surfaces (Fig. 6), there is an almost linear nature of the reduction in the *K* coefficient with an increase in screen height. There is also a distinct quadratic nature of the growth of *K* with an increase in the vertical gap *H*. The most intense growth with a decrease in *d* is observed for the maximum amplitude of oscillations. When changing the gap value between the screen and the

end of the working unit, the slope of the function remains almost unchanged. However, there is some harmful effect of aerodynamics at the maximum value of the screen height. If this gap is equal to the value of the vertical gap between the working surfaces (*z*=1), then the coefficient *K* is 1.12 for parsnip; 1.1 – for lettuce; 1.08 – for dill. When *z* is reduced to a minimum value (0.3 *H*), the *K* coefficient at this point is reduced to 1.

With an increase in the vertical gap between the working surfaces to 8–10 mm, the harmful aerodynamic impact increases intensively, then the surface gradient decreases. For parsnip, this nature of changing the coefficient *K* is more pronounced. For lettuce and dill, it is less noticeable.

The impact of screen height and the vertical gap between the working surfaces on the level of harmful effects of aerodynamic characteristics and moments increases with the growth in the amplitude of oscillations. With an amplitude of oscillations of 0.5 mm, the effect of aerodynamics is quite insignificant. In the absence of an aerodynamic screen, the coefficient *K* does not exceed 1.02–1.07 for *H*=6 mm and 1.05–1.12 for *H*=15 mm.

The above results indicate the absence of an extremum in the function $K = f(\bar{d}, \bar{z}, H, A)$, which shows the pattern of gradual approximation to 1 (elimination of the harmful effects of aerodynamics).

Almost completely the influence of the aerodynamic factor is excluded at *z*=65 % and *d*≥100 % at any amplitudes of oscillations and vertical gap values between working surfaces. With a decrease in the amplitude and (or) vertical gap, an increase in the value of *z* and a decrease in the overlapping *d* are assumed.

As rational geometric characteristics of the aerodynamic screen, the following should be chosen (as a percentage of the vertical gap *H* between the working surfaces of the unit of a vibratory machine):

- a gap between the vertical wall of the screen and the edge of the working surface, 50 ÷ 65 %;
- overlapping the vertical gap, 100 ÷ 110 %. Such geometric characteristics of the screen practically exclude the harmful effects of aerodynamics over the entire range of changing the amplitude of oscillations and the vertical gap between the working surfaces of a vibratory machine’s unit.

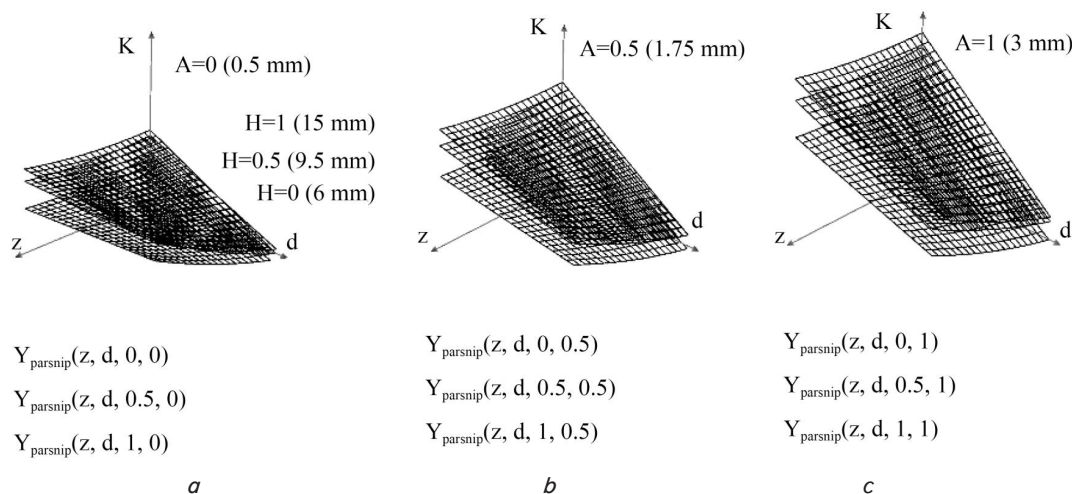


Fig. 5. The level of harmful effects of aerodynamics depending on the geometrical characteristics of the screen at the established values of the vertical gap between the working surfaces: *a* – for the amplitude of oscillations of 0.5 mm; *b* – 1.75 mm; *c* – 3 mm

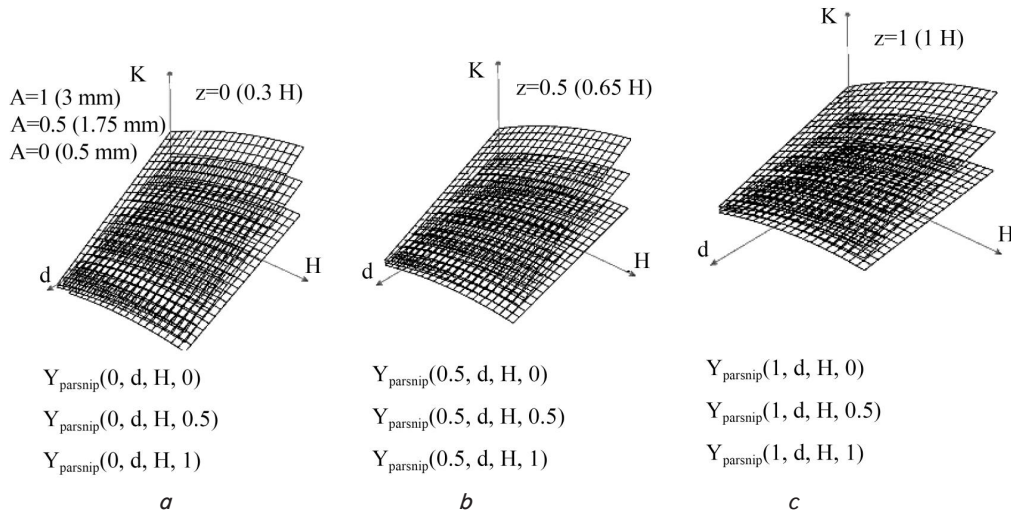


Fig. 6. The level of harmful effects of aerodynamics depending on the height of the screen and the vertical gap between the working surfaces at the established amplitude of oscillations: *a* – for the screen distance from the end of the working unit 0.3H; *b* – 0.65H; *c* – 1H

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

The constructed regression models (15) to (17) make it possible to replace the mathematical model of vibration motion of seeds [13] in the part relating to the adjustment of the parameters of the technological process of processing certain seed mixtures. The use of a mathematical model requires significant computer time and is associated with the labor-intensive process of input (the geometric shape of seeds, the geometry of the working bodies of the machine). By applying the reported regression equations, it is possible to develop various algorithms for solving the problems of optimizing the design and modes of operation of vibratory machines when processing certain seed mixtures, without referring, at the same time, to labor-consuming numerical modeling.

The resulting regression equations are the second-order equations with a pronounced nonlinear nature of the dependence on the vertical gap between the working surfaces and the distance of the aerodynamic screen from the end of the vibratory machine unit. However, the formed surface does not have an optimum. There is no change in the sign of the first derivatives. Given this, optimal parameters must be found at the boundaries of the established area of existence of the investigated function. Therefore, the problem of optimizing the design and mode of operation of a vibratory machine should be stated taking this feature into consideration.

The limitation of the current study is that the degree of adequacy of the derived regression models is confirmed only by the adequacy of the mathematical model of vibration motion used [13]. It is advisable to conduct research into building regression models of the harmful effects of the aerodynamic factor in the vibration processing of seed mixtures of the specified crops based on the results of a natural experiment.

7. Conclusions

1. We have proposed an indicator of measurement of the level of a harmful effect of an aerodynamic factor on the

process of vibration separation of lightweight seed mixtures sensitive to air movement. The indicator measures the relative increase in the statistical characteristics of scattering the trajectories of the seeds of different fractions of the mixture due to the action of aerodynamic forces and moments in the process of vibration motion of seeds.

2. The regression parameters, in this case, include the relative distance of the aerodynamic screen from the end of the working unit; the relative height of the vertical wall of the screen; the vertical gap between two working surfaces, and the amplitude of the oscillations of the working unit. At the same time, numerical modeling on the construction of a training sample for a regression model was carried out according to a four-factor three-level plan in the established working ranges for changing certain parameters.

3. Regression models for assessing the effectiveness of separating the seeds of parsnip, lettuce, and fragrant dill in vibratory machines with measures to reduce the harmful effects of the aerodynamic factor have been constructed. The formed regression equations are the linear equations of the second order, which include all regressors of the first order; most of the regressors of cross-bonds, and part of regressors of the second power. In this case, the following values for the coefficient of determination in regression equations have been achieved: for parsnip – 0.96; for lettuce – 0.967; and for fragrant dill – 0.956.

4. Based on the results of parametric analysis, carried out with the help of the constructed regression models, it can be argued that the most sensitive to the movement of air were parsnip seeds, the least – fragrant dill seeds. The harmful effects of the aerodynamic factor increase with an increase in the amplitude of oscillations and the vertical gap between working surfaces while they decrease when the height of the aerodynamic screen is increased and it is close to the end of the working unit. The most appropriate geometric characteristics of the screen are the relative distance from the end is less than 65 %, the relative height of the screen is more than 100 %. This reduces the harmful effects of the aerodynamic factor to a level of not more than 10 % with any amplitudes of oscillations and vertical gaps between working surfaces.

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