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MATHEMATICAL JUSTIFICATION OF THE OAT GRAIN DEHULLING PRODUCTS SEPARATION PROCESS IN A VIBRO-IMPACT SEPARATOR MACHINE

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The relevance of using paddy machines in the groat industry is significant due to the growing demand for high-quality groats and the need for precise and efficient grain processing. Paddy machines are capable of processing a variety of raw materials, including oats, buckwheat, and rice, expanding the capabilities of enterprises. However, there is a lack of developed engineering calculation methods for these machines, and the analysis of the sorting process is crucial for determining the optimal parameters for machine operation.

This study focuses on the development of a mathematical model for the separation of oat dehulling products in a vibro-impact separator. The model incorporates theoretical principles, such as the interaction of grain particles with the sorting table and channel surfaces, to evaluate the movement of the grain during different stages of the sorting process. The research explores factors such as the table's inclination angle, oscillation amplitude, and friction forces, which influence the sorting efficiency.

Numerical calculations reveal that, during the table's acceleration phase, unhulled grain remains stationary due to the zero initial velocities, while transverse oscillations of the table help displace the mixture, pushing lighter and larger unde-husked grains to the surface. The results indicate that optimizing the table's parameters, such as its tilt angle, oscillation amplitude, and friction coefficient, is essential for improving sorting efficiency and machine productivity.

In conclusion, the developed mathematical model enables the determination of optimal parameters for effective oat grain separation, offering valuable insights for enhancing the sorting process and achieving high productivity in the groat industry. Further research may focus on fine-tuning operating conditions to further optimize separator performance.

Key words: *grain, separation, cleaning, peeling, division, vibro-impact action, modeling, optimization.*
Eq. 9. Fig. 7. Ref. 12.

1. Problem formulation

The relevance of using paddy machines in the groat industry today is high, as modern technologies require efficient and precise grain processing methods. The main factors determining the feasibility of using paddy machines in the groat industry include [1–2]:

– Growing demand for high-quality groats – consumers increasingly prefer products with high nutritional value, which requires delicate processing of groat grains and minimization of grain damage;

– Adaptation to different types of raw materials – paddy machines can process not only oats but also other crops (such as buckwheat and rice), expanding the capabilities of enterprises.

Given these aspects, the use of paddy machines is an important step for groat industry enterprises seeking to improve competitiveness and product quality [3–4].

Despite the widespread use of paddy machines for separating various bulk products, engineering calculation methods for these machines are currently insufficiently developed. Recommendations regarding the selection of machine parameters or improvements to its design can only be provided based on an analysis of the sorting process. Some understanding of this process can be gained by analyzing the interaction of a single mixture particle with the table surface and the channel walls.

2. Analysis of recent research and publications

The process of separating oat dehulling products in a vibro-impact separation machine is a crucial stage in the production of high-quality groats. To develop a mathematical model of this process, it is necessary to consider the results of previous research in the fields of bulk material mechanics, vibration system dynamics, and the operational characteristics of separation machines.

Scientific studies in the field of bulk material mechanics [5–6] describe the movement of grain particles in flows subjected to mechanical influence. They examine friction forces, inertia, and the aerodynamic properties of dehulling products. Research also shows that the distribution of particles in the separation channel depends on their geometric dimensions and physico-mechanical properties.

Studies in the field of vibration system dynamics [7–8] indicate that the use of vibration and impact loads in separation processes significantly improves the efficiency of grain mixture sorting. Modeling the movement of particles on a vibro-impact surface demonstrates that amplitude and frequency of oscillations have a substantial impact on sorting outcomes.

Modern approaches to the mathematical description of grain mixture separation processes [9–10] involve the use of differential equations of motion, hydrodynamic flow theory, and numerical modeling methods. The authors propose using the finite element method to analyze the interaction of particles with separation surfaces, allowing for the prediction of separation efficiency.

Domestic and international studies on the operation of vibro-impact separators [11–12] demonstrate their effectiveness in separating grain mixtures with different densities and particle sizes. The application of these machines in the groat industry improves the quality of the final product and reduces losses.

Based on the analysis of literary sources, it can be concluded that the mathematical modeling of the separation process of oat dehulling products in vibro-impact separators requires a comprehensive approach. It is necessary to consider bulk material mechanics, vibration system dynamics, and modern mathematical modeling methods. Further research may focus on developing optimal operating modes for the separator to enhance the efficiency of the separation process.

3. The purpose of the article

The aim of the study is to develop a mathematical model of the process of separating oat dehulling products in a vibro-impact separation machine.

4. Results and discussion

Let's consider the theoretical prerequisites for selecting the parameters of a paddy machine.

Selection of the inclination angle of the sorting table surface using the example of a mixture of hulled and unhulled oat grains.

Structurally, the sorting table of the machine consists of two parts: the upper step surface, which is inclined at an angle to the horizontal plane (Fig. 1), and the lower step surface, oriented at an angle.

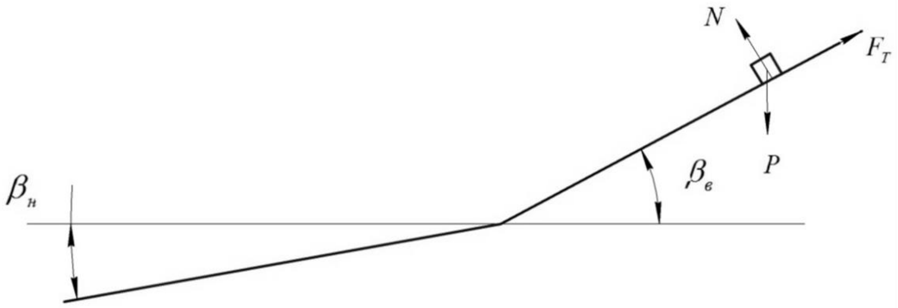

Fig. 1. Diagram of forces acting on the grain in the vertical plane

By considering the equilibrium of the unhulled grain on the surface of the upper step, we obtain:

$$F_T = P\sin\beta_в;\ N = P\cos\beta_в, \quad (1)$$

where: F_T – friction force; N – normal reaction force; P – weight of the grain.

To determine the angle $\beta_в$, we analyze the movement of the grain on the upper step surface. Let the relative movement of the grain during the acceleration phase of the table start from the extreme right position of the grain in the channel (Fig. 2), while the table moves along the x-axis according to the equation:

$$x = -a\cos\omega t\ ,$$

where: a – vibration amplitude of the table; ω – cyclic frequency of the drive.

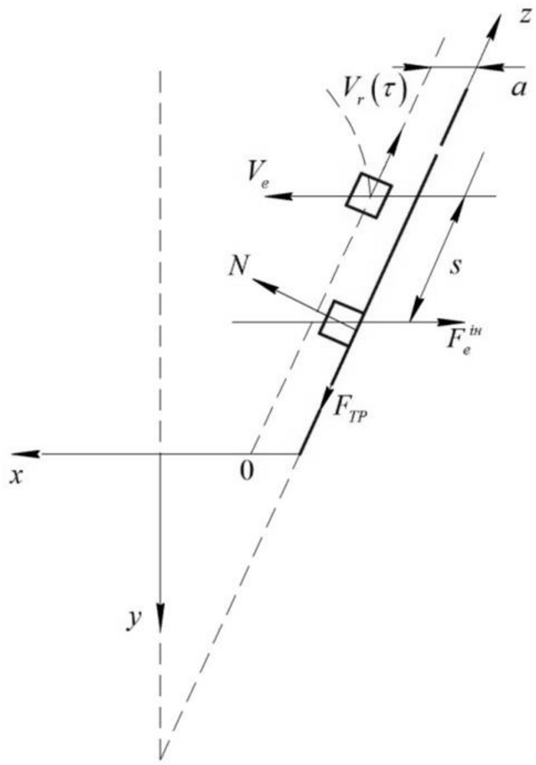

Fig. 2. Diagram of forces acting on the grain in the table plane

The velocity of the table is determined as:

$$\dot{x} = a\omega\sin\omega t$$

$$\ddot{x} = a\omega^2\cos\omega t + a\varepsilon\sin\omega t,$$

During the acceleration phase τ, the table covers a distance a and imparts a transport velocity to the grain $V_e(\tau) = \dot{x}_{max} = a\omega$.

For the relative velocity along the channel edge, we derive the differential equation:

$$m\ddot{z} = F_e^{ін}\sin\alpha - F_{TC} - F_{TБ} - P\sin\alpha\ , \qquad (2)$$

where: $F_e^{ін}$ – mass of the grain $F_e^{ін} = m\ddot{x}$; F_{TC} – friction force on the table surface: $F_{TC} = f\cdot P\cos\beta_в$; $F_{TБ}$ – lateral friction force on the edge surface: $F_{TБ} = f\cdot F_e^{ін}\cos\alpha$.

Thus, the equation of relative motion takes the form:

$$m\ddot{z} = F_e^{ін}\left(\sin\alpha - f\cos\alpha\right) - P\left(f\cos\beta + \sin\beta\right).$$

For zero initial velocity:

$$V_r = \frac{1}{m}\left(\sin\alpha - f\cos\alpha\right)\int_0^{\tau} F_e^{ін}dt - g\left(f\cos\beta + \sin\beta\right)\tau$$

Using Simpson's rule, we obtain the final expression:

$$V_r = \frac{\sin\alpha - f\cos\alpha}{m}\cdot\frac{\tau}{3}\left[F_e^{ін}(0) + 4F_e^{ін}\left(\frac{\tau}{2}\right) + F_e^{ін}(\tau)\right] - g\left(f\cos\beta + \sin\beta\right)\tau =$$
$$= \frac{\tau}{3}\left(\sin\alpha - f\cos\alpha\right)\left[\ddot{x}(0) + 4\ddot{x}\left(\frac{\tau}{2}\right) + \ddot{x}(\tau)\right] - g\left(f\cos\beta + \sin\beta\right)\tau. \qquad (3)$$

Example Calculation. Given the following initial parameters: $\alpha = 30^\circ$; $\beta = 6{,}5^\circ$; $f = 0{,}35$; $\tau = 0{,}18$ s; $\ddot{x}(0) = 20{,}4$ m/s²; $x\left(\frac{\tau}{2}\right) = 10{,}1$ m/s²; $x(\tau) = 0$, where τ and $x(\tau)$ are obtained as a result of numerical integration, and the parameters α, β and f are taken for the operating table during oat grain sorting.

From equation (3), we obtain:

$$V_r = \frac{0{,}18}{3}\left(sin30^\circ - 0{,}35cos30^\circ\right)\left(20{,}4 + 4\cdot 10{,}1 + 0\right) - 0{,}18\cdot 9{,}81\left(0{,}35cos6{,}528^\circ + sin6{,}528^\circ\right) = -0{,}0965 \text{ m/s.}$$

As the calculation shows, for unhulled grain on the surface of the upper step, the grain cannot move upward if the initial velocities of both the grain and the channel are zero. Evidently, during the acceleration phase of the table, the grain will not move downward either, remaining in a state of relative rest, pressed against the channel edge and moving together with the table.

The same situation occurs on the surface of the lower step when the initial velocity of the hulled grain is zero.

During the deceleration phase of the table, the differential equations of grain motion, when the grain is given the maximum possible velocity by the channel in the direction of table movement, take the form:

$$m\ddot{x} = -F_x^T$$
$$m\ddot{y} = -F_y^T + P\cos\beta, \tag{4}$$

where F_x and F_y are the projections of the force F_T on the x and y axes (Fig. 2).

Considering equations (1), we obtain:

$$F_x = fmg\cos\beta\frac{\dot{x}}{\sqrt{\dot{x}^2 + \dot{y}^2}};\ F_y = fmg\cos\beta\frac{\dot{y}}{\sqrt{\dot{x}^2 + \dot{y}^2}}.$$

Then

$$m\ddot{x} = fmg\cos\beta\frac{\dot{x}}{\sqrt{\dot{x}^2 + \dot{y}^2}}, \tag{5}$$

$$m\ddot{y} = mg\sin\beta - fmg\cos\beta\frac{\dot{y}}{\sqrt{\dot{x}^2 + \dot{y}^2}}, \tag{6}$$

The given formulas describe the movement of a grain on the table, but they can also be used for analyzing the movement of the mixture under the assumptions that will later be proposed for the calculation scheme.

As observations show (several photos 1 and 2), the periodic transverse movement of the table with an amplitude *a* leads to the transverse displacement of the mixture, which, at each stage of the table's deceleration, is alternately pressed against the side walls of the channel, as shown in Fig. 3, for the final right position (position -*a*).

In such transverse oscillations of the mixture, lighter and larger unpeeled grains will be pushed from the deeper layers of the mixture to the surface (Fig. 4), while peeled grains will remain in the lower part of the flow cross-section. Moreover, as observations show, the shape of the contact base of the mixture mass and the table surface in the extreme positions of the channel remains virtually unchanged. In the direction of oscillations, the speed at the extreme left and right positions is zero. Based on the observations, we will first assume that the cross-sectional area of the cleaned grain flow remains constant along the length of the channel. The flow cross-section will be considered as a cross-section of a continuous medium, the area of which changes shape during transverse oscillations, and in the extreme positions, at the end of the table deceleration, the entire flow in the transverse direction has zero speed. We will assume that in the extreme positions, the cross-sectional area of the cleaned flow has a triangular shape (it is shaded in Fig. 3), and the center of mass of this area in the transverse direction to the flow direction oscillates with an amplitude

$$a_c = \left(b + 2a - \frac{2}{3}b\right)\cdot\frac{1}{2} = \frac{b}{6} + a \tag{7}$$

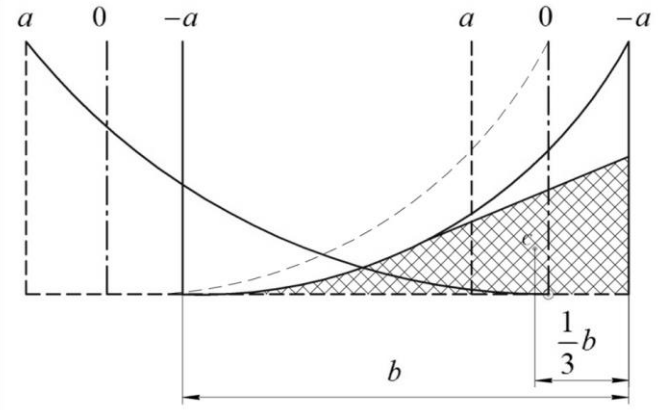

Fig. 3. Approximate depiction of the cross-section of the mixture flow in the channel at the extreme right position

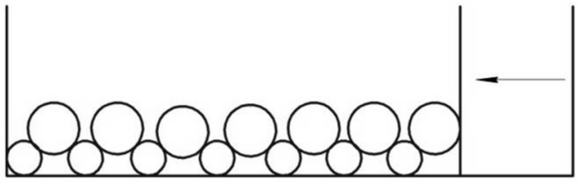

Fig. 4. Diagram of the extrusion of unpeeled grain

Taking the equation of motion for the transverse oscillations of the center of mass of the flow cross-section

$$x = -a_c \cos \omega t\,, \tag{8}$$

From the differential equation (6), we will obtain

$$\ddot{y} = g \sin\beta - fg\cos\beta \frac{\dot{y}}{\sqrt{\left(a_c\omega\cdot \sin\omega t\right)^2 + \dot{y}^2}} \tag{9}$$

The differential equation (9) describes the movement of the peeled grain flow, which is not uniform during one period of the table's oscillation and, in general, stops at the stages when the table, along with the grain flow, accelerates over a period of time $t = \frac{\tau}{2}$.

The numerical solution of the differential equation (9), the results of which are presented in Fig. 3, allows us to determine the velocity of the grain flow when it leaves the table, as well as its average velocity and its dependence on sorting parameters such as the table's tilt angle and its angular velocity.

When sorting oat grains, for the table tilt angle $\beta_н = 1{,}528^\circ$, the obtained average velocity of the peeled grain flow is $V = 0{,}0066$ m/s.

For the minimum channel width of cm, the cross-sectional area of the flow in one channel is taken as.

$$S_k = \frac{1}{2}bh = \frac{1}{2}\cdot 21\cdot 0{,}35 = 36{,}75\,\text{cm}^2$$

Total area

$$S = S_k \cdot k = 36{,}75\cdot 24 = 882\,\text{cm}^2$$

Machine productivity

$$Q = S\cdot V\cdot\gamma = 882\cdot 0{,}599\cdot 0{,}5 = 264{,}16\frac{г}{c} = 950{,}97\ \text{kg/h}.$$

The calculated graphs of the peeled grain flow velocity during the deceleration of the sorting table, the dependence of the velocity on the friction coefficient, oscillation amplitude, and its tilt to the horizon are shown in Figs. 5–7.

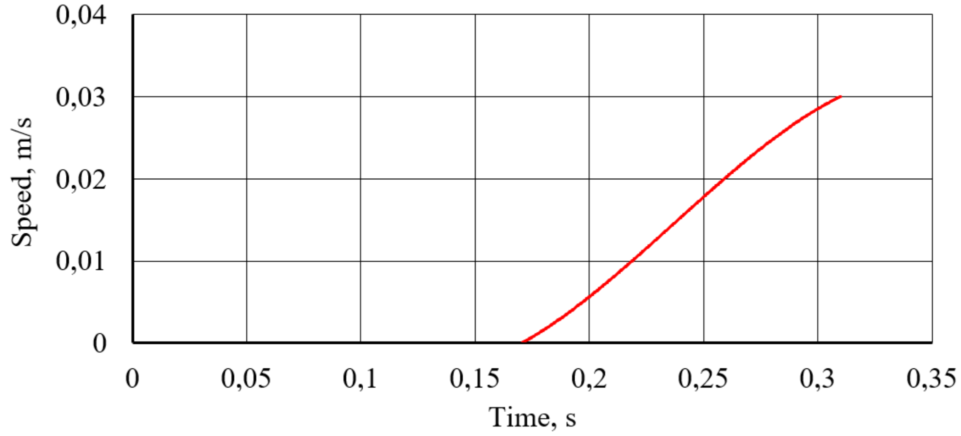

Fig. 5. Graph of the dependence of the peeled grain flow velocity during table deceleration

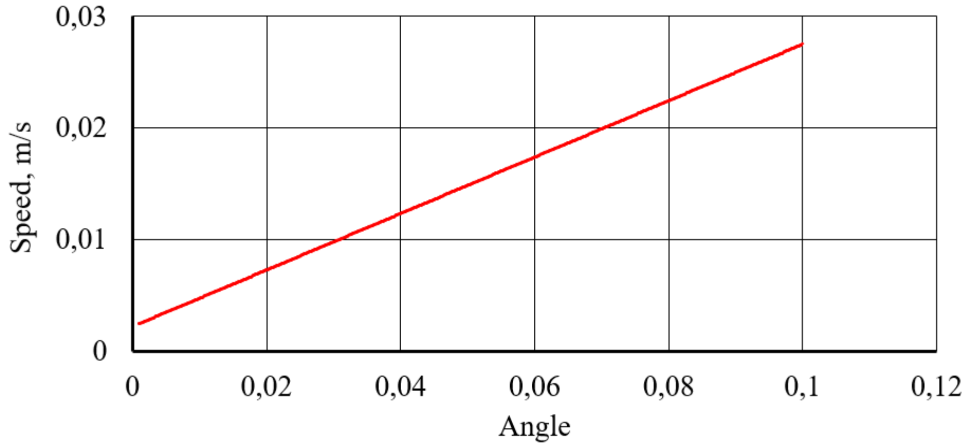

Fig. 6. Graph of the dependence of the grain flow velocity on the table tilt angle.

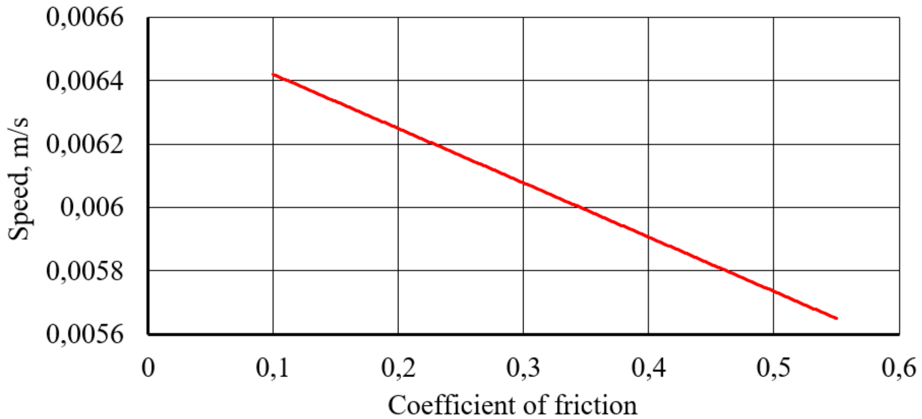

Fig. 7. Graph of the dependence of the grain flow velocity on the friction coefficient

5. Conclusion

The development of a mathematical model for the process of separating dehusked oat grain products on a vibration-impact separator allows for the determination of optimal parameters for effective grain sorting. The analysis shows that at the stage of the table's acceleration, the grain cannot move up or down with zero initial speeds, as it remains in a state of relative rest, pressed against the edge of the channel and moving together with the table. Furthermore, the transverse oscillations of the table contribute to the displacement of the mixture, pushing lighter and larger unde-husked grains to the surface, which improves the sorting process.

The mathematical model describes the movement of the grain and the mixture, taking into account the friction on the table surface and the interaction between the grains and the channel surface. Calculations for various parameters, such as the table's inclination angle, oscillation amplitude, and friction coefficient, allow the determination of the average speed of the dehusked grain and the machine's productivity. The obtained results show that optimizing these parameters is key to improving sorting efficiency and achieving high productivity in the separation of oat grain.

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МАТЕМАТИЧНЕ ОБҐРУНТУВАННЯ ПРОЦЕСУ ПОДІЛУ ПРОДУКТІВ ЛУЩЕННЯ ЗЕРНА ВІВСА НА СЕПАРУВАЛЬНІЙ МАШИНІ ВІБРОУДАРНОЇ ДІЇ

Актуальність використання лущильних машин в індустрії круп є значною через зростаючий попит на високоякісні крупи та необхідність точного й ефективного оброблення зерна. Лущильні *машини здатні обробляти різноманітні сировини, зокрема вівсяне, гречане та рисове зерно, що розширює можливості підприємств. Однак, існує дефіцит розроблених методів інженерних розрахунків для цих машин, а аналіз процесу сортування є важливим для визначення оптимальних параметрів роботи машин.*

Це дослідження зосереджене на розробці математичної моделі для розподілу продуктів лущення вівса в віброударному сепараторі. Модель враховує теоретичні принципи, такі як взаємодія частинок зерна з поверхнею сортувального столу та стінками каналу, для оцінки руху зерна на різних етапах процесу сортування. У дослідженні розглядаються такі фактори, як кут нахилу столу, амплітуда коливань та сили тертя, що впливають на ефективність сортування.

Числові розрахунки показують, що на етапі прискорення столу незрощене зерно залишається нерухомим через нульові початкові швидкості, тоді як поперечні коливання столу сприяють переміщенню суміші, виштовхуючи легші та більші нелущені зерна на поверхню. Результати свідчать, що оптимізація параметрів столу, таких як його кут нахилу, амплітуда коливань та коефіцієнт тертя, є необхідною для покращення ефективності сортування та продуктивності машини.

У підсумку, розроблена математична модель дозволяє визначити оптимальні параметри для ефективного розподілу вівсяного зерна, надаючи цінні інсайти для покращення процесу сортування та досягнення високої продуктивності в індустрії круп. Подальші дослідження можуть бути спрямовані на уточнення умов експлуатації для подальшої оптимізації роботи сепаратора.

Ключові слова: *зерно, сепарація, очищення, лущення, поділ, віброударна дія, моделювання, оптимізація*

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