UDC: 631.361.81
DOI: 10.56407/bs.agrarian/4.2023.18

Ukrainian Black Sea Region Agrarian Science
Vol. 27, No. 4

Study of the nature of the movement of the crushed mass on the surface of the sieves of the vegetable and melon seed separator

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Abstract. Improvement of equipment for processing vegetable and melon crops requires research on the nature of the movement of the crushed mass to reduce material damage and obtain high-quality seeds, which will bring the vegetable and melon industry to a new level of development. The aim of the study is to analyse the movement of the crushed mass on the surface of the sieves of the vegetable and melon seed separator. The nature of the movement of the crushed mass on the surface of the sieves of the proposed design solution was substantiated on the basis of the use of methods of physics, theoretical mechanics and analysis and study of the physical and mechanical characteristics of the technological mass. As a basic design for the study, a vegetable and melon separator were used, the feature of which is the use of a two-screen system of sieves. In this system, the upper sieve separates the peel, and the lower sieve separates the seeds and pulp; the pulp and juice are the final product of the second sieve. The sieve, which performs inertial motion, helps to remove the seeds associated with the peel. As a result of the research, the functional dependence of the amplitude of oscillations on the frequency of oscillations for different operating modes of the separator is presented. To determine the average speed of material movement in the technological zone of the separator, formulas are provided for the upper screen operating in the inertial separator mode and for the lower screen operating in the vibration

Article's History:
Received: 23.08.2023
Revised: 19.11.2023
Accepted: 12.12.2023

Suggested Citation:
Babenko, D., Dotsenko, N., Gorbenko, O., & Batsurovska, I. (2023). Study of the nature of the movement of the crushed mass on the surface of the sieves of the vegetable and melon seed separator. *Ukrainian Black Sea Region Agrarian Science*, 27(4), 18-35. doi: 10.56407/bs.agrarian/4.2023.18.

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separator mode. In the context of the above-mentioned features of the proposed design solution, the nature of the movement of the crushed mass along the surface of the inertial and vibrating screens was studied. In the course of theoretical calculations, dependencies were obtained to determine the average particle velocity in the working area of these sieves. On the basis of the theoretical analysis, a methodology for calculating the main parameters of a double-screen separator was developed. The mechanical and technological properties of vegetable and melon seeds separated by the proposed design solution were determined. In laboratory conditions, the composition of the components of the separated seed mass was studied and analysed, which indicates the feasibility of using the proposed design solution for the separator of vegetable and melon crops and the practical application of the obtained theoretical dependencies for regulating its technological parameters

Keywords: inertial separator; vibrating separator; mechanical and technological properties; particle motion

INTRODUCTION

The transition to the cultivation of vegetable and melon crops in private households has led to an increase in the gap between the real producer and the achievements of the latest technologies and has significantly limited the opportunities for the development of this industry and the production of quality seeds. There is a need to develop equipment for the production of vegetable and melon seeds that can be adapted to the conditions of small farms. To create and design machines and equipment for the processing of vegetable and melon seeds, it is necessary to theoretically substantiate the nature of the movement of seeds along the moving parts of the machine in order to prevent their injury and increase germination.

Considerable attention has been paid to research on the cultivation of vegetable and melon crops and constructive solutions for seed extraction. In order to meet the needs of modern agriculture, it is essential to obtain high-quality seeds of vegetable and melon crops in order to reduce costs and eliminate the need to purchase them from third-party producers (Mukhopadhyay *et al.*, 2021). Yield estimation of new varieties of hybrid watermelons was paid attention to by researchers A. Wahyudi *et al.* (2022). It was proved that the production of watermelon seeds within an agricultural enterprise can increase the production and income of watermelon farmers. Seed evaluation and selection are important steps in a plant breeding programme.

The influence of the mechanical and technological parameters of vegetable and melon seeds on the subsequent seed quality was studied by S. Kale *et al.* (2020), and K. Fayzullaev *et al.* (2021) presented the development of a machine for sowing vegetable and melon crops. Tests have shown that the developed machine reliably performs the specified technological process, and its performance fully meets the requirements. D. Tlevlessova *et al.* (2023) noted that the transition to cultivation in households and small farms has led to the need to introduce scientific advances and the latest technologies for obtaining high-quality seeds. The authors emphasised that one of the key problems of industrial pumpkin production is the transition of production from large agricultural enterprises to small private farms, which currently account for more than 90% of the total. At the same time, the transfer of production to the private sector brings additional income to small producers and may be their only source of income. The current situation shows that private peasant farms are more adapted to the specifics of market relations.

C. Osuji *et al.* (2023) conducted a comparative study between mechanised and manual seed hulling of vegetable and melon crops. The seeds were peeled manually and mechanically using a mechanical melon peeler and a press machine. The efficiency of seed extraction using these machines was evaluated. The huller was the most efficient of the mechanised processes. The cleaned seeds were evaluated by mechanical and technological parameters. The study showed that the choice of a suitable variety, seed separator and packaging material is crucial for the overall efficiency and high-quality production of vegetable and melon seeds.

Studies of the probability of seed passage through the sieve holes indicate that by changing the geometric dimensions of the sieve holes it is impossible to achieve a separation level of more than 53…58%. In order to improve the quality of separation, it is necessary to study and theoretically substantiate the kinematic mode of operation of the sieve in order to determine the range of optimal speeds at which the content of impurities in the mass of freshly separated seeds is minimal with the maximum percentage of conditioned seeds that have passed through the sieve holes. At the same time, an increase in the relative speed of the separator sieves above 0.23…0.24 m/s negatively affects the operation of separation mechanisms due to the movement of the technological mass beyond the working surface. In view of this, there is a need to conduct theoretical studies to substantiate the process of separating seeds from the crushed crust and pulp obtained during the grinding of seed fruits. The kinematic scheme of horizontally oscillating separators is almost identical. The quality of separation is influenced by the degree of seed fruit grinding, seed shape, shape of sieve holes, type of separator, and the nature of sieve movement. The literature does not contain enough specific recommendations on the design schemes of vegetable and melon crop separators, their kinematic modes, which allow intensifying the process of separating seeds from organic impurities. Therefore, the purpose of the article was to identify the factors that have the greatest impact on the quality of the technological process.

LITERATURE REVIEW

The literature review provides an important analytical overview of aspects of the entire cycle of cultivation and processing: from a thorough study of melon cultivation parameters to research on improving technologies to obtain high-quality seeds. For example, Erniati *et al.* (2022) studied the cultivation of melons and the optimal parameters for obtaining high-quality material. Particular attention was paid to the growing parameters, the study focused on monitoring such indicators as air temperature, relative humidity, radiometric sunlight intensity, plant age, leaf area, plant height to predict leaf area and plant height for the next two days. The author W. Nascimento (2002) noted that seed preparation and improvement can be a good option to increase the survival rate of melon crops. Primed seeds demonstrate better performance during germination, especially at low temperatures. The author discusses some aspects related to seed preparation and its impact on melon seed germination and yield formation.

In the context of the study of the full cycle of vegetable and melon crops cultivation and seed production, experiments on improving the environment for growing vegetable crops were conducted by P. Mazuela & M. Urrestarazu (2009), who noted that there is a need to increase the number of producers of vegetable and melon seeds. Obtaining high-quality seeds helps to increase yields, and grafting technology is also highly effective in reducing seed injury and, consequently, yield losses. The issue of automation of machinery for growing vegetable crops was addressed by J.M. Lee *et al.* (2010). Ukrainian scientists A.O. Lymar & V.A. Lymar (2012) paid attention to the issues of melon growing in Ukraine, who in their monograph described the technical, technological and agronomic aspects of melon growing in Ukraine. M. Zayachuk (2012) analysed the territorial differentiation of production of major vegetable crops in the regions of Ukraine. Research on melon varieties that can be grown in Ukraine was conducted by O.S. Shablya & O.G. Kholodnyak (2022). They present a device for classifying quality watermelon fruits using microwave technology. This device converts radio frequency to DC so that the voltage of mature fruits is higher than that of immature ones. The experiment of K. Kuchakorn *et al.* (2021) shows good separation of unripe and ripe watermelons. The study paid attention to determining the ripeness of fruits using specialised equipment and its suitability for further seed extraction. The properties of melon seeds as a food additive were also investigated by B. Gutyj *et al.* (2017).

Studies have also been conducted on the processing of vegetable and melon seeds. O.V. Tsurkan *et al.* (2015) highlighted the hydrodynamics of the process of filtration dehydration of freshly cleaned seeds with vibration activation. The authors studied the effect of pressure drop and mainly vertical vibrations on the intensity of dehydration, and compared the calculated and experimental values. O.V. Stanislavchuk *et al.* (2017) also presented the kinetic features of vibration and filtration dehydration of freshly peeled pumpkin seeds. On the basis of the constructed graphical dependence, the drying coefficients depending on the main parameters of the process of vibration of freshly peeled pumpkin seeds and combined dehydration, as well as the coefficient of relative drying, were determined. The dependencies for calculating moisture and dehydration time in the studied range of changes in the parameters of the drying process are presented. G. Kaletnik *et al.* (2020) investigated the determination of the kinetics of the process of vibratory convective seed drying. The research is driven by the need to solve the problem of fast and high-quality post-harvest processing at minimal cost. Existing technologies and equipment do not provide high productivity of the drying process in the post-harvest period or carry it out with significant time and resources. The main objective of the study was to determine the rational parameters of the process and equipment for drying pumpkin seeds. The results of the study of the intensification of vibration impact indicate a direct correlation between the vibration frequency of the drying chamber and the drying duration: the higher the frequency, the greater the intensity of vibroconvection drying, as well as the reduction in drying time with an increase in vibration amplitude. The determination of the parameters and operating modes of the structures of new solar collectors for drying grain and plant materials by active ventilation was carried out by B. Kotov *et al.* (2019). The article presents the results of experimental studies of the efficiency of air heating in solar collectors with different surface shapes, developed to justify their use in agricultural equipment. The authors also analyse the technological parameters of a vibration centrifugal mixer and their influence on the kinetics of the process of preparing bulk solids. The analysis of the obtained experimental data made it possible to establish the rational operating parameters of the experimental vibrating machine, provided that the energy consumption for the organisation of the studied process is reduced (Kaletnik & Yanovych, 2017). Considering bulk or individual units of agricultural material, it is important to have an accurate estimate of the shape, size, volume, density, specific gravity, surface area and other mechanical characteristics that can be considered as design parameters for food production. Measurement techniques allow for the calculation of these parameters, which can provide information on the impact of processing (Dobrzanski & Stepniewski, 2013). Studies have also been conducted on the physical properties of vegetable crops (Tang *et al.,* 2014). Thus, the study of physical properties of vegetable crops and methods of their measurement is an integral part of the field of food production and agricultural technology.

MATERIALS AND METHODS

The study used the methods of physics (Lerner & Trigg, 1991), theoretical mechanics and analysis (Lanczos, 1986), and the study of the physical and mechanical characteristics of the technological mass (State Standard of Ukraine DSTU 8439:2015, 2015). In the course of analysing the movement of the crushed mass on the surface of the sieves of the vegetable and melon seed separator, a stepwise integration method was used, which allows more precisely determining the moments of transition of particles from one separation mode to another, from one direction of movement to the opposite. On the basis of the theoretical analysis, in accordance with the assumptions made, mathematical dependencies were established that allow determining the main structural and kinematic parameters of the vibrations of a sieve separating seeds, pulp and pulp from the crust. The theoretical study of the movement of seeds, pulp and hull along a sieve moving in a vibrating mode allowed to obtain formulas for determining the acceleration, speed and movement of the separated mass in the technological zone of the separating device. The greatest influence on the quality of the technological process was found to be the angle of inclination of the sieve, the frequency of oscillations, the amplitude of oscillations and the angle of additional forced oscillations. These factors were taken into account during the experimental studies.

Using the expression that characterises the mode of operation of sieve oscillations, the dependencies for determining the amplitude *A* and frequency of its oscillations ω and the angle of additional forced oscillations β were derived. To carry out engineering calculations, formulas were obtained that allow to calculate the average speed v_{cp} of the movement of particles of the crushed mass in the working space of the proposed design, productivity *Q* and drive power *N*. The determination of the mechanical and technological properties of vegetable and melon seeds separated by the proposed design solution was carried out using statistical analysis methods. During the study of mechanical and technological properties, the mass after the grinding device was considered. The determination of the percentage of suspended components of the crushed mass of seeds entering the separation was based on the following calculation:

$$C_i = \left(\frac{m_i}{\sum_{i=1}^{n} m_i}\right) \cdot 100\%, \tag{1}$$

where C_i, m_i – percentage and weight of the i-th fraction.

The interdependence of the fraction components was determined by the formula:

$$C_j = \left(\frac{m_j}{\sum_{j=1}^{k} m_i}\right) \cdot 100\%, \tag{2}$$

where C_j, m_j – percentage and weight of the i-th component

The methodology for determining the size and weight, physical and mechanical parameters of seeds and fruit elements is based on specific conditions of experiments with the development and manufacture of the necessary instruments and devices. Statistical methods of research and mathematical processing are used to distinguish natural changes from random indicators. Selective statistical observation was used to characterise the general population (all seeds of the studied varieties) by discrete variation traits. The extreme values of each observation are denoted as X_{min} AND X_{max}. The total number of samples n for each trait was taken as at least 50. At the same time:

$$n = \sum_{i=1}^{n} l(i). \tag{3}$$

The statistical series of the feature *X* was divided into a number of classes $N_k = 10$ at $n \geqslant 50$. In this case, the class step:

$$t = \frac{X_{max} - X_{min}}{N_k}. \tag{4}$$

The lower limit of the class:

$$X_{k-1} = X_{min}. \tag{5}$$

The upper limit of the class:

$$X_k = X_{k-1} + t. \tag{6}$$

Relative frequency of observations from any k-th class

$$P_k = \frac{n_k}{n}, \tag{7}$$

where n_k – number of variants falling into the k-th class.

The results were checked by the expression:

$$\sum_{k=1}^{N} P_k = 1. \tag{8}$$

The average arithmetic value of a feature by class:

$$X_{k.aver} = \frac{(X_{k-1}+X_k)}{2}. \tag{9}$$

The statistical distribution of discrete values was determined:

$$X_a = \sum_{k=1}^{N} X_{k.aver} \cdot P_k. \tag{10}$$

The estimate of the scatter (dispersion) of the values of the random variable X around the average statistical value Ha was determined by the formula for the mean square of the deviation (variance) S:

$$S = \sum_{k=1}^{N} (X_{k.ch} - X_a)^2 \cdot P_k. \tag{11}$$

To compare the spread of values near the centre of the distribution and a random variable, the standard deviation is calculated σ:

$$\sigma = \sqrt{S}, \tag{12}$$

as well as the coefficient of variation or variability of the trait v:

$$v = (\sigma / X_{aver}) \cdot 100\%. \tag{13}$$

The experience error rate should not exceed 4.0% :

$$\rho = \pm \frac{\sigma}{X_a \cdot \sqrt{n}} \cdot 100\%. \tag{14}$$

In order to determine the dynamic and kinematic parameters of the proposed design solution for a vegetable and melon seed separator, such indicators as the dependence of seed deformation on the applied force, the dependence of elongated testis lengths on the average transverse size, and the dependence of fruit deformation on the applied static and dynamic force are of interest.

For the mathematical description of the studied dependencies, the least squares method was used, followed by a check of the obtained functional dependence for adequacy using Fisher's criterion. The functional dependence $y = f(x)$ of the studied trait was determined at j fixed values of the argument, with $j \geqslant 4$. The repetition of the experiment at each point of the fixed argument value was $n = 5$. Based on the results of the experiments, the average value of the function at each point was calculated, i.e:

$$Y_j = \frac{1}{n} \cdot \sum_{i=1}^{n} Y_{ij}. \tag{15}$$

After that, the Cochrane criterion was determined, which confirms the accuracy of the results. At the next stage of processing the experimental data, it was assumed that the obtained dependence could be described by a first-degree function:

$$Y = ax + b. \tag{16}$$

After that, the adequacy was checked by Fisher's criterion F_k. If the condition $F_{tabl} \geqslant F_k$ is met, with a given number of degrees of freedom, the hypothesis of adequacy of the description of the studied dependence by the function of the form (92) is accepted with the level of significance recommended for research in agriculture of 0.95. If $F_k \geqslant F_{tabl}$ the hypothesis of the linear nature of the studied dependence was rejected, its description by the following expression was used with a repeated check of adequacy:

$$Y = a \cdot X^2 + b \cdot X + C \text{ or } Y = a \cdot X^3 + b \cdot X^2 + c \cdot X + d. \tag{17}$$

RESULTS

Figure 1 shows the proposed design solution for a vegetable and melon seed separator. The final cleaning of seeds from impurities is carried out on separate machines that are part of the technological chain after the seed separators.

The technological process of the proposed design solution of the vegetable and melon crop separator is as follows: the fruits are loaded into the hopper 2 of the chopper 3 by a special conveyor. The material crushed by drums 4-5 falls into the screen 10. Seeds, pulp and small equal-sized particles of peel (subgrade product) fall on the surface of the sieve of the second screen 11. Seeds with impurities on its surface are subjected to final cleaning, while other components are sent to the pump 4. The presented design solution provides for the following adjustments: the rotational speed of the cranks and, consequently, the frequency of the screen oscillations was changed by V-belt variators 19-20; the angle of inclination of the sieves was changed by adjusting the lengths of the hinge suspensions 12-13; partitions were made to change the length of the working part of the sieve.

The separator is a system consisting of two screens. The upper screen separates the coarse fraction of the crushed peel, while the lower screen separates the seeds. The remaining fractions, such as pulp, pulp particles and juice, fall into the tray. To reduce seed losses in the peel fraction, it is advisable to use the inertial separator mode. Additional friction of the material against the edges of the holes in the peel fraction reduces the seed content. The mode of the vibrating conveyor for the second sieve is used to increase the passage of the pulp through the sieve holes.

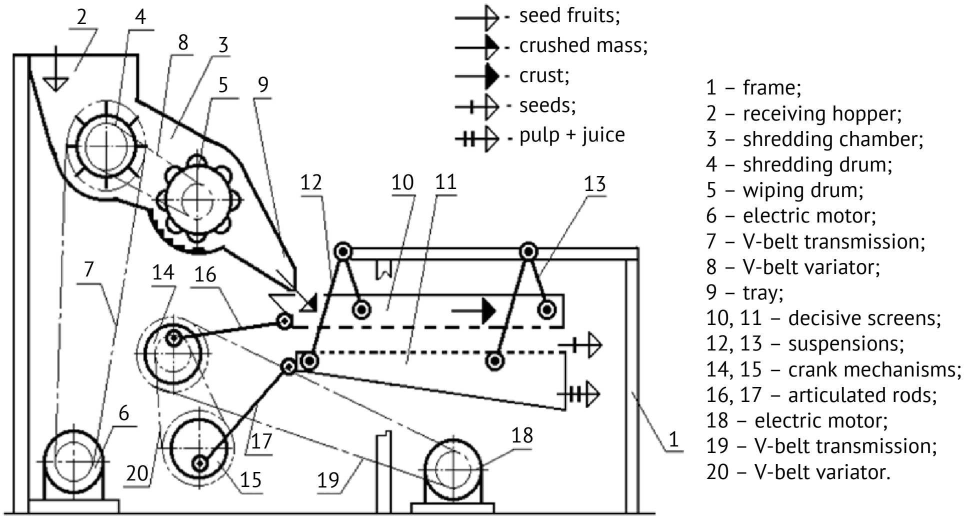

***Figure 1.** Proposed design solution for a vegetable and melon crop separator*
***Source:** developed by the authors*

To study the nature of the movement of the crushed mass on the surface of the sieves of the vegetable and melon seed separator, it is necessary to analyse the nature of the material movement on sieves that perform inertial and vibratory movement. In the context of analysing the movement of material along an inertial sieve of a separator, Figure 2 shows a general case of seed movement along an inclined plane. The angle of inclination of the sieve plane to the horizon α and the angle of inclination of the vibrations to the sieve plane β are within the limits:

$$\begin{cases} -\frac{1}{2}\cdot\pi \le \alpha \le \frac{1}{2}\cdot\pi \\ 0 \le \beta \le \frac{1}{2}\cdot\pi. \end{cases} \quad (18)$$

Projections of sieve movement $\tilde{\xi}$; $\tilde{\eta}$ described by the system:

$$\begin{cases} \tilde{\xi} = A \cdot Cos\beta \cdot Sin\omega t \\ \tilde{\eta} = A \cdot Sin\beta \cdot Sin\omega t' \end{cases} \quad (19)$$

where *A* and ω – oscillation amplitude and frequency.

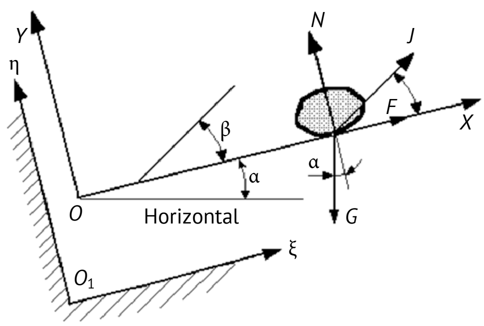

***Figure 2.** General case of seed movement on an inclined plane*
***Source:** developed by the authors on the basis of theoretical mechanics (Maas, 2017)*

Relative material movement in projections on moving axes:

$$\begin{cases} m \cdot x'' = -m \cdot \xi'' - m \cdot g \cdot Sin\alpha + F \\ m \cdot y'' = -m \cdot \eta'' - m \cdot g \cdot Cos\alpha + N \end{cases}. \quad (20)$$

Substituting into the system of equations the expressions for the projections of the force of inertia -*m* ξ'' and -*m* η'', obtained after double differentiation in t equations, the system has the form:

$$\begin{cases} m\cdot x'' = m\cdot A\cdot\omega^2\cdot Cos\beta\cdot Sin\omega t - m\cdot g\cdot Sin\alpha + F \\ m\cdot y'' = m\cdot A\cdot\omega^2\cdot Sin\beta\cdot Sin\omega t - m\cdot g\cdot Cos\alpha + N. \end{cases} \quad (21)$$

The normal reaction is determined:

$$N = N(t) = m \cdot g \cdot Cos\alpha - m \cdot A \cdot \omega^2 \cdot Sin\beta \cdot Sin\omega t. \quad (22)$$

Condition $N(t) > 0$ transforms:

$$Sin\omega t < \frac{g \cdot Cos\alpha}{A \cdot \omega^2 \cdot Sin\beta} = Z_0, \quad (23)$$

or, using the concept of the operating mode factor:

$$G = \frac{A \cdot \omega^2 \cdot Sin\beta}{g \cdot Cos\alpha} \leq 1. \quad (24)$$

The relative equilibrium equation is as follows:

$$F^{(0)} = F^{(0)}(t) = m \cdot g \cdot Sin\alpha - m \cdot A \cdot \omega^2 \cdot Cos\beta \cdot Sin\omega t. \quad (25)$$

The condition of relative calm is represented by:

$$-f_1 \cdot N(t) < F^{(0)}(t) < f_1 \cdot N(t). \quad (26)$$

Transforming the first equation of system (21), the equation of motion of a particle on the sieve surface is obtained:

$$x'' = \frac{d^2x}{dt^2} = -g \cdot \frac{Sin(\alpha \pm \rho)}{Cos\rho} + \\ +A \cdot \omega^2 \cdot \frac{Cos(\beta \mp \rho)}{Cos\rho} \cdot Sin\omega t. \quad (27)$$

Substituting the values of $N(t)$ from (22) and the value of $F^{(0)}(t)$ from (25), is determined along the axis ωt the boundary of the sub-interval of the particle staying on the sieve surface in relative rest:

$$Sin\omega t > Z_{1+}; \quad (28)$$

$$\sigma_1 \cdot (Z_{1-} - Sin\omega t) > 0, \quad (29)$$

where the following designations are introduced:

$$Z_{1\pm} = \frac{g \cdot Sin(\alpha \pm \rho_1)}{A \cdot \omega^2 \cdot Cos(\beta \mp \rho_1)}; \quad (30)$$

$$\sigma_1 = Sign\left[\frac{\pi}{2} - (\beta + \rho_1)\right] = \\ = \begin{cases} 1 & at \quad \beta + \rho_1 < \pi/2 \\ -1 & at \quad \beta + \rho_1 > \frac{\pi}{2}. \end{cases} \quad (31)$$

Then the time limits for the intervals $t = t_+^k$ ($k = 0, 1, 2, \ldots$) can be determined from the equations:

$$Sin\omega t_+^k = Sin\delta_+^k = Z_+; \quad (32)$$

$$Sin\omega t_-^k = Sin\delta_-^k = Z_-, \quad (33)$$

and the condition of continuous motion of the particle on the sieve surface is:

$$Sin\omega t > \frac{g \cdot Cos\alpha}{A \cdot \omega^2 \cdot Sin\beta} = Z_0 > 1. \quad (34)$$

The time limits of the intervals of continuous movement of particles on the surface of the separator sieve are defined as:

$$Sin\omega t_0^k = Sin\delta_0^k = Z_0. \quad (35)$$

In the following δ_0, δ_+ i δ_- denote the roots of the equations defined by the relations:

$$\begin{cases} \delta_0 = arcSinZ_0 \\ \delta_+ = arcSinZ_+ \\ \delta_- = \begin{cases} \pi - arcSinZ_- \ at\ \sigma_1 = 1 & i.e.\ at \quad \beta + \rho_1 < \pi/2 \\ \quad arcSinZ_- \ at\ \sigma_1 = -1 & i.e.\ at \quad \beta + \rho_1 > \pi/2, \end{cases} \end{cases} \quad (36)$$

where $arcSinZ$ means the main value of the function lying in the interval -0.5π...+0.5π. The differential equation is transformed into a more convenient form for further calculations:

$$x'' = \frac{d^2x}{dt^2} = A \cdot \omega^2 \cdot \frac{Cos(\beta \mp \rho)}{Cos\rho} \cdot \\ \cdot \left[Sin\omega t - \frac{g \cdot Sin(\alpha \pm \rho)}{A \cdot \omega^2 \cdot Cos(\beta \mp \rho)}\right], \quad (37)$$

by entering the following notation:

$$\delta = \omega t; \quad (38)$$

$$a_\pm = A \cdot \omega^2 \cdot \frac{Cos(\beta \mp \rho)}{Cos\rho}; \quad (39)$$

$$Z_{1\pm} = \frac{g \cdot Sin(\alpha \pm \rho_1)}{A \cdot \omega^2 \cdot Cos(\beta \mp \rho_1)}. \quad (40)$$

Equation (37) will have the following form:

$$x'' = \frac{d^2x}{dt^2} = a_\pm \cdot (Sin\delta - Z_\pm). \quad (41)$$

The values of sums and angle differences are limited to: $-0.5\pi \leqslant (\alpha \pm \rho) \leqslant 0.5\pi$ and $-0.5\pi \leqslant (\beta \mp \rho) \leqslant 0.5\pi$. Since condition (28) was accepted, the values of the terms of equation (41) will also be limited: $a_\pm > 0$; $Z_+ > 0$; $Z_- < 0$. For positive and negative direction, the phase angles are δ'_+ and δ'_-, and the phase angles of the end of these motions are respectively δ^*_+ and δ^*_-. The particle will slide in the positive direction if the acceleration $x'' = \frac{d^2x}{dt^2} > 0$, i.e. at

$$Sin\delta'_+ \geqslant Z_+, \quad (42)$$

and its sliding in the opposite (negative) direction when the condition:

$$Sin\delta'_- \leqslant Z_-. \quad (43)$$

The conditions for starting a slip are indicated by:

$$Sin\delta_{0+} = Z_+ = \frac{g \cdot Sin(\alpha+\rho)}{A \cdot \omega^2 \cdot Cos(\beta-\rho)}; \quad (44)$$

$$Sin\delta_{0-} = Z_- = \frac{g \cdot Sin(\alpha-\rho)}{A \cdot \omega^2 \cdot Cos(\beta+\rho)}. \quad (45)$$

If to each of the angles δ_{0+} and δ_{0-} the share was at a relative standstill, meaning that the previous slide had already ended, therefore $\delta'_+ = \delta_{0+}$ and $\delta'_- = \delta_{0-}$. To fulfil this condition, it is necessary that the projections of velocities on the *X*-axis are equal to 0. By integrating the equations of relative motion, the phase angles are determined δ_{0+} and δ_{0-}, the corresponding stopping points for each of the displacements. When integrating, the following relations should be taken into account:

$$\delta = \omega t;\ d\delta = \omega \cdot dt; \quad x'' = \frac{d^2x}{dt^2};\ \frac{dx}{dt} = \omega \cdot \frac{dx}{d\delta}. \quad (46)$$

The first integrals of the equation for the intervals of relative motion of the particle in the positive and negative directions are respectively:

$$x' = \frac{dx}{dt} = \frac{a_+}{\omega} \cdot [(Cos\delta_{0+} - Cos\delta) - Z_+ \cdot (\delta - \delta_{0+})]; \quad (47)$$

$$x' = \frac{dx}{dt} = \frac{a_-}{\omega} \cdot [(Cos\delta_{0-} - Cos\delta) - Z_- \cdot (\delta - \delta_{0-})]. \quad (48)$$

The right-hand sides of these equations go to zero when the sliding stops, i.e., when the angles of δ take the values δ^*_+ and δ^*_-. Therefore,

$$Cos\delta_{0+} - Cos\delta^*_+ = Z_+ \cdot (\delta - \delta_{0+}); \quad (49)$$

$$Cos\delta_{0-} - Cos\delta^*_- = Z_- \cdot (\delta - \delta_{0-}). \quad (50)$$

By solving the transcendental equations, the values of the phase angles δ^*_+ and δ^*_- corresponding to the stopping of the particle when it moves in the positive and negative directions of the *X*-axis are determined. Then for this mode it can be written as:

$$\begin{cases} \delta'_- = \delta^*_+ \\ \delta^*_- = 2\pi + \delta'_-. \end{cases} \quad (51)$$

Integrating the differential equation (41) within the limits of $x'_0 = 0$:

$$x' = \frac{dx}{dt} = \frac{a_+}{\omega} \cdot [(Cos\delta'_+ - Cos\delta) - Z_+ \cdot (\delta - \delta'_+)]. \quad (52)$$

For the negative direction of motion of the particle, equation (41) is integrated from δ'_- to δ:

$$x' = \frac{dx}{dt} = \frac{a_-}{\omega} \cdot [(Cos\delta'_- - Cos\delta) - Z_- \cdot (\delta - \delta'_-)]. \quad (53)$$

The moment the slide stops $x'_0 = \frac{dx}{dt} = 0$, the angles δ in equations (52; 53) take, respectively, the values δ and $\delta = \delta^*_-$. After substituting these values into equations (52; 53), the equality is obtained:

$$Cos\delta'_+ - Cos\delta^*_+ = Z_+ \cdot (\delta^*_+ - \delta'_+); \quad (54)$$

$$Cos\delta'_- - Cos\delta^*_- = Z_- \cdot (\delta^*_- - \delta'_-). \quad (55)$$

After substituting the values of δ'_- and δ^*_- from system (35), the equality is obtained:

$$Cos\delta'_+ - Cos(2\pi + \delta'_+) = Z_- \cdot (2\pi + \delta'_+ - \delta^*_+), \quad (56)$$

which in transformed form can be written as follows:

$$Cos\delta'_+ - Cos^*_+ = Z_- \cdot [(\delta^*_+ - \delta'_+) - 2\pi]. \quad (57)$$

Equating the right-hand sides of equations (38) and (41), the formula is obtained:

$$\delta^*_+ - \delta' = 2\pi \cdot \frac{\gamma}{\gamma-1}, \quad (58)$$

where γ is defined by the expression:

$$\gamma = \frac{Z_-}{Z_+} = \frac{Sin(\alpha-\rho) \cdot Cos(\beta-\rho)}{Cos(\beta+\rho) \cdot Sin(\alpha+\rho)}. \quad (59)$$

The following notation has been introduced:

$$\varepsilon = \frac{\delta^*_+ - \delta'_+}{2} = \pi \cdot \frac{\gamma}{\gamma-1}. \quad (60)$$

Converting the left-hand side of equation (58) with the expression (60), the following is obtained:

$$2 \cdot Sin\left(\frac{\delta^*_+ - \delta'_+}{2}\right) \cdot Sin\varepsilon = Z_+ \cdot \varepsilon; \quad (61)$$

$$\frac{\delta^*_+ - \delta'_+}{2} = arcSin\left(\frac{\varepsilon \cdot Z_+}{Sin\varepsilon}\right). \quad (62)$$

Provided that $\frac{\delta^*_+ - \delta'_+}{2}$ is an acute angle, then:

$$\frac{\delta^*_+ - \delta'_+}{2} = \pi - arcSin\left(\frac{\varepsilon \cdot Z_+}{Sin\varepsilon}\right). \quad (63)$$

Grouping equations (61; 63) into a system and solving it, there will be formulas for determining the phase angles of the beginning and end of the particle's motion in the positive direction along the axis *OX*:

$$\delta'_+ = \left(\pi - arcSin\frac{\varepsilon Z_+}{Sin\varepsilon}\right) - \varepsilon; \quad (64)$$

$$\delta^*_+ = \left(\pi - arcSin\frac{\varepsilon Z_+}{Sin\varepsilon}\right) + \varepsilon. \quad (65)$$

Based on the formulas, the following ratios were formed:

$$Sin\delta'_+ = \frac{\varepsilon \cdot Z_+}{tg\varepsilon} + \sqrt{Sin^2\varepsilon - (\varepsilon \cdot Z_+)^2}; \quad (66)$$

$$Sin\delta^*_+ = \frac{\varepsilon \cdot Z_+}{tg\varepsilon} - \sqrt{Sin^2\varepsilon - (\varepsilon \cdot Z_+)^2}. \quad (67)$$

To determine the magnitude of the particle displacements in the positive and negative directions along the axis *OX* for one period of oscillation, it is necessary to integrate equation (52) in the range from δ'_+ to δ^*_+ and equation (53) within $\delta'_- = \delta^*_+$ to $\delta^*_- = 2 \cdot \pi + \delta'_+$. It is necessary to take into account the relationship (46).

$$x_+ = \frac{a_+}{\omega^2} \cdot \left[(Cos\delta'_+ + Z_+ \cdot \delta'_+) \cdot (\delta^*_+ - \delta'_+) - (Sin\delta'_+ - Sin\delta^*_+) - Z_+ \cdot \frac{(\delta^*_+ - \delta'_+)^2}{2}\right]; \quad (68)$$

$$x_- = \frac{a_-}{\omega^2} \cdot \left[(Cos\delta^*_+ + Z_- \cdot \delta^*_+) \cdot (2\pi + \delta'_+ - \delta^*_+) - (Sin\delta'_+ - Sin\delta^*_+) - Z_- \cdot \frac{(2\pi + \delta'_+ - \delta^*_+)^2}{2}\right]. \quad (69)$$

Taking into account the formulas (23; 24; 41; 44; 47-50), it is determined:

$$x_+ = 2A \cdot \frac{Cos(\beta - \rho)}{Cos\rho} \cdot \left(1 - \frac{\varepsilon}{tg\varepsilon}\right) \cdot \sqrt{Sin^2\varepsilon - (\varepsilon \cdot Z_+)^2}; \quad (70)$$

$$x_- = 2A \cdot \frac{Cos(\beta + \rho)}{Cos\rho} \cdot \left(1 + \frac{\pi - \varepsilon}{tg\varepsilon}\right) \cdot \sqrt{Sin^2\varepsilon - (\varepsilon \cdot Z_+)^2}. \quad (71)$$

Average particle velocity:

$$x'_{avr} = \frac{1}{2\pi} \cdot \left(\int_{\delta'_+}^{\delta^*_+} x' d\delta + \int_{\delta'_-}^{\delta^*_-} x' d\delta\right), \quad (72)$$

$$or\ v_{avr} = \frac{x_+ + x_-}{T}, \quad (73)$$

where $T = 2\pi/\omega$.

Substituting (70; 71) into (73), the equation of the average velocity of a particle on an inertial sieve is obtained after transformations:

$$v_{avr} = A \cdot \omega \cdot Cos\beta \cdot Cos\varepsilon \cdot \left[\frac{2}{\pi} \cdot tg\rho \cdot tg\beta \cdot (tg\varepsilon - \varepsilon + \frac{\pi}{2} - 1\right] \sqrt{1 - \left(\frac{\varepsilon \cdot Z_+}{Sin\varepsilon}\right)}. \quad (74)$$

The theoretical study of the nature of the movement of the crushed mass on the surface of the sieve of a vegetable and melon seed separator can be based on various hypotheses about the impact interaction of a particle with a vibrating working surface: the impact can be considered inelastic, partially elastic, or absolutely elastic. Interactions in the tangential direction can be expressed by the coefficient of instantaneous friction, which is taken from one of the following relations. Usually, the relationship between the velocities before and after the impact of a particle with a vibrating surface is taken from one of the following relations:

$$v_{x+} = \left(\frac{dx}{dt}\right)_+ = (1 - \lambda) \cdot v_{x-}\ at\ |v_{x-}| < \left|\frac{f \cdot (v_{y+} - v_{y-})}{\lambda}\right|, (0 \leq \lambda \leq 1), \quad (75)$$

where v_{x-}; v_{x+} – projection of the particle velocity onto the axis of the *OX*, respectively, before and after the impact; v_{y-}; v_{y+} – projection of the particle velocity on the axis *OY*, respectively, before and after the impact; λ – instantaneous friction coefficient equal to the sliding friction coefficient *f*.

$$v_{x+} = \left(\frac{dx}{dt}\right)_+ = v_{x-} - f' \cdot (v_{y+} - v_{y-}) \cdot sign(v_{x-})\ \text{at}\ |v_{x-}| > \left|\frac{f \cdot (v_{y+} - v_{y-})}{\lambda}\right|, \quad (76)$$

where *f'* – impact friction coefficient equal to the sliding friction coefficient.

At the same time, the recovery rate of seeds when they hit the metal surface of the sieve is numerically equal to $R = -\frac{v_{y+}}{v_{y-}}$. In further theoretical analysis, the relation between the particle velocities relative to the sieve plane in the tangential and normal directions is assumed to be λ hypothesis (75).

The differential equations of particle separation at $F \equiv 0$; $N \equiv 0$.

$$x'' = \frac{d^2x}{dt^2} = A \cdot \omega^2 \cdot Cos\beta \cdot Sin\omega t - g \cdot Sin\alpha; \quad (77)$$

$$y'' = \frac{d^2y}{dt^2} = A \cdot \omega^2 \cdot Sin\beta \cdot Cos\omega t - g \cdot Cos\alpha. \quad (78)$$

To obtain a complete system of relations defining the motion of a particle, equations (77) and (78) should be supplemented by equations (75) and (76) defining the law of change of the relative velocity of a particle when it collides with a surface. Since in the steady-state motion the particle systematically hits the vibrating plane, when integrating equations (77) and (78), it is sufficient to assume the initial value of the coordinate

Y is zero, i.e., to consider the flight of the particle starting from the vibrating plane. By placing the origin at the point of the plane from which the particle flight begins $t = t_0^*$, it can be assumed that the X coordinate at the training moment is also equal to zero. As a result of integrating equations (77; 78), taking as initial conditions:

$$x(t_0^*) = 0;\ v_{x0}^* = x'(t_0^*) = 0;\ y(t_0^*) = 0;\ v_{y0_y}^* = y'(t_0^*) = 0, \quad (79)$$

where v_{x0}^*; v_{y0}^* – projections of the particle velocity, respectively, on the axes OX and OY, at the moment of its detachment from the plane at $t = t_0^*$.

The movement of a particle when it is detached:

$$v(t)_x = \frac{dx}{dt} = -A \cdot \omega \cdot Cos\beta \cdot (Cos\omega t - Cos\omega t_0^*) - g \cdot (t - t_0^*) \cdot Sin\alpha + v_{x0}^* + 1; \quad (80)$$

$$x(t) = -A \cdot Cos\beta \cdot (Sin\omega t - Sin\omega t_0^*) - 0.5 \cdot g \cdot Sin\alpha \cdot (t - t_0^*)^2 + A \cdot \omega \cdot (t - t_0^*) \cdot Cos\beta \cdot Cos\omega t_0^* + v_{x0}^* \cdot (t - t_0^*); \quad (81)$$

$$v(t)_y = \frac{dy}{dt} = -A \cdot \omega \cdot Sin\beta \cdot (Cos\omega t - Cos\omega t_0^*) - g \cdot (t - t_0^*) \cdot Cos\alpha + v_{y0}^*; \quad (82)$$

$$y(t) = -A \cdot Sin\beta \cdot (Sin\omega t - Sin\omega t_0^*) - 0.5 \cdot g \cdot Cos\alpha \cdot (t - t_0^*)^2 + A \cdot \omega \cdot (t - t_0^*) \cdot Sin\beta \cdot Cos\omega t_0^* + v_{y0}^* \cdot (t - t_0^*). \quad (83)$$

It is assumed that when a particle falls on the sieve, both a completely inelastic ($R = 0$) and an elastic impact ($0 \leqslant R \leqslant 1$) are present, and that the particle can be detached from the plane at time t_0^*, which is determined from the condition:

$$Sin\omega t_0 = Z_0 = \frac{g \cdot Cos\alpha}{A \cdot \omega^2 \cdot Sin\beta}, \quad (84)$$

and the moment of particle impact on the plane can belong to any period of oscillations of the plane, depending on the values of the system parameters and the initial conditions of motion. The moment of fall of a particle is determined by:

$$y(t_f) = -A \cdot Sin\beta \cdot (Sin\omega t_f - Sin\omega t_0^*) - 0.5 \cdot g \cdot Cos\alpha \cdot (t_f - t_0^*) \cdot Sin\beta \cdot Cos\omega t_0^* + v_{y0}^* \cdot (t_f - t_0^*), \quad (85)$$

by converting which can be written as:

$$\frac{Z_0 \cdot (\phi_f - \delta_0^*)^2}{2} + (Sin\phi_f - Sin\delta_0^*) - (\phi_f - \delta_0^*) \cdot (Cos\delta_0^* + \psi) = 0. \quad (86)$$

The following notations are used in the equation:

$$\psi = \frac{v(y_0^*)}{A \cdot \omega \cdot Sin\beta};\ \omega \cdot t_0^* = \delta_0^*;\ \omega \cdot t_f = \phi_f. \quad (87)$$

This equation is transcendental. To solve it graphically, it is necessary to plot in the coordinates $\{\phi = \omega \cdot t;\ O^*;\ y\}$ sinusoid $y = Sin\phi$ and a parabola described by the expression: $y = F(\varphi) = -\frac{Z_0 \cdot (\varphi - \delta_0^*)^2}{2} + (Cos\delta_0^* + \psi) \cdot (\varphi - \delta_0^*) + Sin\delta_0^*$. The root of equation (85) is the abscissa of the intersection of the curves. Conducting transformations of equations (80; 81), similar to the transformations carried out in the derivation of the formulas, an expression for determining the average speed of a particle on the sieve of a separator of vegetable and melon seeds can be obtained:

$$v_{avr} \cong A \cdot \omega \cdot \left(Cos\beta - \frac{2-\lambda}{\lambda} \cdot Sin\beta \cdot tg\alpha\right). \quad (88)$$

Figure 3 shows the interpretation of the detachment of a particle of material from the sieve.

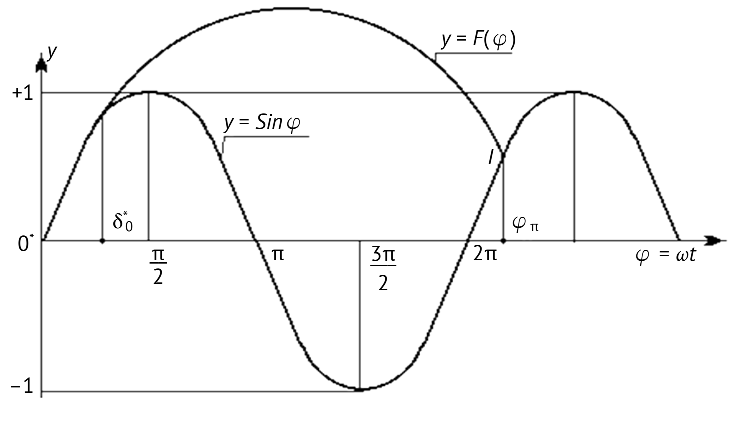

Figure 3. *Interpretation of material particle detachment from the sieve*
Source: *developed by the authors on the basis of theoretical mechanics (Hand & Finch, 2008)*

To determine the kinematic modes of the upper sieve, on which seeds, pulp and pulp are separated from the crust, the expression is transformed to determine the operating mode coefficient and the solution is performed sequentially with respect to A; ω; α and β. Taking the operating mode coefficient $G = 0.5$, it turns out:

$$A = \frac{G \cdot g \cdot Cos\alpha}{\omega^2 \cdot Sin\beta}; \ \omega = \sqrt{\frac{G \cdot g \cdot Cos\alpha}{A \cdot Sin\beta}};$$
$$\beta = arcSin\left(\frac{G \cdot g \cdot Cos}{A \cdot \omega^2}\alpha\right). \quad (89)$$

Based on the analysis of the mechanical and technological properties of the crushed seed mass (Bortz & Schuster, 2010), analytical dependencies are presented that can be used for practical application. The graphical dependence $A = F(\omega)$ for different modes of operation at different angles of application of forced oscillations β is shown in Figure 4. The region of existence of the mode of particle motion without detachment from the separator surface lies to the left of curves I and II. As can be seen from the graphs, at the angle of force application $\beta = 10°$, the screen oscillation frequency should be at least 25 1/s. Reducing the oscillation frequency less than this value leads to an unjustified increase in the oscillation amplitude and complication of the drive mechanism. In the kinematic mode at an angle of $\beta = 30°$, the oscillation frequency can be in the range of 15...20 1/s, while the oscillation amplitude will not exceed 100 mm.

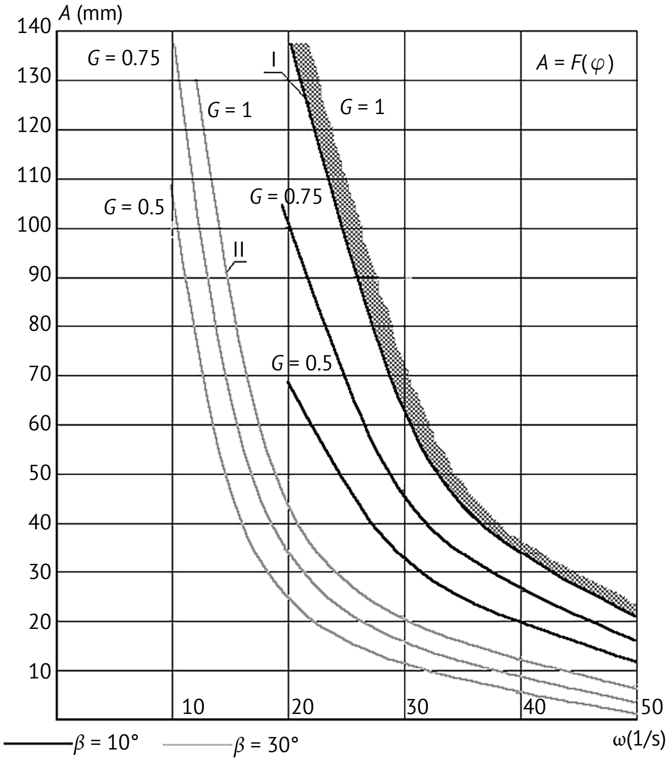

Figure 4. *Functional dependence of oscillation amplitude on oscillation frequency for different separator operating modes*
Source: *developed by the authors*

It is necessary to strive to reduce the amplitude and frequency of oscillations. This reduces the dynamic loads on the drive elements and simplifies the design of the separator. The authors recommend determining the frequency and amplitude of oscillations not separately, but investigating the relationship $A \cdot \omega^2 = F(\beta)$ or:

$$A \cdot \omega^2 = \frac{G \cdot g \cdot Cos\alpha}{Sin\beta}. \quad (90)$$

The graphical interpretation of expression (90) is shown in Figure 5. The zone of existence of the mode of sliding particles without detachment from the plane will also lie to the left of curve I. To determine the average speed of material movement in the technological zone of the separator, use formulas (74) for the upper screen operating in the inertial separator mode and (88) for the lower screen operating in the vibrating separator mode.

The separator capacity is determined by the formula:

$$Q = 3600 \cdot F_0 \cdot \psi \ \ v_{aver} \cdot \gamma, \quad (91)$$

where F_0 – cross-sectional area of the rumble plate; γ – bulk mass of the material; ψ – filling factor.

The drive power for an inertial separator is calculated using the empirical expression:

$$N \approx \frac{4 \cdot 10^{-4} \cdot Q \cdot L}{\eta \cdot tg\beta} \cdot$$
$$\cdot \left(6 \cdot 10^{-4} \cdot \frac{A \cdot \omega^2}{f} + 1\right), \quad (92)$$

and the drive power of the vibrating screen by the formula:

$$N \approx \frac{C \cdot Q}{10^3 \cdot \eta} \cdot k_3 \cdot L, \quad (93)$$

where L – length of the sieve; η – efficiency; C – transportability coefficient; k_3 – coefficient of specific power consumption.

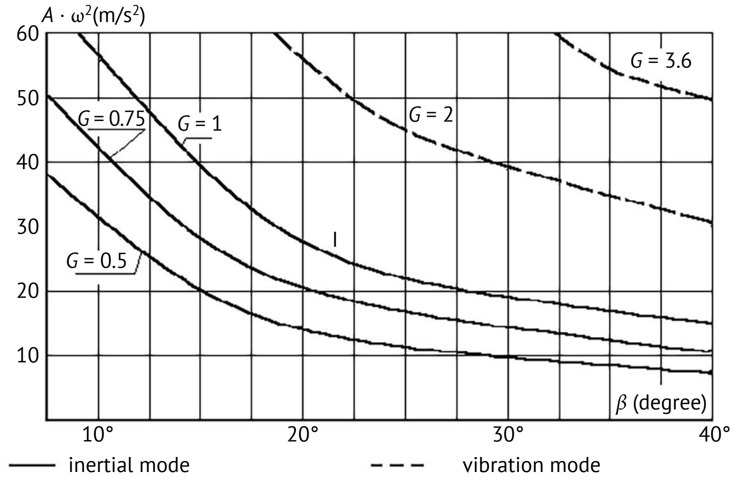

Figure 5. *Dependency graphs*

Source: *developed by the authors*

Based on the theoretical analysis, a methodology was developed for calculating the kinematic and structural parameters of the proposed design solution. The calculation sequence is as follows:

- according to the graph (Fig. 5), the values of the amplitude A and the oscillation frequency ω of the screen and the angle β are selected, with an arbitrary choice of the sieve angle α;
- phase angles of transition δ from one mode of motion to another or from one direction to the opposite are determined;
- determine the maximum speed for each mode, determine the force of interaction between the seeds and the sieve surface;
- calculate the average speed v_{aver}; find the productivity Q, determine the drive power N;
- if the separator capacity Q is specified by regulatory documents (technical specifications or initial requirements for development), the cross-sectional area of the screen F_0 and then its width is determined.

To confirm the effectiveness of the proposed design solution and the feasibility of using the presented analytical dependencies, the selected seeds and peel with pulp were weighed alternately (State Standard of Ukraine DSTU 7160:2020, 2020). The percentage of each component of the crushed mass was determined according to the following dependencies:

$$C = \left(\frac{m_s}{m}\right) \cdot 100\%; \quad C_c = \left(\frac{m_c}{m}\right) \cdot 100\%; \quad C_p = 100\% - (C_s + C_c), \quad (94)$$

where C_s, C_c, C_p – percentage of seeds, crust with pulp and pulp in the obtained material; m_s, m_c – weight of seeds and the weight of crust with pulp in the crushed mass; m is the total weight of crushed seeds. The results are presented in Table 1.

Table 1. *Components of the process mass*

Name of the crop	Components of the process mass, %		
	peel + pulp	seeds	pulp + juice
Cucumber "Konrurent"	41.2	3.8	55.0
Watermelon "Vognyk"	35.0	2.3	62.7
Melon "Kolkhoznitsa"	53.6	3.5	42.9

Source: *developed by the authors on the basis of experimental research*

The percentage of peel in the crushed mass was determined by size group: up to 10 mm, 10-50 mm and over 50 mm using the following formulas:

$$C_{10} = \left(\frac{m_{10}}{m_c}\right) \cdot 100\%; \quad (95)$$

$$C_{50} = \left(\frac{m_{10}}{m_c}\right) \cdot 100\%; \quad (96)$$

$$C_{70} = \left(\frac{m_{10}}{m_c}\right) \cdot 100\%; \quad (97)$$

where m_{10}, m_{50}, m_{70} – mass of peel and pulp of each size group contained in the heap; m_c – total mass of the shredded peel. The results of the study of the components of each of the fractions of the crushed mass are presented in Table 2.

Table 2. *Indicators of the crushed process mass*

Culture	Crushed peel, %			The seed bound to the pulp and crust, %	Injured seeds, %	Seeds, %
	till 10 mm	10-70 mm	more than 70 mm			
Cucumber	12	37	21	7.5	0.5	92.0
Melon	11	53	36	2.4	0.35	97.25
Watermelon	11	57	32	6.6	0.4	93.0

Source: *developed by the authors on the basis of experimental research*

In the process of studying the mechanical and technological properties of the crushed mass of seeds, the friction properties of the peel of vegetable and melon crops were also studied. The values of the friction angles of the peel on the following three surfaces were determined: rubber, metal and sieve plates. Rubber, metal and sieve plates were chosen as friction surfaces. When studying the sliding friction of crushed crust particles, the latter were placed on an inclined plane of the device with a sample of the material under study fixed on it. The inclined plane was raised to the an , at which the particles began to move. The sliding friction coefficient f was determined by the formula:

$$f = tg(\varphi). \quad (98)$$

The replication of the experiments for cucumber variety "Konkurent", watermelon variety "Ogonyok", melon variety "Kolkhoznitsa" was a hundred times, the angles and sliding coefficients of the peel particles from the studied materials are presented in Table 3.

Table 3. *Sliding angles and coefficients of friction of crushed peel*

Friction surface material	Variety of crops under study					
	Cucumber		Melon		Watermelon	
	friction angle	friction coefficient	friction angle	friction coefficient	friction angle	friction coefficient
Rubber plate	24°78'	0.53	22°16'	0.41	22° 59'	0.42
Metal plate	18°46'	0.34	19°57'	0.36	19°29'	0.35
Sieve cloth	19°41'	0.36	21°17'	0.39	21°22'	0.37

Source: *developed by the authors on the basis of experimental research*

The presented research results indicate that the mechanical and technological parameters of the components of the crushed technological mass, namely the ratio of the components of the crushed mass and the indicators of the crushed technological mass, are within the normal range. The use of the proposed design solution and regulation of its modes in accordance with the presented dependences of the amplitude of oscillations on the frequency of oscillations for different modes of operation of the separator and determination of the average speed of material movement in the technological zone of the separator for the upper screen operating in the mode of an inertial separator and for the lower screen operating in the mode of a vibrating separator is advisable.

DISCUSSION

The development of vegetable and melon seed production requires the introduction of industrial models of machines designed for complex mechanisation and automation of production processes. Improvement and development of the seed production industry will help to ensure that agricultural production is supplied with seeds of its own production, which will significantly reduce costs and increase productivity in the industry. Producers of melons and gourds will be able to reduce the cost of production of these crops if they produce their own seeds.

Vibrating machines are widely used to separate seeds of vegetable and melon crops. The study of modelling the sieving of crops at different vibration amplitudes, frequencies and angles is presented (Chen & Yan, 2019). The results show that the angle of deviation of the vibration direction has little effect on the sieving efficiency. Under the influence of other parameters, the sieving efficiency first increases and then decreases. After comparing the data, the best combination of sieving parameters was obtained with an amplitude of 4 mm, a vibration frequency of 13 Hz, a sieve angle of 8° and a vibration direction angle (angle between the vibration line and the *Z*-axis) of 0°. The combination of vibration and inertial motion, as in the case of the proposed design solution, has a positive effect on the quantitative and qualitative indicators of seed separation.

A study has been conducted on the practical application of unbalanced vibration drives in adjustable drives of vibrating sieves (Despotovic *et al.,* 2019). For synchronous operation of vibration drives, frequency control of their exciting force is required, as well as operation of vibrating screens in the so-called "superresonant" mode. This study presents an experiment to determine the amplitude-frequency characteristics of vibrating screens, as well as the most important experimental results obtained under real operating conditions. The design solution proposed by the authors and the use of graphs to optimise its design and operating parameters allow increasing the seed yield and reducing its losses.

Z. Kaliniewicz *et al.* (2021) evaluated the relationships between the main physical properties of seeds of selected species for seed sorting purposes. Physical properties were measured in seeds of five species, and the existence of relationships between these traits was determined using correlation and regression analyses. Seeds should be separated on a sieve equipped with at least two mesh screens with holes. The study emphasises the need for technical means for post-harvest processing on farms, with vibration equipment being particularly effective. The use of the proposed design solution provides not only the use of the properties of vibrating machines, but also additional work in the inertial mode, which ensures high quality seed separation.

The authors M. Ohienko *et al*. (2010) proposed the design of an inclined rotary separator with an irrigation device located on the axis of rotation of the drum. The inclined rotary separator for refining the technological seed mass of vegetable and melon crops consists of a frame, an electric motor, a worm gearbox, a cylindrical mesh drum, a sprinkler, a loading and unloading tray, which differs in that to improve the process of passing seeds through the holes of the drum and removing them outside the machine, it has an irrigation device mounted in the axis of rotation of the drum. The purpose of the utility model is to further separate the seeds on the rotary separator during the passage of the crushed mass along the inner surface of the rotating mesh drum. The peculiarity of the separator is that it can be used as the first in the flow line for refining the processed mass. The proposed design solution is an independent machine for the main operation of separating seeds of vegetable and melon crops, and not as a machine for refining.

The methodology for modelling the technology of processing the seed mass of vegetable and melon crops can be used to determine the optimal values of the design and operating parameters of seed separators (Shebanin *et al.,* 2019). The researchers presented a solution to the problem of predicting seed characteristics using the tested method. The optimisation criteria were seed loss and purity of the resulting material. However, the machine used for the experiment was a pressurising machine, which has a lower quality of seed separation compared to vibrating equipment. In addition, mathematical modelling of the technological process is time-consuming and allows modelling only for a certain sample of varieties of vegetable and melon crops and does not allow predicting the results, unlike the proposed study of the movement of the technological mass of vegetable and melon seeds, which makes it possible to predict the results to some extent and choose the optimal operating modes of the separator using the proposed graphs.

The analysis of trends in the models and types of equipment used for different breeding volumes of vegetable and melon seed production in the southern region of Ukraine shows that the existing equipment for seed selection of vegetable and melon crops in Ukraine is energy inefficient. Significant amounts of seeds are damaged or lost during the selection process. When obtaining seeds of vegetable and melon crops, there are no methods of their analysis, synthesis and optimisation adapted to the systems of complex mechanisation. A. Pastushenko (2021) proposed the analysis and optimisation of technical systems for the integrated mechanisation of vegetable and melon seeds production using graph theory methods, constructed information and flow charts and incident matrices for a prototype production line for processing fruit seeds and producing vegetable and melon seeds. By varying the schematic solutions and/or different variants of the layout of system elements, structural elements and the distance between them, it is possible to determine the optimal technological line, in accordance with a pre-selected optimisation criterion. An algorithm for optimising the system is proposed, which establishes the procedure for calculating mathematical models and its individual elements. The efficiency criteria can be economic, energy, technological or other characteristics of the system. The proposed methodology is effective for determining the optimal combination of equipment for a technological line, but it is not adapted to determine the operating parameters of specific samples and equipment that complete the technological line. It has been determined that the disadvantages of vegetable and melon separators include a significant percentage of injured seeds and loss of conditioned seeds, which can be avoided by predicting the technological process and adjusting the equipment. It can also be noted that there is a need to improve the methods of optimising the mechanisation of this technological process.

The experimental studies in this article allowed to optimise the sieve angle α, the amplitude A and frequency of oscillations ω, the length L and the angle of application of forced oscillations β. The surface of the material has a negligible effect on the sliding friction coefficient. The advantage of using the proposed design solution of the separator is the combination of inertial and vibrational motion of the sieves, as evidenced by the experimental data obtained on the basis of the mechanical and technological properties of the selected samples.

CONCLUSIONS

Theoretical studies have made it possible to identify the main factors influencing the technological process and to obtain analytical dependencies for calculating the amplitude, oscillation frequency, angle of forced oscillations, material movement speed, drive performance and power. The graph-analytical method of studying kinematic modes made it possible to determine the zones of existence of different modes of inertial and vibratory separator screens. Laboratory studies of the mechanical and technological properties of the technological mass made it possible to conclude that it is expedient to separate seeds using the proposed design solution. As a result of statistical data processing, it was determined that the percentage composition of the components of the technological mass depends on the crop and variety. The optimal values of the content of seeds, pulp, peel and juice are presented. The values of the coefficients of friction of the crushed peel can be used in further calculations of the modes of technological equipment.

The obtained theoretical dependences fully characterise the technological process of seed cleaning from pulp, pulp and hull on a two-screen separator with different kinematic modes of each sieve. However, it is necessary to take into account the value of the friction coefficient (friction angle) for both the crust and the freshly separated seeds, the data on the value of which are not available. The absence of data on the mechanical and technological characteristics of seeds and crushed mass does not allow using the obtained dependencies in further practical engineering calculations. To determine their values, it is necessary to conduct additional experimental studies of the physical and mechanical characteristics and dimensional and mass parameters of various components of the crushed mass of seed fruits.

Determination of the size and weight characteristics of seed fruits of a particular crop does not affect the degree of crushing and the mechanical and technological parameters of the crushed mass. The degree of grinding depends only on the design of the impactor and the crop being processed. The size and weight characteristics of the seeds allow to conclude that they can be separated from impurities by the principle of differentiation by seed length. However, it is not possible to use the same type of sieves for all studied crops. Therefore, the prospects for further research are to determine the geometry of the sieve openings and seed resistance to static and dynamic (impact) loads and the effect of the kinematic parameters of the separator on the seed injury parameter.

ACKNOWLEDGEMENTS

None.

CONFLICT OF INTEREST

None.

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Дослідження характеру руху подрібненої маси по поверхні решіт сепаратора насіння овочевих та баштанних культур

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Анотація. Вдосконалення обладнання для переробки овочевої та баштанної культур потребує проведення досліджень характеру руху подрібненої маси для зменшення травмування матеріалу та отримання якісного насіння, що дозволить перевести галузь овоче-баштанництва на новий рівень розвитку. Метою дослідження є аналіз характеру руху подрібненої маси по поверхні решіт сепаратора насіння овочевих та баштанних культур. Обґрунтування характеру руху подрібненої маси по поверхні решіт запропонованого конструктивного рішення виконувалося на базі використання методів фізики, теоретичної механіки та аналізу і дослідження фізико-механічних характеристик технологічної маси. В якості базової конструкції для дослідження використовувався сепаратор овочевих та баштанних культур, особливістю якого є застосування двогрохотної системи решіт. В наведеній системі верхнє решето виконує виділення кірки, а нижнє – насіння та мезги; м'якоть і сік будуть підґратним продуктом другого решета. Решето, що виконує інерційний рух, сприяє вилученню пов'язаного з кіркою насіння. В результаті досліджень представлена функціональна залежність амплітуди коливань від частоти коливань для різних режимів роботи сепаратора. Для визначення середньої швидкості руху матеріалу в технологічній зоні сепаратора надані формули для верхнього грохоту, що працює в режимі інерційного сепаратора і для нижнього грохоту, який працює в режимі вібросепаратора. В контексті вищевказаних особливостей запропонованого конструктивного рішення проведене дослідження характеру руху подрібненої маси по поверхні інерційного та вібраційного решіт. В ході теоретичних розрахунків отримано залежності для визначення середньої швидкості частинки в робочій зоні зазначених решіт. На підставі теоретичного аналізу була розроблена методика розрахунку основних параметрів двогрохотного сепаратора. Здійснено визначення механіко-технологічних властивостей насіння овочевих та баштанних культур виділеного за допомогою запропонованого конструктивного рішення. В лабораторних умовах було проведено дослідження складу компонентів виділеної насіннєвої маси і їх аналіз, який свідчить про доцільність застосування запропонованого конструктивного рішення сепаратора овочевих та баштанних культур та застосування на практиці отриманих теоретичних залежностей для регулювання його технологічних параметрів

Ключові слова: інерційний сепаратор; вібраційний сепаратор; механіко-технологічні властивості; рух частинки