STUDY OF THE PROCESS OF THRESHING LEGUMINOUS GRASS SEEDS WITH A DRUM-TYPE THRESHING DEVICE
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ДОСЛІДЖЕННЯ ПРОЦЕСУ ВИТИРАННЯ НАСІННЯ БОБОВИХ ТРАВ МОЛОТИЛЬНИМ ПРИСТРОЄМ БАРАБАННОГО ТИПУ

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ABSTRACT
The article presents the results of studies of the process of threshing leguminous grass seeds with a drum-type threshing device. The process of material movement in the working gap of the drum deck was modelled and the intensity of the action of the working on the material under optimal operating conditions was substantiated. The dependence of the completeness of threshing alfalfa seeds on the number of rasp bar actions on the material on pendulum copra and in a threshing device was obtained based on the results of laboratory research. The influence of the design and technological parameters of the threshing device on the efficiency of threshing alfalfa seeds, as well as on the energy indicators of their operation, has been determined. The rational parameters of the threshing device are substantiated, which ensure complete threshing of seeds at the level of 96.5-98.2%, and damage to no more than 0.8% of seeds.

РЕЗЮМЕ
У статті наведено результати досліджень процесу витирання насіння бобових трав терковим пристроєм барабанного типу. Проведено моделювання процесу руху матеріалу в робочому зазорі бич-дека та обґрунтовано інтенсивність дії робочих органів на матеріал при оптимальних режимах їх роботи. За результатами лабораторних досліджень отримано залежності повноти витирання насіння люцерни від кількості дій бичів по матеріалу на маятниковому копрі і в терковому пристрої. Визначено вплив конструктивно-технологічних параметрів теркового пристрою на ефективність витирання насіння люцерни, також на енергетичні показники його роботи. Обґрунтовано раціональні параметри теркового пристрою за яких забезпечується повнота витирання насіння на рівні 96,5-98,2%, та пошкодження не більше 0,8% насіння.

INTRODUCTION
To harvest seeds of leguminous grass such as clover, alfalfa and melilotus, grain harvesters are mainly used. Therefore, all known technologies are based on the use of combine harvesters (*Sheichenko et al., 2019*). As an object of processing, legumes grass seed plants have a number of specific features different from grain crops in the structure of plants, inflorescences and seeds, which causes significant differences in the physical, mechanical and technological properties of the processed material (Moss *et al., 2021*). Significant differences in the physical and mechanical properties of the biological mass of legumes grass seed plants from cereal crops complicate the process of seed harvesting, and especially the operations of thrashing and separating seeds with a combine harvester (*Ivan, 2016*).

Special adapters are used for harvesting grass seeds by combine harvesters, which are more suitable for working with such material as unthreshed inflorescence of leguminous grass seeds. This allows reducing seed losses, but still they remain significant and make up 20-30% of the grown crop.

The problematic issue in the operation of threshing unit of combine harvesters is the process of threshing seeds from legume. The percentage of threshing seeds after passing them through the threshing unit is only 45-55%.

Therefore, for threshing the rest of the seeds from the beans, the fraction of unthreshed seeds is re-fed to the threshing unit or to the stand-alone after-threshing devices of the combine, the efficiency of which is too low (*Liao, et al., 2021*). In one pass of the material through the after-threshing devices, only 10-15% of the seeds are threshed off. In addition, due to the low adaptation of the air-sieve cleaning unit to work with a heap of legume grass seeds, a significant part of straw and chaff impurities is fed into the after-threshing devices with unthreshed seeds.

Repeated feeding of the same material into the threshing device leads to recirculation of the material in the thresher of the combine and damage to the seeds (*Chu et al., 2022*). This leads to an overload of the working bodies of the combine thresher and an even greater deterioration in the operation of the air-screen cleaning unit and, accordingly, an increase in the loss of seeds by the thresher of the combine (*Pari et al., 2020*). Significant losses of seeds during the harvesting of leguminous grass seed plants prompt the need to search for and develop new technological and technical solutions for the processes of field and stationary threshing and seed separation.

Studies of the qualitative indicators of the operation of special shelling devices have shown that the use of these devices on combine harvesters for threshing seeds of legumes grass allows increasing the percentage of seeds in the bunker by only 10-15%. But it is not possible to solve the problem of complete threshing of seeds with the thresher of the combine harvester. This produces only up to an increase in the circulation load on the working bodies of the combine thresher and, first of all, the cleaning unit (*Miu & Kutzbach, 2008*).

Another technological solution for harvesting grass seeds may be the option of harvesting the seed part of the material in the field, followed by threshing and separating the seeds in stationary conditions. (*Spirin et al., 2023*). In this case, it is possible to reduce the loss of seeds in the field, but there is a need to justify the degree of contamination of the seed and chaff mixture, both with straw impurities and the content of unthreshed seeds in it. Depending on the clogging of the seed and chaff mixture, the loss of seeds behind the combine will change, as well as the conditions for processing it in stationary conditions (*Stefanoni et al., 2022*). Significant losses of seeds were noted during the harvesting of seed plants of perennial legumes, primarily due to the low quality of work and the low productivity of threshing devices. (*Clifford & McCartin, 1985*).

An analysis of the operation of drum-type devices for threshing grass seeds shows that the main factors affecting the completeness of seed extraction are the exposure of the heap processing and the operating modes of the device (*Khawaja & Khan, 2022*). However, one should take into account the possibility of injury to seeds due to fatigue load with an increase in threshing exposure (*Wang et al., 2023*). The percentage of seed damage also increases with increasing impact energy (*Delfan et al., 2023*).

The absence of machines for dosing and loading material into technical means, as well as the absence of special machines for working with clogged seed heaps, leads to a significant increase in the labor intensity of work and a decrease in the productivity of machines during threshing and separating leguminous seeds. In addition, the efficiency of the machines that can be used in these operations is low, both in terms of quality indicators of work and the reliability of the process.

An analysis of known methods and technical means for threshing seeds of grasses and other crops revealed the advantages of drum-type devices with axial material movement over other types of devices (*Fu et al., 2018*). However, the well-known drum-type threshing devices have a number of design and technological drawbacks, only if they are eliminated, they can be effectively used for threshing seed and chaff mixture of leguminous grass seeds (*Ji et al., 2020*).

The purpose of the research is to intensify the process of legume seeds threshing with drum-type device. This can be achieved due to the intensity of action of the working bodies under optimal operating conditions, increasing the exposure of material processing in the working gap of the device when developing a technical mean.

MATERIALS AND METHODS

The intensity of the seed threshing process and energy consumption depending on the number of actions of the rasp bars on the material was determined using a pendulum tester and an experimental threshing device (Berry et al., 2014). The energy intensity of the process of threshing alfalfa seeds and the necessary number of actions of the rasp bars to completely thresh the seeds from the hook with unthreshed beans were determined on the MK pendulum copra according to the method, which provides for the manufacture of working elements of the rasp bars and the concave similar to the working bodies of the threshing device.

A 50 mm long bar with a grooved surface similar to the threshing rasp bars was attached to the copra pendulum. The deck 60 mm wide and 250 mm long with a corrugated surface was installed with special fasteners on the supporting surface of the copra.

A sample of material with unthreshed alfalfa beans was poured onto the deck, from which the seeds were separated by repeated actions of a pendulum with a bar installed on it. After each action of the bar, energy consumption for the process of releasing seeds and the amount of threshed seeds were determined. Energy consumption was determined based on:

$$A = G \cdot r \cdot (\cos\alpha - \cos\beta) \tag{1}$$

where G is the weight of the pendulum with the rasp bars installed on it, [N];

r is the distance from the axis of suspension of the pendulum to the center of its gravity, [m];

α and β are the angles of rise of the pendulum after the working and idle strokes, respectively.

The threshing of the seeds from the sample was carried out by repeated actions of the bar until the seeds were completely threshed from the sample.

Most of the existing studies on the threshing process in combine harvesters assume a constant mass, which contradicts the phenomenon of separation of grains and short stems in the actual threshing process (Zhong et al., 2013). To describe the movement of unthreshed beans in the working gap of the drum-deck, a model of a particle with a decrease in its mass is used. In the working gap (Fig. 1) the particle is affected by: compression force *N*; friction force on the surface of the deck sheet F_1; friction force on the drum (bar) F_2.

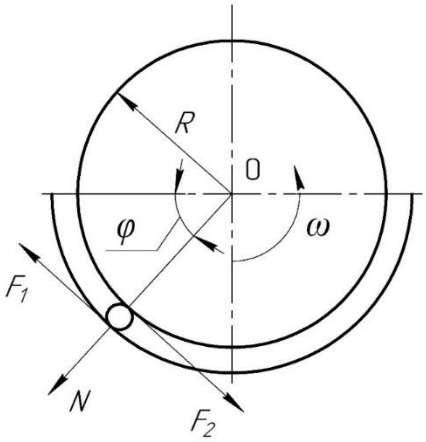

Fig. 1 – The action of forces on a particle in the working gap of the drum-deck

A particle of mass m_0 moves in the working gap Δl between the tray and the drum, rotating with an angular velocity ω_0. The radius of the drum is R. Under the action of the rasp bar on the particle, its mass decreases according to a linear law:

$$m(t) = m_0(1 - k \cdot t) \tag{2}$$

where m and m_0 are the initial and final mass of the particle, [kg];

k is the coefficient of particle mass reduction depending on time *t*.

Considering that the rasp bar of the drum acts impulsively on the particle, the graph of the change in the mass of the particle will have a stepped shape. When rotating, the drum pulls the particle, but due to its sliding along the drum, the particle will have a speed less than the speed of the drum.

Assume that the particle has the shape of a sphere with a radius r. At $r > \Delta l$, the particle is deformed. The particle compression force occurs according to Hooke's law:

$$N = E(r - \Delta l) \tag{3}$$

where E is Young's modulus.

The forces of friction of the particle on the surface of the tray and drum are:

$$F_1 = k_1 \cdot N; \quad F_2 = k_2 \cdot N\ , \tag{4}$$

where k_1 and k_2 is mass friction coefficients on the deck and drum surface.

According to the theorem on the change in the momentum of a particle:

$$R\frac{d}{dt}\left(m\frac{d\varphi}{dt}\right) = F_2 - F_1 = E(k_2 - k_1)(r - \Delta l) \tag{5}$$

Taking into account the formula for the sphere volume, the following equation is obtained:

$$\varphi'' + \frac{1}{x}\varphi' = \frac{E(k_2 - k_1)}{R \cdot m_0 \cdot k^2}\left[\Delta l - \sqrt[3]{\frac{3m_0(1 - k \cdot t)}{4\pi \cdot \rho}}\right] \tag{6}$$

The solution of equation (6) with the initial conditions $\varphi_0 = 0; \quad \varphi'_0 = \omega_0$ allows us to determine the value of $\varphi'(t)$.

Let us consider the process of changing the particle mass in the working gap. To do this, consider the motion of a particle (Fig. 2) first in the interval $0 - t_1$, then in the intervals $t_1 - t_2$ and $t_2 - t_3$, replacing m_0 with $m_0 - \Delta m$. The amount of particle mass reduction Δm can be determined by assuming that the gap between the rasp bar and the deck is δ:

$$\Delta m = \frac{4\pi \cdot \rho}{3} r^3 [\, 1 - \frac{3}{4} \cdot \frac{\delta^2}{r^2} - \frac{1}{4} \cdot \frac{\delta^3}{r^3}] \tag{7}$$

When the rasp bars act on the particle, the ribs of the rasp bars displace it in the axial and radial directions relative to the axis of the drum. The value of the axial displacement of a particle can be determined from the following assumptions that when a rasp bar acts on a particle, it is displaced along the axis of the axial-tangential drum by a value Δx equal to $b \cdot \tan \alpha_1$. Then the axial displacement of the particle according to the k' action of the rasp bars during one pass in the zone of placement of the deck, taking into account the friction coefficient f, is equal to:

$$h_1 = f \cdot k' \cdot b \cdot tan \propto_1 \tag{8}$$

where: k' is the number of actions of rasp bar per particle;

b - the width of the rasp bar, [m];

$\propto_1$- angle of inclination of rasp bar ribs.

The axial movement of the particle in one pass in the upper part of the threshing device casing will be:

$$h_2 = 2\varphi \cdot R \cdot \ sin \propto_2 , \tag{9}$$

where h_2 is the displacement of the particle in the upper part of the threshing device, [m];

R - the casing radius, [m];

φ - the angle of the sector of the casing on which the spiral ribs are installed;

$\propto_2$ - the angle of inclination of the spiral ribs relative to the casing axis

Then the axial displacement of the particle with one turn of displacement around the drum is:

$$h = f \cdot k' \cdot b \cdot tan \propto_1 + \ 2\varphi \cdot R \cdot sin \propto_2 . \tag{10}$$

If m rasp bars are placed on the drum along its perimeter, then it is possible to determine the number of rasp bar actions on the particle during the time t when it moves in the working gap between the rasp bar and the deck. The linear velocity of the particle relative to the drum is:

$$\vec{V}_r = R \cdot (\, \omega_0 - \varphi'), \tag{11}$$

where: $\varphi'(t)$ is determined by the solution of equation (6).

During the time t the particle receives k' actions with rasp bar

$$k' = \frac{t}{\Delta t}, \tag{12}$$

where k' is the number of rasp bar actions per particle;

Δt - the time interval after which the action of the rasp bar on the particle occurs, [s].

$$\Delta t = \frac{2\pi \cdot R}{P \cdot V_r} . \tag{13}$$

Then the number of actions of rasp bars per particle is:

$$k' = \frac{t \cdot P \cdot V_r}{4\pi \cdot R} = \frac{t \cdot P}{4\pi} \ (\omega_0 - \varphi'). \tag{14}$$

If the length of the deck is L, then the particle in the working gap between the deck and the drum passes n turns

$$n = \frac{L}{f \cdot k' \cdot b \cdot tan \propto_1 + 2\varphi \cdot R \cdot sin \propto_2} \tag{15}$$

Studies of the influence of structural and kinematic parameters on the quality parameters of leguminous grass threshing were carried out on an experimental devise consisting of a drum-type tangential-axial threshing device (Fig. 2), a feeding conveyor, and a drive station.

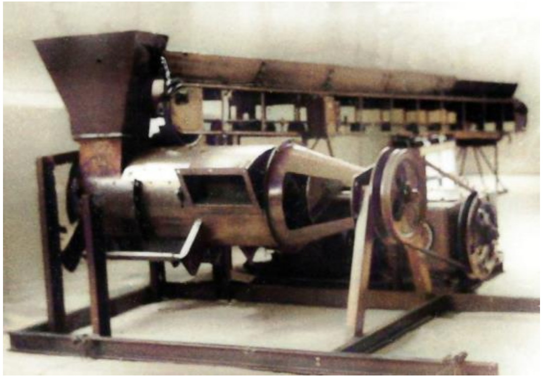

Fig. 2 – General view of a drum-type tangential-axial threshing device

The design of the threshing device is shown in Fig. 3. The threshing device consists of a cylindrical casing 1 with inlet and outlet pipes, in which a drum 3 is placed on bearing units. Drum 3 is made in the form of a supporting cylindrical tube on which rasp bars 15 are placed evenly around the perimeter. Spiral ribs 2 are located on the inner surface in the upper part of the casing 1. Sections 12 and 16 of decks are placed in the lower part of casing 1. Sections of the desk 12 and 16 are articulated connected to the cylindrical casing.

The deck sections have brackets that go out through the holes in the casing 1 and serve for articulated fastening of the sections 12 and 16 with the casing. All gaps between the brackets and the casing are sealed with pads. The gaps between the casing and deck sections are covered with shields.

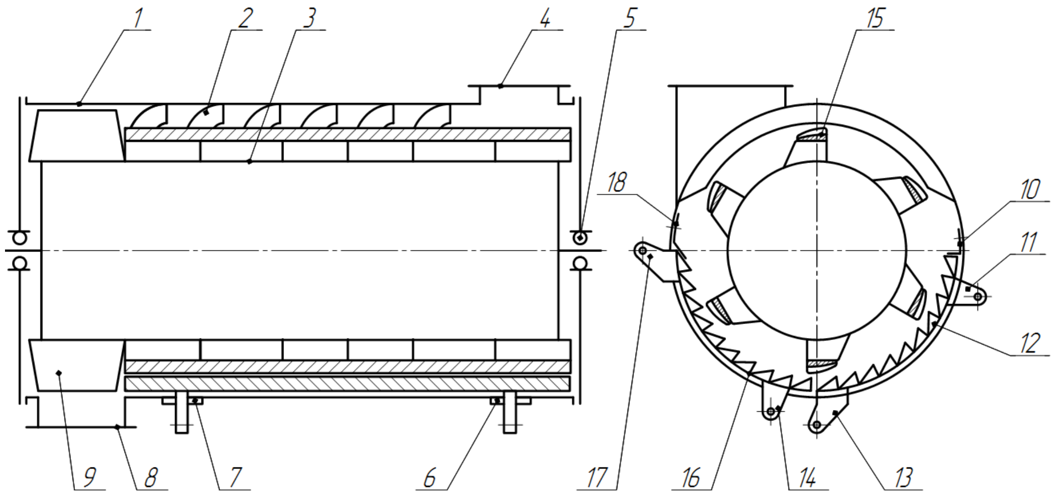

Fig. 3 – Scheme of the drum-type tangential-axial threshing device

1 – casing; 2 – spiral ribs; 3 – drum; 4 - inlet pipe; 5 - bearing; 6, 7 – seal linings; 8 - outlet pipe; 9 - unloading blades; 10, 18 - seal; 11, 13, 14, 17 - deck mounting brackets; 12, 16 - deck sections; 15 - rasp bars

Studies of the threshing process using laboratory equipment were carried out as follows. A heap with unthreshed alfalfa seeds was placed out on the conveyor belt. Turning on the electric motor of the drive station caused the drum of the threshing device to rotate. After that, the engine of the inquiring conveyor was turned on. The material placed on the belt was fed into the inlet pipe of the threshing device. The material threshed in the experimental device at the exit from the outlet pipe was taken into the sampler.

The feed rate of seed heap to the threshing device varied within 1.0-2.0 kg/s with the speed of the feed conveyor belt. As an object of processing, a non-threshed seed heap of alfalfa, obtained by harvesting with a combine in the form of under threshing, was used. In the process of research, the size of the working gaps between the rasp bars of the drum and sections of the decks was changed within 1.0-3.0 mm, at the exit from the deck. The rotation speed of the drum was changed by the variator drive in the range of 80-120 rad/s.

Several variants of decks with different working surfaces were used. The operation of a threshing device with a different number of rasp bars was studied. The design of the upper part of the cylindrical casing was designed in such a way that it made it possible to shift the inlet pipe along the length of the device, thereby changing the length of the deck.

In addition, it is possible to change the angle of inclination of the spiral ribs relative to the axis of the drum within 45-75 degrees. The heap processing exposure was determined depending on the length of the deck, which varies in the range L = 200-800 mm and the angle of inclination of the spiral ribs to the drum axis.

The material from the threshing device was taken into a sampler. The sampler had a five-section frame with suspended sleeves. The frame moved in the grooves of the threshing device's unloading pipe, which made it possible to take three samples of the material in the steady state mode.

The studies were planned and carried out according to the methodology of a single-factor and multifactor experiments. The experiments were carried out according to the plan-matrix or the plan of single-factor studies under the appropriate modes and operating parameters of the threshing device. The main levels and intervals of variation of all factors were taken on the basis of preliminary experiments (Table 1). The optimization criterion by which the operation of the threshing device was evaluated is the completeness of seeds threshing from the beans and crushing the seeds during the operation of the device.

Table 1

Variable factors and limits of their variation for determining the percentage of unthreshed and injured seed when threshing alfalfa beans at the experimental device

Factor	Value	Encoded value	Limits of variation	Levels of variation		
				lower	middle	upper
Angular velocity of the drum, rad/s	ω	X_1	40	80	100	120
Material feed rate, kg/s	Q	X_2	1.0	1.0	1.5	2.0
Gap between bar and deck, mm	δ	X_3	2.0	1.0	2.0	3.0
Number of bars on the drum	m	X_4	4	2	4	6
Content of threshed seeds in the starting material, %	C	X_5	6.0	0	3.0	6.0

RESULTS

As a result of experimental studies and statistical processing, dependences were obtained for the completeness of threshing alfalfa seeds depending on the number of rasp bar actions on a material on a pendulum impact tester and an experimental threshing device (Fig. 4). In the course of experiments on a pendulum tester, elements of a rasp bar and a deck of an experimental threshing device were used.

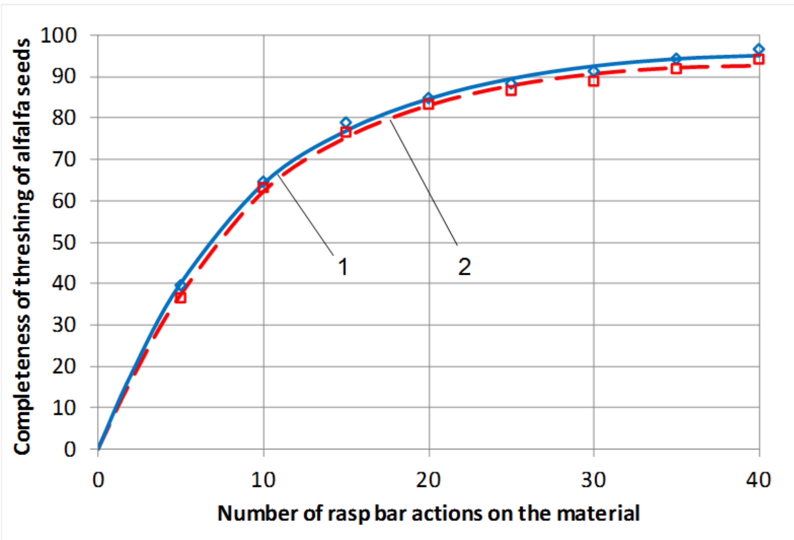

Fig. 4 - Dependences of the completeness of threshing of alfalfa seeds depending on the number of rasp bar actions on the material

1 – studies carried out with a pendulum impact tester; 2 – studies carried out with an experimental device

It has been established that the intensity of threshing of alfalfa seeds on a pendulum impact tester decreases with an increase in the number of actions of the rasp bar on a material, which has a significant impact on energy consumption.

So, during the first ten actions of the rasp bar, about 60% of the seeds from the beans are threshed off. The energy consumption for threshing one seed from a bean averages 0.2^{-10} J. To threshing out 20% of the residue of unthreshed seeds in beans, it is necessary to double the number of rasp bar actions over the material, compared to the number of the rasp bar actions that was spent at the beginning process for threshing 60% of the seeds. At the same time, the energy consumption for the process increases significantly. So after 33-34 actions of the rasp bar, the energy consumption for threshing one seed increases ten or more times and reaches 2.8^{-10} J.

The completeness of threshing seeds and the number of actions of rasp bars over a material in the working gap of the experimental threshing device, depending on the exposure of its processing, were determined. The number of rasp bar actions per particle was determined by formula (14).

Dependence 2 (Fig. 4) of the completeness of threshing of alfalfa seeds on the number of actions of rasp bars on the material was obtained, which with a 90% probability is adequate to dependence 1. It has been established that in an experimental threshing device, the completeness of seed extraction at the level of 96.5-99.1% of alfalfa is ensured by the duration of processing the heap of 0.39-0.40 s, with forty actions of rasp bars on the material. The results of the study allow us to determine the rational length of the deck. With a deck radius and curvature of 236 mm, with a wrapping angle of the drum deck of 180° and with an angle of inclination of the spiral ribs to the drum axis of 75°, the length of the deck is 800 mm.

As a result of studies influence of structural and kinematic parameters on the quality parameters of leguminous grass threshing and statistical processing of experimental data, regression mathematical models were obtained that adequately reflect the dependences of percentage of unthreshed seed Y_1 and percentage of injured seed Y_2:

$$Y_1 = 51.807 + 40.999 \cdot m + 133.432 \cdot Q - 3.485 \cdot \omega - 3.052 \cdot m^2 - 0.481 \cdot m \cdot \delta - 3.245 \cdot m \cdot Q - \\ -0.1149 \cdot m \cdot \omega - 2.794 \cdot \delta \cdot Q + 0.09134 \cdot \delta \cdot \omega - 29.608 \cdot Q^2 - 0.2046 \cdot Q \cdot \omega + 0.01739 \cdot \omega^2; \tag{16}$$

$$Y_2 = 0.678 + \frac{0.777}{m} + \frac{1.042}{\delta} + \frac{0.971}{Q} - \frac{93.80}{\omega} - \frac{0.005}{C}. \tag{17}$$

The analysis of the regression equations showed that they are adequate to the experimental data for the 5% significance level. The graphic dependence of percentage of unthreshed seed on material feed rate and angular velocity of the drum is shown in Fig. 5.

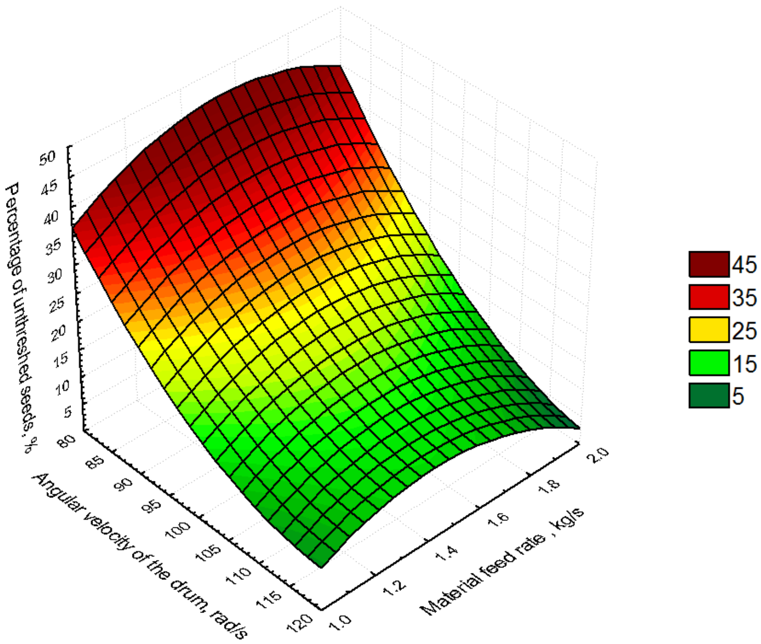

Fig. 5 - Dependence of percentage of unthreshed seed on material feed rate and angular velocity of the drum at the number of bars on the drum m = 6 and gap between bar and deck δ = 2 mm

The graphic dependences of percentage of injured seed on structural and kinematic parameters of experimental threshing device are shown in Fig. 6 and Fig. 7.

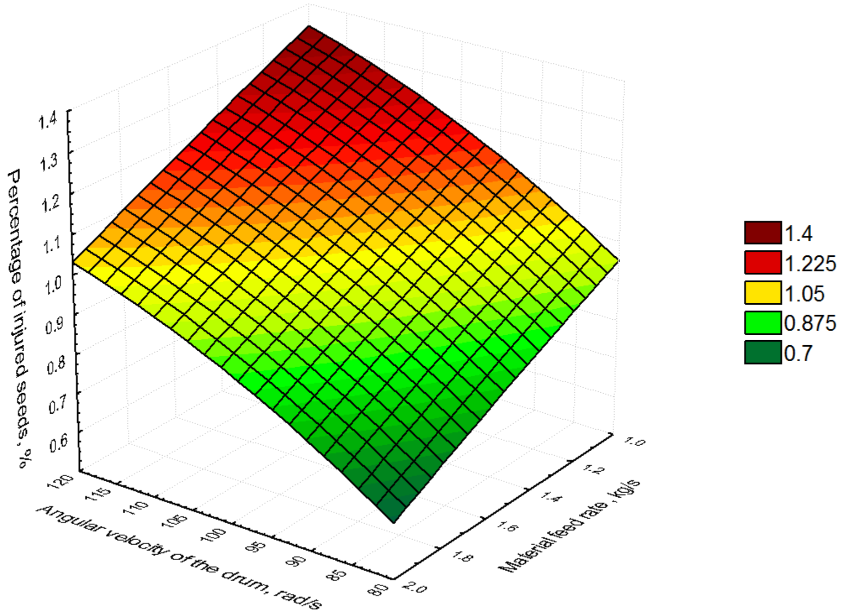

Fig. 6 - Dependences of percentage of injured seed on material feed rate and angular velocity of the drum at the number of bars on the drum m = 6 and gap between bar and deck δ = 2 mm

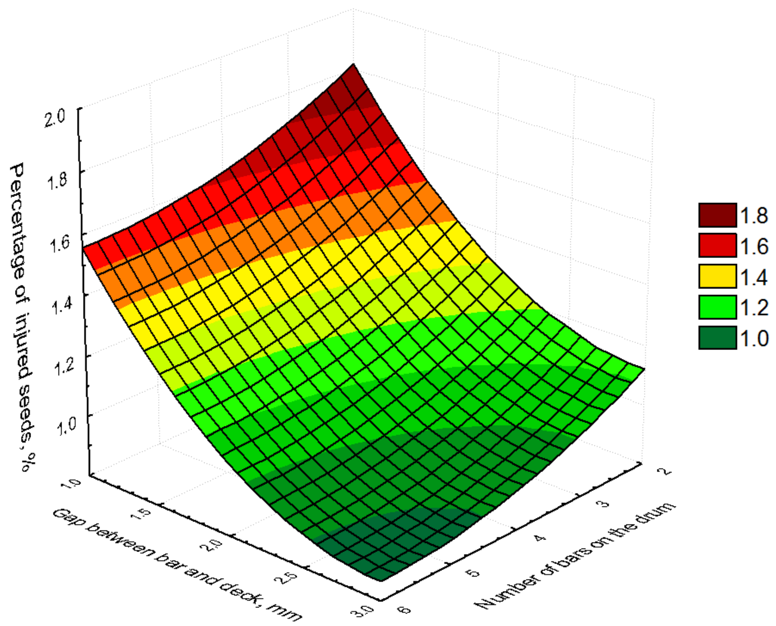

Fig. 7 - Dependences of percentage of injured seed on gap between bar and deck and the number of bars on the drum at material feed rate Q = 1.5 kg/s and angular velocity of the drum ω = 100 rad/s

By analyzing the two-dimensional sections of the response surfaces, described by equations (16) and (17), the rational parameters of the experimental threshing device are determined: the angular speed of rotation of the drum n = 105-110 rad/s; the number of rasp bar on the drum m = 6; material feed rate Q = 1.5-2.0 kg/s; the gap between bar and deck δ = 2.0 mm. An experimental threshing device with above-defined rational parameters provides 96.5% 98.2% completeness of threshing the seeds, while damaging no more than 0.8% of the seeds.

According to the research results, a prototype drum-type tangential-axial threshing device was developed. A study of the developed device in the field with combine and stationary technologies for harvesting seed plants of perennial legumes was carried out. The influence of the material moisture on the quality indicators of the device operation was studied (Fig. 8).

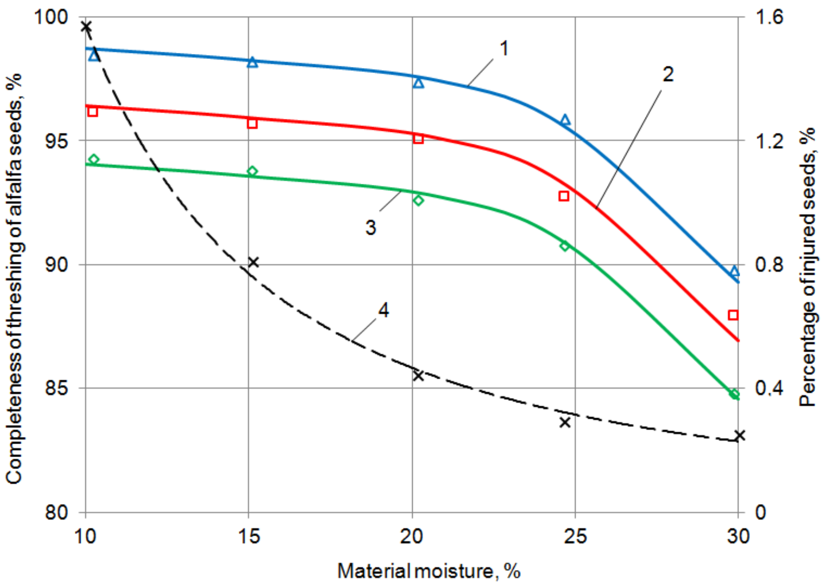

Fig. 8 - Dependences of the completeness of threshing (1-3) and seed injury (4) on the moisture content of the threshing material

1 – Q = 2.0 kg/s; 2 – Q = 1.5 kg/s; 3 – Q = 1.0 kg/s

An analysis of the results of studies of the influence of the moisture content of an unthreshed material of alfalfa on the completeness of threshing seeds showed that with an increase in the moisture content from 10 to 20%, the completeness of threshing seeds decreases slightly from 98.2 to 97.2%, or by 0.7%. Only with a further increase in the moisture content of the material from 20 to 30%, the effectiveness of the threshing process significantly decreases, since the flower shell of the seeds becomes softer and more elastic, it becomes more and more difficult to destroy it.

CONCLUSIONS

The probability of alfalfa beans threshing in the working gap between the drum and the deck is considered as the process of the action of the rasp bars on the particle with a decrease in its mass in the process of its movement. Dependence of the completeness of threshing of alfalfa seeds on the number of actions of rasp bars on the material in the experimental threshing device was obtained, which with a 90% probability is adequate to dependence obtained on the pendulum impact tester.

According to the research results the rational parameters are determined and a prototype drum-type tangential-axial threshing device is developed. A developed threshing device provides 96.5-98.2% completeness of threshing the seeds, while damaging no more than 0.8% of the seeds at moisture content of unthreshed alfalfa material is within 10-20%.

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