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Damage to seeds by screw working bodies

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A R T I C L E I N F O

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A B S T R A C T

Seed damage caused by screw working bodies of agricultural machines reduces the seed quality and increases the total cost of crop production. This paper describes the impact interaction of a particle with screw flights when seeds are fed into the transportation zone. There are velocity dependences during the impact and reflection of seeds on the screw surface at the maximum distance of the radius from the screw rotation axis. The potential energy lost by seeds when interacting with screw flights is determined. The paper considers the way transporting the seed material by screw working bodies impacts seed damage. The potential energy accumulated after impact by the reflecting surface and the particle depends on the magnitude and direction of the falling velocity to the screw belt, the auger geometric and kinematic parameters (the screw diameter; the inclination angle of the helix to the screw axis and the angular velocity), as well as the physical and mechanical properties of the particle and the reflecting surface (recovery and friction coefficients). Previous studies have shown that the critical angular velocity of the screw flight depends on the screw casing and the reduction factor of the circumferential velocity. In turn, the reduction factor depends on the transported seed material and the geometric parameters of the screw. It is possible to diminish the destruction of the seed material due to impact interaction with the working surface of the screw by reducing the inclination angle of the screw flight α, the angular speed of the screw rotation ω and its radius R. It also requires direct the seed flow closer to the rotation center. Reducing injury to seeds during transportation in a screw device requires a higher critical angular velocity of the screw. To increase the working angular velocity of the screw without exceeding its threshold of critical angular velocity, it is advisable to use screws with a large pitch and polymer screws with a wider pitch.

1. Introduction

The occurrence of mechanical damage to seeds caused by the operative components of agricultural machinery stands as a critical determinant contributing to qualitative losses in prospective harvest yields [1–3]. Cleaning and sorting machines can hardly detect and

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separate seeds with microtrauma from the bulk being extremely undesirable for the seed industry [4–6].

Previous findings have shown that grain damage is inevitable, but its type and percentage depend on the design and operating modes of the combine harvester, the feed rate of plant mass, the physical characteristics of grain crops and their humidity [7].

Seed damage intensity depends on the physical and mechanical properties, geometric characteristics and the impact force of the contacting working body.

Data from Ref. [8] suggests that due to the braking that occurs between the touching pea seeds in the flow of the seed material, forces on the seed surface are redistributed, and seeds are less damaged compared to seeds moving separately on the working surface of machines. When seeds move on the working surfaces of agricultural machines, there can be considerable friction forces, depending on the physical, geometric and mechanical properties of the contacting bodies being a source of the grain shell destruction.

The seed quality affects the quality of the resulting harvest. Russian State Standard GOST 28674–90 (2003) claims that the number of injured seeds should not exceed 6% of the total volume. The strict regulations are justified by the fact that if damaged seeds are sown, some of these seeds will give weakened shoots, and the other part will not spring up [9–11].

It was found that screw working bodies of farm machines have the highest traumatic effect on seeds. They destroy the integrity of treated seeds from 34.6 to 50.0% [5,12].

The seed moisture content also contributes to their damage. Some investigators provide evidence that a higher moisture content in seeds increases their elasticity making them harder, causing greater energy absorption during impact and thereby increasing damage resistance [13]. At a lower moisture content seeds become more fragile and susceptible to external mechanical impact [13].

Most researchers believe that mechanical injuries to grain occurs under dynamic loads when the grain freely hits the surface of the working bodies of machines. Moreover, each seed type has its limiting impact velocity, at which its integrity is violated and cracks appear. Previous findings have indicated grain damage from backlogging as a result of bucket overflow (especially at higher belt speed), and grain pinching between buckets, walls and norium belt. It was found that as the norium belt speed increases from 0.9 m/s to 2.1 m/s, the reverse grain overflow rises by 2.3 times, and at a higher speed to 2.9 m/s by 3.2 times. Studies have shown that buckets should not be filled at more than 90% of their capacity at the norium belt speed ranging from 0.93 m/s to 2.1 m/s [8].

Researchers have found that seed injury increases with higher the angle of grain falling on the work surface and the number of impacts experienced by seeds, reaching a maximum of 9% in absolute terms at a 90° inclination angle and decreases with a lower inclination angle and the number of impacts, reaching a minimum at 45° inclination angle [14]. Higher speed of the working bodies of machines leads to more damage to seeds. Thus, earlier findings have demonstrated that an increase in the rotation speed of the combined drum to 600 min-1 inflicted higher seed damage by 3.04–5.58 g or 1.52–2.79%, and at 750 min-1, the number of injured seeds increased by 7.7 g or 3.85%, compared with the rotation speed of the drum 450 min-1 and the gap between the drum and the deck is 38 … 22 mm. The largest number of damaged seeds was 10–11% at the speed of the combined drum 750 min-1 and 34 … 18 mm gaps between the drum and the deck [15].

Scientists have found that the moisture content has an effect on seed damage at higher impact velocities than at lower ones [16–18]. It has been previously observed that there is some optimum moisture content for each seed variety, at which seed damage under impact forces is minimal [16].

High-speed operation modes of the equipment increase the frequency of mechanical action of the working bodies on the seed material and result in its higher damage. Though high-speed modes are required for a higher operation rate of mechanized work. Therefore, it is necessary to study the interaction mechanism of seeds with the working bodies of machinery to improve existing equipment and develop new machines. The working bodies should be arranged to provide working operations without the reduced

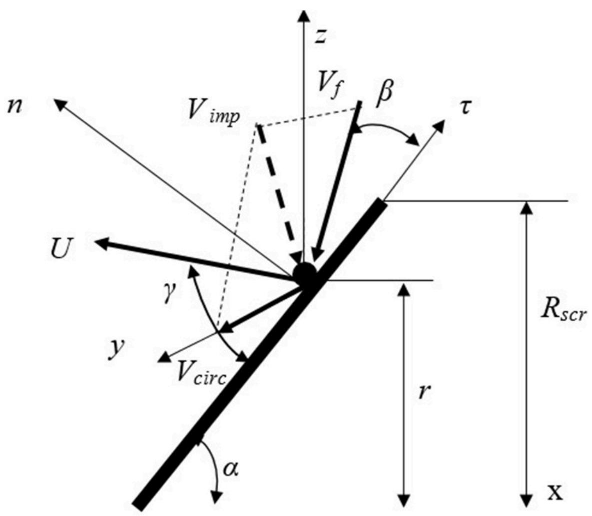

Fig. 1. To the analysis of the particle interaction with the screw belt.
Source: author's development

operation rate. They must maintain the seed integrity without reducing their viability.

The work provides generalized data on seed damage by the working bodies of pre-sowing treaters of seed material [19–21]. They found that screw working bodies of agricultural machines destroy the integrity of 34.6–50.0% of the treated seeds.

This work aims to study the effect of the screw working body on the seed material during their interaction.

The objectives of the study are as follows.

1. To develop a mechanical and mathematical model of the interaction of the seed as a particle of the granular material with the working surface of the screw.
2. To analyse the effect of the transportation process by screw devices on seed damage.
3. To determine rational geometric parameters and kinematic operation modes of screw devices that contribute to reducing their traumatic effects on seeds.

2. Materials and methods

2.1. Research design

Let's consider the interaction of the seed with the screw flights when feeding the seed material into the transportation zone (Fig. 1). The present research explores the working surface of the screw as an inclined surface. It allows using the findings of the study for different types of screws, both horizontal and vertical. The scope of the work is limited by examining the interaction of an individual particle of the granular material with the working surface of the screw.

The study relies on the following assumptions.

1. The seed material is presented in the form of a granular medium.
2. The seed is considered a particle of the granular medium.

Investigating the causes of seed damage during the interaction of a particle of the granular medium and a screw working body, we first consider the impact collision of a loose particle with an inclined working surface, and then the process of its transportation by a screw.

2.2. Calculations

Let the particle weighing ***m*** fall on the screw belt at a speed of V_f. The contact point of the particle with the screw belt is located at a distance ***r*** from the rotation axis (***x*** axis). The lead angle of the screw is $\boldsymbol{\alpha}$ (Fig. 1). The vector of the falling velocity is the angle β with the axis τ.

This interaction results in an impact. The impact velocity is defined as the vector sum of the falling speed and the circumferential velocity of the contact point with the screw belt:

$$\overline{V}_{sp} = \overline{V}_f + \overline{V}_{cv}, \tag{1}$$

where $V_{circ} = \omega\, r$ ***is*** the circumferential velocity of the particle contact point with the screw belt.

Then the impact velocity modulus will be equal to

$$V_v = \sqrt{\left(V_p \sin(\alpha+\beta)\right)^2 + (\omega \cdot r)^2} \tag{2}$$

The impact velocity vector to the normal will have angle $\boldsymbol{\delta}$, equal to

$$\delta = arctg\left(\frac{\omega \cdot r}{V_f \sin(\alpha+\beta)}\right). \tag{3}$$

The particle will be reflected from the screw belt at a velocity ***U*** at an angle $\boldsymbol{\gamma}$, the tangent of which is equal to

$$tg\gamma = \frac{|U_n|}{|U_\tau|} \tag{4}$$

where U_n is the projection of the reflection velocity vector onto the normal to the screw flight;

U_τ is the projection of the reflection velocity vector on the tangent line to the screw flight.

The projection of the reflection velocity vector onto the normal

$$U_n = k\sqrt{\left(V_f \sin(\alpha+\beta)\right)^2 + (\omega \cdot r)^2} \cdot \cos\left(arctg\frac{\omega \cdot r}{V_f \sin(\alpha+\beta)}\right). \tag{5}$$

and the tangent line to the screw belt

$$U_\tau = \sqrt{\left(V_f \sin(\alpha+\beta)\right)^2 + (\omega \cdot r)^2} \cdot \cos\beta\,(1 - f(1+k)) \cdot tg\beta. \tag{6}$$

Then

$$tg\gamma = \frac{|U_n|}{|U_\tau|} = \frac{k\sqrt{(V_n \sin(\alpha+\beta))^2 + (\omega \cdot r)^2}\cos\left(arctg\frac{\omega \cdot r}{V_n \sin(\alpha+\beta)}\right)}{\sqrt{\left(V_p \sin(\alpha+\beta)\right)^2 + (\omega \cdot r)^2}\cos\beta(1 - f(1+k)) \cdot tg\beta}, \tag{7}$$

where k is the particle recovery coefficient; f is the particle friction coefficient on the screw belt.

The reflection velocity modulus is equal to $U = \sqrt{(U_n)^2 + (U_\tau)^2}$.

Substituting expressions for the normal and tangential components of the velocity into the formula and performing transformations, we obtain:

$$U = V_{sp}\sqrt{\left(k^2\cos^2\left(arctg\frac{\omega \cdot r}{V_f \cdot \sin(\alpha+\beta)}\right)\right) + \cos^2(1 - f(1+k)) \cdot tg^2\beta} \tag{8}$$

The greatest value of the reflection velocity will be in the case of a particle falling at the maximum distance R from the screw rotation axis. Then the velocities of impact and reflection will be determined by the equations:

$$\text{Impact velocity } V_{imp}^{max} = \sqrt{(V_n \sin(\alpha+\beta))^2 + (\omega_s R)^2} \tag{9}$$

2.3. Reflection velocity

$$U_{sp}^{max} = V_{imp}^{max}\sqrt{\left(k^2 \cos^2\left(arctg\frac{\omega \bullet R}{V_f \cdot \sin(\alpha+\beta)}\right)\right) + \cos^2(1 - f(1+k)) \bullet tg^2\beta} \tag{10}$$

The obtained equation makes it possible to conclude that the impact velocity will increase with the higher inclination angle of the screw flight ***α***, the angular rotation speed of the screw ω and its radius R_{scr}. Therefore, it is necessary to direct the seed flow closer to the rotation center and reduce the inclination angle of the screw flights.

When interacting with the working surface, part of the kinetic energy of the falling particle after impact is returned back. The other part of the kinetic energy is converted into potential energy accumulated by the particle and the reflecting surface. Ignoring the thermal losses, it can be assumed that the potential energy accumulated by the particle after impact is spent on its deformation.

The potential energy of the reflecting surface is used to overcome friction forces and surface deformation.

The kinetic energy of the particle before impact on the work surface is equal to

$$T_k = \frac{m \cdot \left(V_p \sin(\alpha+\beta)\right)^2 + (\omega \cdot R)^2}{2} \tag{11}$$

The kinetic energy of the particle reflected by the surface after impact is determined by formula (12):

$$T_0 = \frac{m \cdot (V_f \cdot \sin(\alpha+\beta))^2 + (\omega \cdot R)^2}{2} \cdot \left(\left(k^2 \cdot \cos^2\left(arctg\frac{\omega \cdot R}{V_f \cdot \sin(\alpha+\beta)}\right)\right) + \cos^2(1 - f(1+k)) \cdot tg^2\beta\right) \tag{12}$$

The difference of kinetic energies before impact T_n and after impact T_0 is equal to the potential energy absorbed by the particle and the reflecting surface, that is

$$P = T_n - T_o. \tag{13}$$

After substituting the incoming values and transformations, we get:

$$P = \frac{m \cdot \left(V_f \cdot \sin(\alpha+\beta)\right)^2 + (\omega \cdot R)^2}{2} \cdot \left(1 - \left(k^2 \cdot \cos^2\left(arctg\frac{\omega \cdot R}{V_f \cdot \sin(\alpha+\beta)}\right)\right) + \cos^2(1 - f(1+k)) \cdot tg^2\beta\right) \tag{14}$$

This expression describes the part of the energy that is lost by the particle when interacting with the screw flights.

The potential energy accumulated by the reflecting surface and the particle depends on the value of the falling velocity V_f and the direction of the falling velocity vector to the screw belt (angle β), the geometric and kinematic parameters of the screw ($D_{scr} = 2R_{scr}$ is the screw diameter; ω is the angular velocity, angle α is the inclination angle of the helical line to the screw axis), as well as the physical and mechanical properties of the particle and the reflecting surface (recovery coefficient k and friction coefficient f).

The potential energy consists of the potential energy absorbed by the reflecting surface P_{rs} and the potential energy accumulated by the particle P_p, that is

$$P = P_{rs} + P_p \tag{15}$$

The dependence to determine the potential energy accumulated by the reflecting surface was obtained earlier [22].

The potential energy accumulated by the particle largely depends on the properties of the reflecting surface. The replacement of the steel screw belt with an elastomer-based alternative leads to a considerable decrease in the potential energy accumulated by the particle. As a result, seed damage is lowered, providing more variations for the kinematic and geometric parameters of the screw conveyor.

Let's analyse the way the transportation process in screw devices affects seed damage.

The granular material makes a plane-parallel movement during transportation and mixing. As a result, products shift from the vertical axis towards the direction of the circumferential velocity vector (Fig. 2).

The seed material movement depends on the workspace load factor of the screw cross-section ψ.

The workspace load factor is found by the formula:

$$\psi = \frac{A_m}{A_c} = \frac{(\alpha_g - 0.5 \sin 2\alpha_g)}{\pi \cdot (1 - \mu^2)}, \tag{16}$$

where A_m is the cross-section area of the seed material,

A_c is the cross-section area of the casing;

D – the inner diameter of the screw casing

$\mu = D_{sft}/D$ is a coefficient depending on the ratio of the inner diameter of the screw casing and the shaft diameter;

D_{sft} stands for shaft diameter;

α_g is half of the central contact angle of the granular material.

The functioning of screw devices is carried out at the values of the load factor $\psi < 0.5$. In this case, the center shift of the grain mass from the screw rotation center R_g can be determined on the basis of existing methods for calculating screw devices [23]:

$$R_g = \frac{D \cdot \sin^2 \alpha_g}{3\mu \cdot (1 - \mu^2) \cdot \varphi}, \tag{17}$$

To analyse the effect of the transportation process on seed damage, consider the forces acting on loose products (Fig. 3).

The product friction on the screw belt is found in the expression

$$P_{fr} = F_{scr} \cdot f_{scr} \cdot V_{scr}. \tag{18}$$

Where F_{scr} is the pressure force of the seed material on the screw surface; V_{scr} is the movement rate of the seed material along the screw belt; f_{scr} is the particle friction coefficient on the screw belt.

To determine the pressure force F_{scr} of the material on the screw tape, we compose equilibrium equations (Fig. 3, a):

- the sum of moments of all the forces acting on the loose products relative to the screw rotation axis (Fig. 3, b):

$$\sum m = F_{scr} \frac{D_0}{2} (f_{scr} \cos \alpha_0 + \sin \alpha_0) - F_c \cdot f_c \cos \beta \cdot \frac{D_0}{2} - mg \cdot \cos \theta \cdot e = 0 \tag{19}$$

- the sum of the force projections on the screw axis (Fig. 4, a):

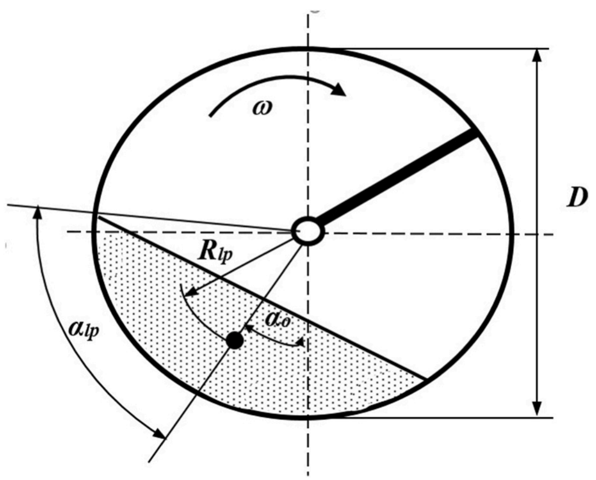

Fig. 2. Feeding the granular material to the working volume of the screw.
Source: author's development

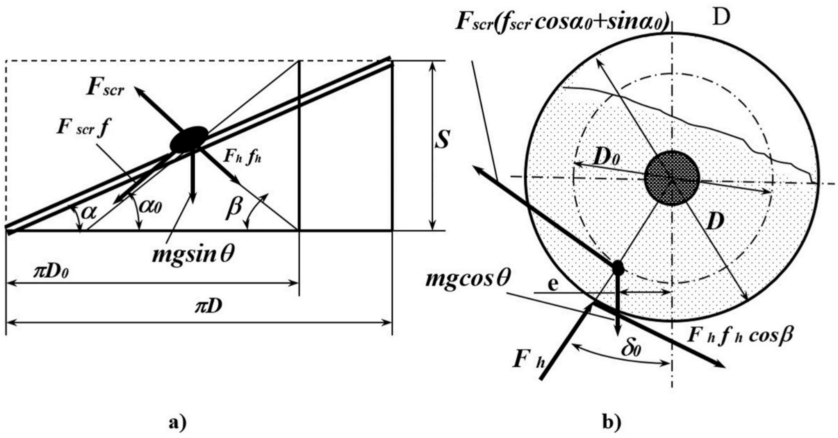

Fig. 3. Forces acting on the seed in the screw conveyor.
Source: author's development

$$\sum F_x = F_{scr}(\cos \alpha_0 - f_{ш} \sin \alpha_0) - F_c \cdot f_c \cdot \sin \beta - mg \cdot \sin \theta = 0 \tag{20}$$

where F_c is the pressure force of the loose products on the screw casing; D_0 *is* the diameter of the pressure centres on the screw; α_0 is the lead angle of the helical line; β - the inclination angle of the pressure center line, f_c – the friction coefficient of the particle on the screw casing walls.

The center shift of the grain mass *e*, depending on the load factor, is ψ determined by the expression [21]:

$$e = \frac{f_c \cdot (1 + \pi \cdot f_{scr}) \cdot (1 - \psi) \cdot D}{2\sqrt{(\pi - f_{scr})^2 + (1 + \pi \cdot f_{scr})^2 \cdot f_c^2}}, \tag{21}$$

Substituting formula (21) into formulas (19) and (20) provides equations:

$$F_k = \frac{mg(2e \cdot C_1 \cos \theta - \lambda \cdot C_2 \sin \theta)}{D \cdot f_k(\lambda \cdot C_2 \sin \beta - C_1 \cos \beta)} \tag{22}$$

where $C_1 = \cos \alpha_0 - f_{scr} \sin \alpha_0$; $C_2 = f_{scr} \cos \alpha_0$ - $\sin \alpha_0$; $\lambda = D_0/D$.

$$F_{scr} = mg\left[\frac{(\lambda \cdot (C_2 \cos \beta - 2e \cdot C_1 \sin \beta) \sin \beta}{C_1 \cdot D \cdot (C_1 \cos \beta - \lambda \cdot C_2 \sin \beta)} + \frac{\sin \theta}{2}\right] \tag{23}$$

The work of the friction forces $A\ (F_{fr})$, equal to the sum of the work of the forces F_c and F_{scr}, is converted into potential energy spent on damage to the working surface of the casing and screw, seed damage and heat losses. Neglecting the heat losses, we get $A(F_{fr}) = L \cdot$

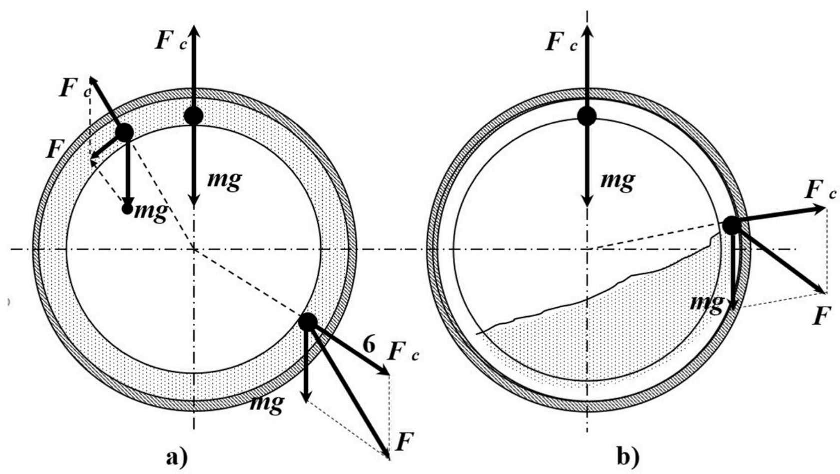

Fig. 4. To determine the critical angular velocity of the screw.
Source: author's development

$(F_k + F_{scr}) = P_{fr},.$

After substituting the incoming values (22) and (23) into the last expression and making changes, we obtain

$$P_{fr} = mg \cdot \left[\frac{(\lambda \cdot D \cdot (C_2 \cos \beta - 2e \cdot C_1 \sin \beta) \sin \beta}{C_1 \cdot D \cdot (C_1 \cos \beta - \lambda \cdot C_2 \sin \beta)} + \frac{(2e \cdot C_1 \cos \theta - \lambda \cdot C_2 \sin \theta)}{D \cdot f_\kappa (\lambda \cdot C_2 \sin \beta - C_1 \cos \beta)} + \frac{\sin \theta}{2} \right] \tag{24}$$

The expression in square brackets is a transportation friction coefficient C_0.

The transportation friction coefficient for a horizontal screw conveyor or mixer will be determined by the expression [18]:

$$C_0 = \frac{\pi \cdot e \cdot \left(\lambda \cdot f_{scr} \cdot \sin^2 \beta + C_1 \cdot \sin \alpha \right)}{S \cdot \cos \alpha \cdot \sin \beta \cdot (\lambda \cdot C_2 \cdot \sin \beta - C_1 \cdot \cos \beta)} \tag{25}$$

The conveyed seed material performs both translational and rotational motions (Fig. 4).

Using the kinetostatics principle, it is possible to show the equilibrium of a dynamic system of forces by applying fictitious inertia forces to a particle in addition to external forces. It is known that under the centrifugal force of inertia at a certain critical value of the angular velocity ω_{cr}, the granular material will be distributed along the periphery of the screw device in the form of a cylindrical surface (Fig. 5).

If the gravity force *mg* is less than the centrifugal force of inertia F_c, then the particles located in the uppermost part of the screw casing will not be able to separate from the layer of the conveyed material and being pressed by the centrifugal force of inertia will rotate with the casing. In this condition of the seed material, there are higher risks for seed pinching and damage by the screw flights.

According to the provisions of mechanics, the fictitious centrifugal force of inertia is known to be found by the expression:

$$F_{cf} = m \cdot \omega^2 \cdot R, \tag{26}$$

The particle speed will decrease when it is distanced from the surface of the screw casing. For particles located in the granular mass distant from the working surface, we introduce a linear velocity reduction factor for the particle:

$$k_V = \frac{V_i}{V_1} \tag{27}$$

where V_1 is the linear velocity of a particle located in the layer of the granular mass being directly in contact with the cylindrical surface of the casing;

V_i is the linear velocity of the i-th particle located in the subsequent layers.

The linear velocity reduction factor of the particle functionally depends on the physical and mechanical properties of the conveyed seed material and the geometric parameters of the screw.

By changing formula (30) based on equation (27) and accepting that the linear velocity of the particle is proportional to the angular velocity of the screw rotation, we obtain:

$$F_{cf} = \frac{m \cdot (V_1 \cdot k_V)^2}{R} \tag{28}$$

where R is the maximum rotation radius of the particle equal to half the casing diameter.

When seeds are transported in the screw device, they incur damage by being stuck between the screw surface and flights. Studies conducted by scholars of the Voronezh State Agrarian University named after Emperor Peter I showed that significant crushing of seeds (over 3.6%), exemplified by winter wheat Moskovskaya 39, occurs when the clearance between the screw and the casing wall is no more than 10 mm [12]. The researchers explain this by seed jamming between the casing and flights and recommend a clearance of at least 10 mm.

The occurrence of seed jamming can be reduced not only by a larger clearance but also by the high-speed operation of the screw device. When the critical angular velocity is reached, the particles of the granular material will move as one with the rotating screw casing. The angular velocity of the screw casing will reach a critical value ω_{cr} if the gravity force of the granular material and the

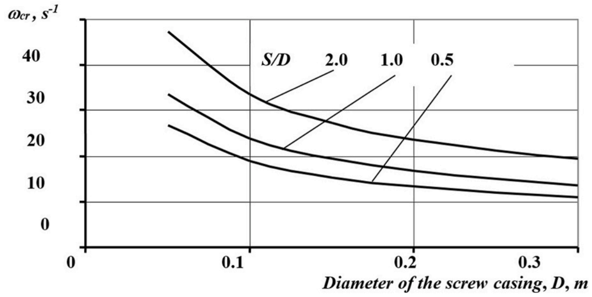

Fig. 5. Dependence of the critical angular velocity of the screw rotation on the geometric parameters of the device.
Source: author's development

centrifugal force of inertia are equal: $mg = F_{cf} = m \cdot \omega_{cr}^2 \cdot R \cdot k_V^2$.

From where we get an equation for determining the critical angular rotation velocity of the screw device casing:

$$\omega_{\lim} = \frac{\sqrt{g/R}}{k_V} \tag{29}$$

The dependence (29) shows that the value of the critical angular velocity of the screw decreases with the higher screw casing radius R and the circumferential velocity reduction factor k_V.

3. Results

Fig. 5 shows dependence graphs of the critical angular velocity on the screw diameter *D* and the ratio of the screw pitch to its diameter *S/D.* The graph analysis illustrates that the value of the critical angular velocity decreases with the higher screw diameter and the lower *S/D* ratio. Therefore, it is advisable to use screws with a larger pitch to increase the working angular velocity of the screw without exceeding its threshold.

The reduction of the maximum operating value of the angular velocities of the screw ω_{scr} occurs when mixing components that have a greater value of the friction angles of the particles against the screw casing. Fig. 6 shows the dependencies of the friction angles of the seed material on the casing of the steel screw. The graphs of Fig. 6 demonstrate that in the seed material processing with a friction angle $\varphi = 0.7$, the critical angular velocity decreased by an average of 8 … 12% while conveying particles with a friction angle $\varphi = 0.3$, the value of the critical angular velocity increased.

Hence, to reduce seed damage when using a screw device, it is necessary to adhere to the condition: $\omega \le \omega_{lim}$.

When designing screw devices, it is essential to take into account that their productive operation is possible when the angular speed of the screw rotation does not significantly differ from the critical velocity. It is possible to diminish the destruction of the seed material due to impact interaction with the working surface of the screw by reducing the inclination angle of the screw flight $\boldsymbol{\alpha}$, the angular speed of the screw rotation ω and its radius R. It also requires direct the seed flow closer to the rotation center.

Less particle impact on the inclined surface of the screw can be ensured by keeping the seed flow closer to the screw rotation center and using highly elastic polyurethane materials for screw manufacture. The potential energy accumulated by the particle largely depends on the properties of the reflecting surface. Substituting the steel screw belt with elastomer-based belt results in a notable reduction of the potential energy accumulated by the particle. As a result, seed damage is lowered, providing more variations for the kinematic and geometric parameters of the screw conveyor. The replacement of steel screws with polyurethane ones will allow varying the kinematic and geometric parameters of the screw conveyor in a wider range.

4. Discussion

Seed treatment before sowing is necessary and undeniable. It is an important and integral component of farming practices. One of the most commonly used methods of seed treatment is dressing the seed material with chemicals. A previous computerized analysis of the soybean germination efficiency after chemical treatment revealed the phytotoxicity of chemical dressing reducing the physiological characteristics of soybean seeds [2,24]. The findings of a group of scientists have shown that seeds with a higher rate of mechanical damage are more susceptible to phytotoxic effects resulting from pre-sowing chemical treatment [18].

The harmful impact of the working bodies of machines on seed viability and quality has been a question of great interest for many investigators around the world. Damage to the seed material occurs during mechanical interaction between biological material (seeds) and the working bodies of agricultural machines – steel, rubber and other materials [4,18]. Most authors admit that seed damage takes place mainly during harvesting and transportation when seeds are exposed to the periodic effects of working bodies [4,13,18]. Injury to seeds due to impact depends on a number of factors, such as the impact velocity, the granulometric composition of the seed, the physico-mechanical properties, the seed moisture content, the ripeness stage and the settings accuracy of a particular working unit of the machine [16,17,25].

Among the above factors, the seed moisture content and impact interaction are important causes of seed damage. Some scholars

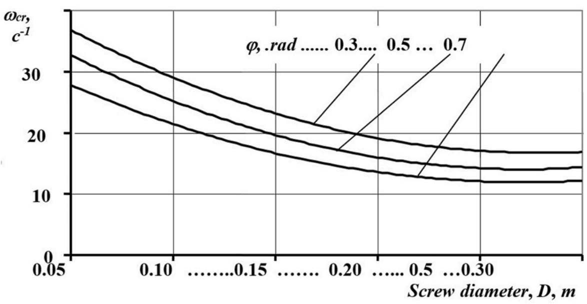

Fig. 6. The effect of friction angles on the critical angular velocity of the screw.
Source: author's development

investigated the impact velocity and the moisture content at the impact interaction and found that seed damage increases notably as the moisture content reduces since the impact energy rises [17–19]. Researchers utilize different equipment and devices to assess seed damage during impact and simulate real loads [5,19].

The impact on seeds during their treatment is rather complex making it difficult to provide precise control and regulation of mechanized processes. In this context, the implementation of automated control and adjustment mechanisms within the developed mechanized systems, aimed at facilitating seed preparation for both sowing and harvesting processes, is advocated [13]. Automatic control of mechanized processes has been discussed by F. Shahbazi and R. Shahbazi [17]. Their theoretical calculations and experimental data provide a larger-scale model for predicting the actual operation of a mechanical system and assessing the impact of a number of independent variables on several dependent indicators in corn seed treatment. The scholars assessed the impact damage of corn seeds and determined the impact of the working bodies of mechanical devices and the moisture content of the seed material on seed damage. An empirical model has been developed describing the relationship between the percentage of mechanical damage to Pinto bean seeds under shock load at different moisture content. The researchers found that an increase in the impact energy from 0.1 to 0.3 J caused an increase in the average percentage of physical damage to seeds from 23.73 to 83.49% [19]. Their findings showed that the impact on bean seeds is higher at the lower moisture content. The researchers assert that to mitigate mechanical harm to corn seeds the impact energy should be limited to a maximum of 0.1 J. As the moisture content increased from 7.60 to 20%, the average value of seed damage decreased by 1.92 times. Thus, at the moisture content of 7.6%, seed injury increased from 60.79 to 100% with higher impact energy from 0.1 to 0.3 J. Scientists have determined the optimal moisture content at which impact damage to seeds is minimal, amounting to about 17–20% [19].

Studies of soybean damage from mechanical action [24] have demonstrated the importance of determining mechanical damage before seed treatment. It has conclusively been shown that [26] damaged soybean seeds are more susceptible to coat filing when exposed to large doses of the sprayed preparation. As a result, the physiological parameters of the seeds decrease.

Collectively, all the investigators indicate the scientific and practical significance of studies on seed material damage by working bodies of machines. This study has presented theoretical dependences aimed at obtaining new knowledge. They can explain the common mechanism of the traumatic effect of screw working surfaces on loose particles without isolating any particular seed variety and type. The findings of this study can be used in developing technical devices with screw working bodies for processing and transporting seed material.

5. Conclusions

Seed damage by screw working bodies can reach from 17 to 50.0% of the total amount of the seed material due to the impact interaction of seeds with the screw working surface and the friction of the seed material on the working surface when moving in the working area of the technical device. The seed interaction with the working surface of the screw results in an impact. The potential energy accumulated after impact by the reflecting surface and seeds depends on the magnitude and direction of the falling velocity to the screw belt, the screw geometric and kinematic parameters (the screw diameter; the inclination angle of the helix to the screw axis and the angular velocity), as well as the physical and mechanical properties of the particle and the reflecting surface (recovery and friction coefficients).

To reduce the friction, it is necessary to increase the critical speed limit at which free mixing of the seed material slows down while seed resistance on the work surface increases. Previous studies have shown that the critical angular velocity of the screw flight depends on the screw casing radius and the reduction factor of the circumferential velocity. In turn, the reduction factor depends on the physical and mechanical properties of the seed material and the geometric parameters of the screw.

To reduce injury to the seed material, it is necessary to increase the critical angular velocity limit of the screw relative to the working surface of the casing, at which the action of centrifugal forces does not adversely affect the quality of mixing, and also to produce screws with a large winding step using highly elastic polymer materials.

The obtained theoretical dependencies can be used in designing different mechanical devices with screw working bodies for different seed varieties and types. They can help to develop and produce screws with minimal traumatic effects without reducing the viability of seeds.

Author contribution statement

Mayya Sukhanova: Performed the experiments; Analyzed and interpreted the data. Eduard Khasanov: Conceived and designed the experiments; Wrote the paper. Alexander Butenko: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data. Shamil Fayzrakhmanov: Performed the experiments; Wrote the paper. Rinat Fayzullin: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Data availability statement

Data will be made available on request.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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