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INVESTIGATION OF SEED MOVEMENT IN THE DISTRIBUTOR OF A PRECISION SEEDER FOR SMALL-SEEDED CROPS

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This article presents the results of theoretical and experimental studies on the sowing process of small-seeded crops using a selective seeder equipped with an electromechanical sowing apparatus with adjustable structural parameters. Particular attention is given to improving the uniformity of seed distribution in the flow, which is critical in breeding seed production where accuracy and consistency of sowing directly affect the quality of field research and the reliability of breeding outcomes.

The study employs a comprehensive approach that includes numerical modeling of seed flow in the STAR-CCM+ software environment, analytical substantiation of the influence of the guiding surface inclination angle β and divergence angle γ on the throughput of the apparatus, as well as experimental verification of the obtained data. As a result, second-order two-factor regression models were constructed to assess the dependence of the variation coefficient of throughput capacity on changes in the structural parameters of the sowing apparatus.

The proposed technical solutions reduce the coefficient of variation to minimal values, ensuring high accuracy and uniformity of seed delivery into the sowing channels. This, in turn, improves early plant development, reduces interplant competition, and enhances the efficiency of using breeding material. The research findings have practical significance for improving the design of seeders intended for research and breeding purposes and can be implemented in the operations of agricultural research institutions.

Additionally, the research identifies the optimal operating parameters of the electromechanical sowing apparatus that ensure stable seed flow under varying vibration conditions and seed sizes typical for small-seeded crops. The results of parametric optimization indicate that adjusting the rotor speed and the amplitude of oscillation of the guiding surface allows maintaining a consistent seed trajectory and minimizing losses during dosing. The implementation of the developed model in experimental prototypes demonstrated improvement in the uniformity of seed distribution compared to conventional mechanical systems, confirming the efficiency of the proposed design solutions for high-precision sowing technologies.

Key words: *small-seeded crops, selective seeder, electromechanical sowing apparatus, seed distribution uniformity, STAR-CCM+, structural parameters, regression model, coefficient of variation, even distribution in the furrow, sowing accuracy.*

Eq. 6. Fig. 6. Table. 3. Ref. 12.

1. Problem formulation

In modern breeding production of small-seeded crops, sowing accuracy plays a crucial role, especially during variety trials and the initial stages of multiplication of new cultivars. The uniform placement of seeds in the soil significantly influences the further development of plants, their competitiveness, and ultimately, yield. One of the key components of a seeder that determines the quality of crop formation is the seed metering device. Its design and operating principle largely affect the uniformity of dosing and seed delivery to the furrow.

Sowing small-seeded crops presents a particular challenge due to the seeds' low mass, tendency to clump together, and inconsistency in shape and size. These factors complicate controlled dosing and uniform distribution. Electromechanical seeders, which are widely used in breeding practice and offer several advantages, still often fail to ensure sufficient uniformity of sowing along the row. As a result, areas of both excessive and insufficient plant density can occur within the rows, negatively affecting the objectivity of breeding research outcomes.

The reasons for such unevenness are often associated with random processes that occur during seed movement inside the metering device, especially at the stage when the seeds pass through the distributor. Modern analytical methods describing seed movement mechanics typically require solving complex systems of differential equations, which complicates their practical application. Therefore, numerical modeling becomes a relevant and effective tool for studying and improving the processes of seed dosing and transportation.

Thus, there is a need for scientific justification of the design parameters of the guiding elements within the distributor of a breeding seeder's metering unit. These parameters must be analyzed in terms of their influence on throughput capacity and the uniformity of small-seeded crop distribution. Improving this aspect will contribute to enhanced sowing precision and, consequently, the quality of crop stands in the breeding process.

2. Analysis of recent research and publications

Recently, there has been a significant increase in interest regarding the sowing process in the seed production of small-seeded crops within breeding programs. This is due to the importance of obtaining high-quality crops at the initial stages of research and the preliminary propagation of new varieties and hybrids of small-seeded crops [4].

The seed metering device is one of the most critical working units of a seeder. It functions to select a specific quantity of seeds from the total mass and to form an output seed flow with defined parameters [5]. Therefore, the advantages and disadvantages of seeders in terms of seed distribution quality along the row and across the sown field are primarily determined by the performance of the seed metering devices.

Electromechanical seeders have become widely used for sowing small-seeded crops on variety testing plots and in the preliminary propagation stages [8]. However, a key issue in their application is the insufficient uniformity in seed distribution along the row, caused by random processes occurring during sowing. This results in uneven crops – with clusters or sparse areas of plants in the row – ultimately leading to a decrease in the yield of breeding-valuable small-seeded crops.

The sowing process for small-seeded crops using electromechanical metering devices involves dosing and transporting the seeds to the seed tube [8]. In most designs, seeds are discharged into the hopper of the metering device, where they form, from a mathematical perspective, a random packing. Then, using a shutter through the resulting dosing openings, the seeds enter the distributor and are transported to the seed tube. Given these considerations, the research was aimed at developing a model of the random packing of small-seeded crop seeds within the hopper of a breeding seeder’s metering device.

Modern theoretical studies of the mechanical-technological processes of seed movement under the influence of technical implement components rely on analytical methods. These methods lead to the formulation of complex systems of differential equations with boundary and initial conditions [2]. Such systems are practically unsolvable by traditional means, necessitating the use of numerical solutions through computer modeling.

In light of the above, research aimed at improving the seed dosing process of breeding seeders’ metering devices holds significant scientific and practical value.

The objective of the research is to increase the accuracy of seed sowing by a breeding seeder for small-seeded crops through numerical modeling of seed movement within the metering device distributor.

3. The purpose of the article

The purpose of the article is to improve the accuracy and uniformity of sowing small-seeded crops by optimizing the design and operating parameters of the electromechanical sowing apparatus through analytical modeling, numerical simulation, and experimental verification.

4. Results and discussion

The guide in the distributor of the metering unit of the breeding seeder is designed as a chute along which the seeds move (Fig. 1) [8]. The main objective of the analytical research is to determine the inclination angle β and the divergence angle γ (the angle between two opposite generatrices of the guide – the apex angle of the guide) at which the throughput capacity of the breeding seeder's metering unit Q_d` is uniform, that is, when the deviation $\Delta(Q_d`)$ is minimized.

$$\Delta(Q_d`) = \frac{\sigma(Q_d`)}{\overline{Q_d`}}, \quad (1)$$

where $\Delta(Q_d`)$ – coefficient of variation of the throughput capacity of the breeding seeder's metering unit $Q_d$`; $\sigma(Q_d`)$ – standard deviation of the throughput capacity of the breeding seeder's metering unit $Q_d$`, seeds/s; $\overline{Q_d`}$ – mean value of the throughput capacity of the breeding seeder's metering unit $Q_d$`, seeds/s.

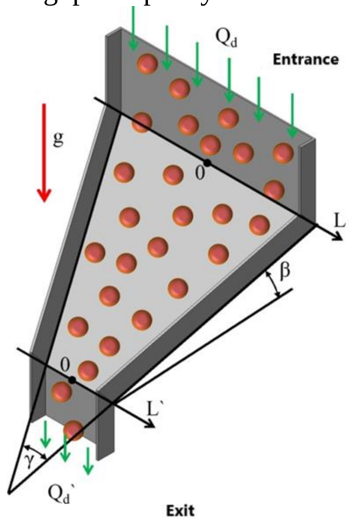

Fig. 1. Scheme of research of seed movement in the distributor of the sowing apparatus of the small-seeded crop selection seeder

The study of seed movement in the distributor of the sowing machine was carried out using numerical modeling methods in the STAR-CCM+ software package [6, 8, 11]. The research factors and their levels are presented in Table 1. The smallest value of the angles was chosen taking into account that the seeds should move along the inclined plane without forming clumps, i.e. $\beta_{min} = \gamma_{min}$ = arctg(k) = arctg(0,58) = 0,525 (where k is the coefficient of friction of the seed at rest on the surface of the guide). The number of repetitions is 3. The research plan is a full-factorial design with a total number of experiments – $3^3 = 27$.

The visualization of the results of numerical modeling is presented in Figures 2-4, the analysis of which suggests a decrease in the average throughput of the sowing machine Q_d` compared to the throughput of the metering unit $Q_d$ and an increase in its uniformity due to a decrease in the coefficient of variation $\Delta(Q_d`)$. The numerical data of the research results are given in Table 1.

Table 1

Factors, levels and results of research on seed movement in the distributor of the sowing apparatus of a small-seeded seeder

№	Dosing capacity Q_d, pcs/s	Angle γ	Tilt angle β	Throughput of the sowing machine Q_d`				Coefficient of variation of the throughput of the sowing machine $\Delta(Q_d`)$			
				1	2	3	Ave.	1	2	3	Ave.
1	20	0,524	0,524	7,9	7,9	7,4	7,7	0,61	0,58	0,57	0,59
2	20	0,524	0,785	13,4	13,3	12,5	13,1	0,67	0,60	0,60	0,62
3	20	0,524	1,047	15,7	15,9	15,3	15,6	0,84	0,79	0,81	0,81
4	20	0,785	0,524	9,4	9,6	8,7	9,2	0,65	0,58	0,59	0,61
5	20	0,785	0,785	15,0	14,8	14,2	14,7	0,71	0,62	0,66	0,66
6	20	0,785	1,047	17,7	17,0	16,8	17,2	0,91	0,85	0,85	0,87
7	20	1,047	0,524	10,1	9,9	9,5	9,8	0,74	0,68	0,70	0,71
8	20	1,047	0,785	15,3	15,2	14,4	15,0	0,78	0,71	0,71	0,73
9	20	1,047	1,047	18,1	17,9	17,1	17,7	0,98	0,89	0,91	0,93
10	60	0,524	0,524	23,6	23,4	22,7	23,2	0,63	0,57	0,56	0,59
11	60	0,524	0,785	38,9	38,9	38,3	38,7	0,65	0,62	0,60	0,62
12	60	0,524	1,047	47,3	46,8	46,3	46,8	0,88	0,80	0,81	0,83

13	60	0,785	0,524	28,0	27,4	27,0	27,5	0,67	0,62	0,60	0,63
14	60	0,785	0,785	43,4	43,3	42,6	43,1	0,70	0,63	0,64	0,66
15	60	0,785	1,047	51,5	50,8	50,6	51,0	0,91	0,85	0,85	0,87
16	60	1,047	0,524	29,3	29,2	28,6	29,0	0,74	0,67	0,69	0,70
17	60	1,047	0,785	44,7	44,5	44,2	44,5	0,77	0,74	0,73	0,75
18	60	1,047	1,047	52,7	52,5	52,1	52,4	0,97	0,91	0,93	0,94
19	100	0,524	0,524	39,2	38,6	38,2	38,7	0,64	0,59	0,57	0,60
20	100	0,524	0,785	64,8	64,7	64,4	64,6	0,66	0,62	0,63	0,64
21	100	0,524	1,047	78,2	77,8	77,2	77,7	0,87	0,80	0,80	0,82
22	100	0,785	0,524	46,3	45,9	45,4	45,9	0,68	0,59	0,62	0,63
23	100	0,785	0,785	71,8	72,0	71,4	71,7	0,69	0,62	0,66	0,66
24	100	0,785	1,047	85,2	85,0	84,4	84,9	0,90	0,81	0,85	0,85
25	100	1,047	0,524	48,2	48,3	47,8	48,1	0,72	0,68	0,69	0,70
26	100	1,047	0,785	74,8	74,1	73,9	74,3	0,80	0,74	0,74	0,76
27	100	1,047	1,047	87,3	87,1	86,7	87,0	0,96	0,93	0,91	0,93

Using the Wolfram Mathematica software package, the second-order regression equations for the throughput of the sowing machine Q_d` were obtained in coded form:

$$Q_d` = 43{,}1321 + 26{,}2741\ x_1 + 0{,}0259259\ x_1^2 + 2{,}87099\ x_2 + 1{,}85926\ x_1 x_2 - 1{,}4537\ x_2^2 + 11{,}7327\ x_3 + 7{,}77593\ x_1 x_3 - 0{,}0277778\ x_2 x_3 - 3{,}87593\ x_3^2. \quad (2)$$

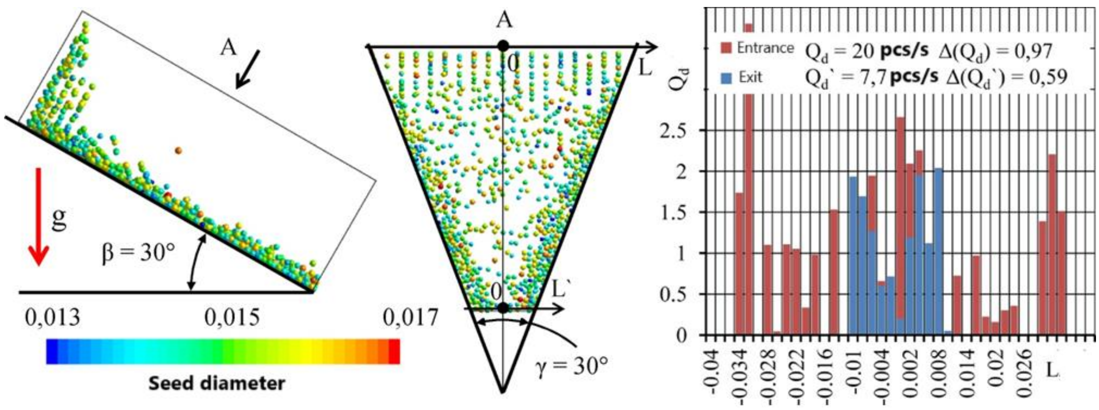

Fig. 2. Visualization of the results of numerical modeling of experiment № 1 (Table 1)

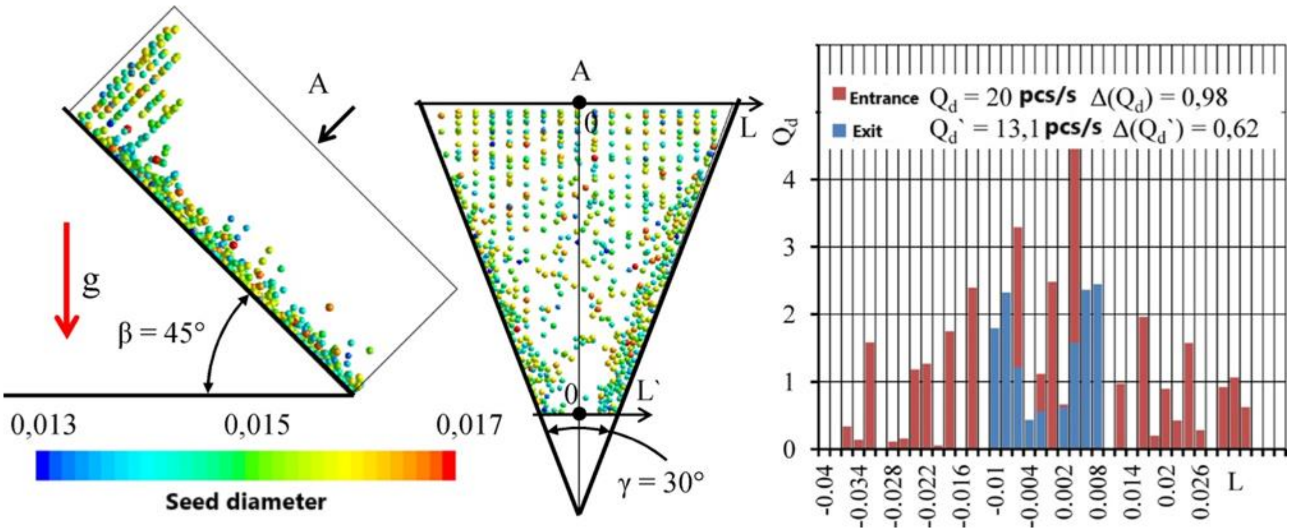

Fig. 3. Visualization of the results of numerical modeling of experiment № 2 (Table 1)

Statistical processing of Equation (2) is presented in Table 2. Taking into account the tabulated value of Student's t-test t(0.05;54) = 2.00, the insignificant coefficients were eliminated, resulting in the following equation for the throughput capacity of the seed metering device Q_d` in the decoded form (Fig. 5):

$$Q_d` = –44{,}5759 – 0{,}0648676\ Q_d + 33{,}5619\ \beta + 0{,}17741\ Q_d\ \beta – \\ – 21{,}1774\ \beta^2 + 88{,}9114\ \gamma + 0{,}741978\ Q_d\ \gamma –56{,}4642\ \gamma^2. \quad (3)$$

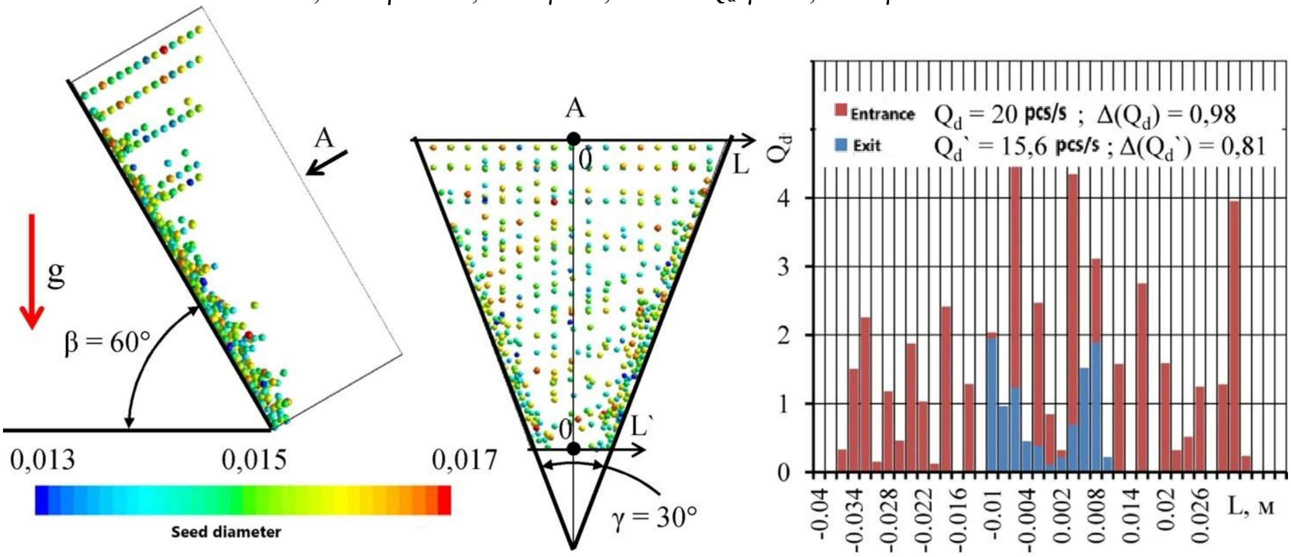

Fig. 4. Visualization of the results of numerical simulation of experiment № 3 (Table 1)

Table 2

Statistical processing of Equation (2)

Coefficient	Significance	Student's t test
a_{00}	43,1321	63,3971
a_{10}	26,2741	83,4256
a_{20}	2,87099	9,11598
a_{30}	11,7327	37,2538
a_{12}	1,85926	4,82021
a_{13}	7,77593	20,1594
a_{23}	– 0,0277778	– 0,0720152
a_{11}	0,0259259	0,0475276
a_{22}	– 1,4537	– 2,66494
a_{33}	– 3,87593	– 7,10537

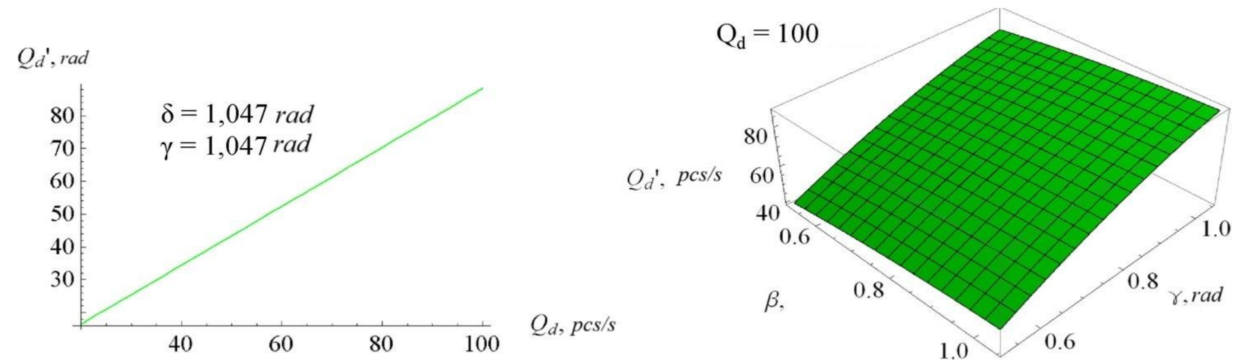

Fig. 5. Dependence of the throughput capacity of the seed metering device Q_d`on the throughput capacity of the dispenser Q_d, solution angle γ, and inclination angle β

Analysis of Fig. 5 shows that as the throughput capacity of the dispenser Q_d, the solution angle γ, and the inclination angle β increase, the throughput capacity of the seed metering device Q_d` also increases. Using the Wolfram Mathematica software package, second-order regression equations were obtained for the coefficient of variation of the throughput capacity of the seed metering device Δ($Q_d$`) in the coded form:

$$\Delta(Q_d`) = 0{,}664815 + 0{,}00333333\ x_1 – 0{,}00222222\ x_1^2 + 0{,}0564815\ x_2 – \quad (4)$$

$$– 0,00111111\ x_1 x_2 + 0,0216667\ x_2^2 + 0,117407\ x_3 –$$
$$– 0,00222222\ x_1 x_3 + 9,61481 \cdot 10^{-17}\ x_2 x_3 + 0,0777778\ x_3^2.$$

Statistical processing of Equation (4) is presented in Table 3. Taking into account the tabulated value of Student's t(0,05;54) = 2,00, the insignificant coefficients were eliminated, yielding the equation for the coefficient of variation of the throughput capacity of the seed metering device $\Delta(Q_d`)$ in the decoded form (Fig. 6):

$$\Delta(Q_d`) = 1,03654 – 0,279974\ \beta + 0,315638\ \beta^2 – 1,33078\ \gamma + 1,13306\ \gamma^2. \quad (5)$$

Table 3

Statistical processing of Equation (4)

Coefficient	Significance	Student's t test
a_{00}	0,664815	141,526
a_{10}	0,00333333	1,53292
a_{20}	0,0564815	25,9744
a_{30}	0,117407	53,9927
a_{12}	– 0,00111111	-0,417207
a_{13}	– 0,00222222	-0,834413
a_{23}	$9,61481 \cdot 10^{-17}$	$3,61023 \cdot 10^{-14}$
a_{11}	– 0,00222222	– 0,590019
a_{22}	0,0216667	5,75269
a_{33}	0,0777778	20,6507

Analysis of Fig. 5 shows that with an increase in the solution angle γ\gammaγ and the inclination angle β, the coefficient of variation of the throughput capacity of the seed metering device $\Delta(Q_d`)$ increases. The throughput capacity of the dispenser $Q_d$ does not affect $\Delta(Q_d`)$.

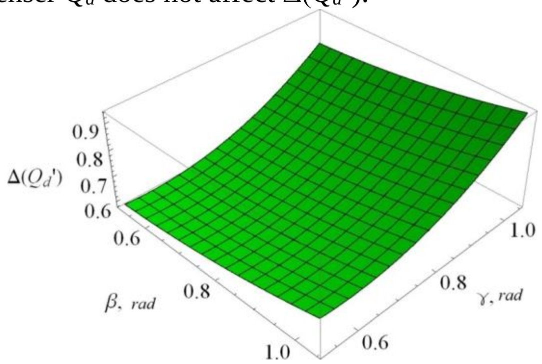

Fig. 6. Dependence of the coefficient of variation of the throughput capacity of the seed metering device $\Delta(Q_d`)$ on the solution angle γ and the inclination angle β

Analyzing the obtained dependencies, we conclude that to ensure the optimal parameters of the proposed guide in the seed metering device distributor, the coefficient of variation of the throughput capacity of the seed metering device $\Delta(Q_d`)$ should be minimized, while the throughput capacity of the seed metering device $Q_d`$ should be maximized:

$$\begin{cases} \Delta(Q_d`) \to \min, \\ Q_d` \to \max, \\ 20 \le Q_d \le 100, \\ 0,524 \le \beta \le 1,047, \\ 0,524 \le \gamma \le 1,047. \end{cases} \quad (6)$$

Solving the system of Equations (6) together with (6) and (5) yields, for any Q_d: β= (42°), γ=0.785 (45°). At these values, the coefficient of variation of the throughput capacity of the seed metering device $\Delta(Q_d`)$ = 0,65, which is 1.5 times higher than the coefficient of variation of the throughput capacity of the dispenser $\Delta(Q_d)$. This allows us to assert an improvement in the sowing accuracy of the developed seed metering device.

5. Conclusion

To achieve even higher sowing accuracy, it is necessary to install a seed guide in the distributor, which represents a chute along which the seeds move.

Based on the results of numerical modeling of seed movement in the distributor of the seed metering device of a precision seeder for small-seeded crops, dependencies of the throughput capacity of the seed metering device Q_d` and the coefficient of variation of the throughput capacity $\Delta(Q_d`)$ on the throughput capacity of the dispenser Q_d, the solution angle γ\gammaγ, and the inclination angle β were obtained.

Analysis of these dependencies showed that, to ensure optimal parameters of the proposed guide in the distributor of the seed metering device, the coefficient of variation of the throughput capacity $\Delta(Q_d`)$ should be minimized, while the throughput capacity $Q_d`$ should be maximized. Solving the system of Equations (6) together with (3) and (5) provided, for any Q_d: the values β = 0.7328 (42°) and γ = 0.785 (45°). At these values, the coefficient of variation of the throughput capacity $\Delta(Q_d`)$ is 0.65, which is 1.5 times higher than the coefficient of variation of the throughput capacity of the dispenser $\Delta(Q_d)$. This confirms an improvement in the sowing accuracy of the developed seed metering device.

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ДОСЛІДЖЕННЯ РУХУ НАСІННЯ У РОЗПОДІЛЬНИКУ СІВАЛКИ ТОЧНОГО ВИСІВУ ДЛЯ ДРІБНОНАСІННЄВИХ КУЛЬТУР

У статті представлено результати теоретичних і експериментальних досліджень процесу висіву дрібнонасіннєвих культур із використанням селекційної сівалки, обладнаної електромеханічним висівним апаратом із регульованими конструктивними параметрами. Особливу увагу приділено підвищенню рівномірності розподілу насіння у потоці, що є критично важливим у селекційному насінництві, де точність і стабільність висіву безпосередньо впливають на якість польових досліджень і достовірність селекційних результатів.

У дослідженні застосовано комплексний підхід, який включає чисельне моделювання руху насіння в середовищі програмного забезпечення *STAR-CCM+*, аналітичне обґрунтування впливу кута нахилу напрямної поверхні β та кута розходження γ на пропускну здатність апарата, а також експериментальну перевірку отриманих даних. У результаті побудовано двофакторні регресійні моделі другого порядку для оцінювання залежності коефіцієнта варіації пропускної здатності від зміни конструктивних параметрів висівного апарата.

Запропоновані технічні рішення дають змогу зменшити коефіцієнт варіації до мінімальних значень, забезпечуючи високу точність і рівномірність подачі насіння у висівні канали. Це, у свою чергу, покращує початковий розвиток рослин, знижує конкуренцію між ними та підвищує ефективність використання селекційного матеріалу. Результати досліджень мають практичне значення для вдосконалення конструкції сівалок, призначених для науково-дослідних і селекційних цілей, та можуть бути впроваджені у діяльність аграрних наукових установ.

Крім того, у роботі визначено оптимальні режими роботи електромеханічного висівного апарата, що забезпечують стабільний рух насіння за різних умов вібрації та розмірів насіння, характерних для дрібнонасіннєвих культур. Результати параметричної оптимізації показали, що регулювання частоти обертання ротора та амплітуди коливань напрямної поверхні дозволяє підтримувати сталу траєкторію руху насіння та мінімізувати втрати під час дозування. Впровадження розробленої моделі в експериментальні зразки показало покращення рівномірності розподілу насіння порівняно з традиційними механічними системами, що підтвердило ефективність запропонованих конструктивних рішень для високоточного висіву.

Ключові слова: дрібнонасіннєві культури, селекційна сівалка, електромеханічний висівний апарат, рівномірність розподілу насіння, STAR-CCM+, конструктивні параметри, регресійна модель, коефіцієнт варіації, рівномірний розподіл у борозні, точність висіву.

Ф. 6. Рис. 6. Табл. 3. Літ. 12.

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