Theoretical Studies of Design Parameters of Machine Elements for Surface Planting of Rice

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Abstract. The paper presents the definition of the main parameters and operating modes of spreading centrifugal devices of technical means when using them in the surface planting technology. It has been determined analytically and experimentally that under the existing operating modes of centrifugal apparatus, in order to reduce reflection, grooved blades should be used, the upper planes of which are tilted from the horizontal position by an angle of 5-10 °, the angle of the blades should be $\leq 15^\circ$. According to the results of theoretical and experimental studies, a prototype was made, the productivity of which when sowing rice in comparison with serial machines increased by 1.5 times with an uneven distribution over the working width not exceeding 15%.

The Krasnodar Territory is the main rice-producing region in Russia. Kuban annually produces more than 80% of the rice produced in the country. Rice is one of the high-yielding grain crops and with the use of modern technologies, its yield can be 7–8 t/ha and reach up to 10 t/ha. A significant drawback in rice production is planting. This is due to the fact that the rice planting process has specific features and differs significantly from planting grain crops [1, 2].

At present, rice planting can be done by the surface method and by the row method.

The advantage of rice cultivation technology with surface planting is that regardless of climatic conditions, this technology is applicable in any zone of the region. Surface planting of rice leads to a significant reduction in the planting time, which is reflected in the rice maturation. Labor costs are reduced by 4.5 people h/ha compared to the basic technology of row planting [3].

A disadvantage of surface planting is violation of agricultural requirements for this operation, which consists of failure to ensure the distribution uniformity of seeds over the entire working width, which is reflected in the increased consumption of seed, uneven planting, and a decrease in the yield of the main product. The identified shortcomings lead to the need to study and determine the main parameters and operating modes of spreading centrifugal devices for further development of technical means when using them in technology with surface planting [4].

The main parameters of the centrifugal device of the machine for surface planting, with the help of which it is possible to most effectively influence seed distribution across the working width, are the spreading angle and the uniformity of distribution. In order to obtain

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a uniform distribution over the spreader's working width, it is necessary to adjust the centrifugal apparatus for the optimal distribution of the seed along the spreading angle, taking into account other parameters of the distribution zone.

However, for this it is necessary to establish a connection between the distribution of seeds according to the angle of spreading and their distribution at the feeding place on the disc. The solution to this problem is complicated by the fact that in addition to the particles of seeds flying off the ends of the blades under the action of the centrifugal force, some of them are reflected by the working body, that is, the so-called disordered flying occurs [5, 6].

When studying the reflection of fertilizers, let us consider the process of interaction of the seed with the blade of the centrifugal disc, taking into account friction forces acting at the point of contact. The forward speed of the spreader, due to its low value in comparison with the peripheral speed of the centrifugal disc, was neglected.

At the moment when the particle meets the blade, an oblique, not quite elastic impact occurs. The flight range of the reflected particle will depend on its velocity $\vec{U}$ after the impact and angle μ between the vector of this velocity and the horizon (Figure 1).

Fig. 1. Scheme of velocities and forces acting on a particle at the moment of impact

According to Newton's hypothesis, the normal components of the particle velocity before ($\vec{V}_n$) and after ($\vec{U}_n$) the impact are related by the ratio: $(\vec{V}_n) (\vec{U}_n)$:

$$\vec{U}_n = -k_b \vec{V}_n, \tag{1}$$

where k_b – recovery factor.

The tangential component $\vec{U}_t$ of the particle velocity after impact is influenced by the friction force $\vec{F}_{tp}$. If $\vec{F}_{tp} \approx 0$, then $U_t \approx V_t$. If $\vec{F}_{tp} \neq 0$ and during the entire impact time the particle slides along the reflecting surface, then the following relation holds: $U_t \tau F_t$:

$$S_t = f S_n, \tag{2}$$

where S_t, S_n – tangential and normal components of the shock impulse $\vec{S}$;
 f – friction coefficient.

In this case:

$$U_t = V_t - V_n f (V_b + 1), \tag{3}$$

And velocity module U of the particle after the impact and angle μ are determined by the following formulas:

$$U = \sqrt{k_{\text{B}}^2 (V_e \cos i + V_a \sin i)^2 + [(V_e \sin i - V_a \cos i) - f(k_{\text{B}} + 1)(V_e \cos i + V_a \sin i)]^2}, \quad (4)$$

$$\mu = i + \arctg \left[\frac{V_e \sin i - V_a \cos i}{V_e \sin i + V_a \cos i} + f(k_B + 1) \right], \quad (5)$$

where V_ϕ – peripheral speed, points of contact of the blade, m/s;

V_a – absolute particle velocity before impact, m/s;

i – angle between the reflecting surface and the y-axis.

If at some moment of impact, the sliding of the particle on the reflecting surface stops, then the end of the vector $\vec{S}$ of the shock pulse will move from the generatrix MK (Figure 2) of the friction cone to straight line KL of zero slip (according to Routh), determined by the equation:

$$S_\tau + \frac{2}{7}mV_\tau = 0, \quad (6)$$

Fig. 2. Change graph of shock impulse $\vec{S}$

In this case U_T and V_T are related by the ratio:

$$U_\tau = \frac{5}{7}V_\tau, \quad (7)$$

And U and μ are determined by the formulas:

$$U = \sqrt{k_{\text{R}}^2 (V_e \cos i + V_a \sin i)^2 + 0,51 (V_e \sin i - V_a \cos i)^2}, \quad (8)$$

$$\mu = i + \arctan \frac{5}{7k_R} \frac{V_e \sin i - V_a \cos i}{V_e \cos i + V_a \sin i}, \quad (9)$$

An experimental verification of this part of the theoretical study was carried out by comparing the calculated angles μ with the actual ones obtained as a result of processing photoprints of particle flight trajectories before and after reflection. The difference in all considered cases did not exceed 5° .

The calculations using the obtained formulas (4), (5), (8), (9) and the experiments have shown that the flight range of reflected seed particles is, on average, 3 times less than the flight range of particles flying off the disk under the action of the centrifugal force, as a result, the working width decreases and the quality of the spreader's work deteriorates.

As a result of the experiments, it was found that particles were reflected mainly by the upper edges of the blades of the centrifugal apparatus. The mass fraction of seeds reflected by the upper edges of the blades of serial spreaders is from 10 to 40% and depends on the

speed of the seeds fed to the disc, speed of the disc rotation, number of blades, size and shape of their upper edges.

It was determined analytically and experimentally that in the existing operating modes of centrifugal apparatus, in order to reduce reflection, grooved blades should be used, the upper planes of which are deviated from the horizontal position by an angle of 5-10 °, the angle of the blades should be $\leq 15^\circ$. At such a tapering angle of the blades, the proportion of reflected fertilizers is 3% or less.

The setting of the centrifugal apparatus for the optimal distribution of seeds along the spreading angle is simplified in the case when the seeds supplied to the disc are picked up by the blades on the fly. To ensure this condition, the design parameters and operating modes of the centrifugal apparatus must satisfy the inequality:

$$z \geq \frac{V_n + \sqrt{V_n^2 + 2gh}}{2nh}, \quad (10)$$

where z – number of blades per disc;

V_n – seed flow velocity when meeting with disc blades, m/s;

h – height of the blades, m;

n – disk rotation frequency, s^{-1} ;

g – free fall acceleration, m/s^2 .

The seed flow rate V_n was determined on the basis of experimental data as follows. An impeller was installed on the flow path, the rotation frequency of which could be smoothly changed. The length of the impeller blades was chosen so that the flow of seeds was completely crossed. By smoothly changing the impeller rotation frequency, the one at which fertilizers stopped slipping into the space between the blades was chosen. Substituting the obtained result into the formula, the seed flow rate in the area of the impeller installation was calculated:

$$V_n = hnz - \frac{g}{2nz}, \quad (11)$$

At high rates of application of seeds, it is possible to pour them over the blades, which increases the disorder in the flow of fertilizers on the disc. To exclude this phenomenon, the selected number of blades on the disk was refined according to the formula obtained for the blades of the grooved profile:

$$z \geq \frac{8BQV_{a2}}{\pi n L h^2 \gamma}, \quad (12)$$

where B – spreader working width, m;

Q – seed application rate, kg/m^2 ,

V_{a2} – spreader speed, m/s;

L – the length of the bulk body at the initial moment after its capture by the blade, m;

γ – seed density, kg/m^3 .

The search for methods of influencing the distribution of seeds by the angle of spreading was carried out on a laboratory setup.

The spreading angle and distribution of seeds along it were determined using a device, which is a hollow ring that encloses a spreading disc. The inner cavity of the ring was divided by thin partitions into cells, each of which covered an angle of 10 °. In order to prevent seeds from jumping out of the cells, the partitions were installed at an angle to the radius of the device, and the back wall was made of dense fabric. The seeds, flying off the rotating disc, fell into the cells of the device and rolled down the conical bottom to the dis-

charge windows. By the number of cells in which the seeds were located, one could judge the spreading angle, and by the mass of seeds in each of the cells, the distribution over it.

As a result of the experiments, it was found that if the seeds fed to the centrifugal disc are picked up by the blades on the fly, then the spreading angle practically does not depend on the number of blades on the disc, nor on the frequency of its rotation. Experiments have shown that by changing the diameter of the disc, the angle of the blades to the radius of the disc, the coefficient of friction of seeds, it is impossible to purposefully influence the distribution of seeds over the angle of spreading.

When looking for ways to change the distribution of seeds by the angle of spreading, the main attention was paid to the distribution of seeds at the place of feeding on the centrifugal disc. It turned out that the change in the mass fractions of seeds supplied to individual sections of the common place of supply can, within a wide range, affect the distribution of seeds by the angle of spreading.

Moreover, the sum of distributions from individual feed sites differs little from the distribution obtained as a result of simultaneous supply of seeds to all sites.

To implement the specified distribution of seeds by the angle of spreading, it was necessary to establish a relationship between the distribution of seeds by the angle of spreading and their distribution at the place of supply to the centrifugal disc.

It is known that each point of seed supply to the centrifugal disc corresponds to a certain point of their departure from it, but one can find a number of delivery points, which will correspond only to one common point of departure. If one knows the geometric location of the feed points, providing one common point of gathering, then it will become possible to change the mass fraction of seeds flying off at this point [7, 8].

Using the technique of N.M. Vasilenko, we examined the motion of a particle along the blade of a centrifugal disk. At the same time, it was agreed that if the blade forms an obtuse angle with the vector of the peripheral speed of its end, then angle α_R between the blade and the radius of the disk is considered positive, if it is acute, then - negative.

As a result of solving the differential equation of motion, a formula was obtained for determining the values of the current radius r (m), which characterizes the trajectory of the absolute motion of particles:

$$r = \sqrt{\left[\left[\frac{fg}{\omega^2} - r_o \frac{\cos(\psi_o \pm \varphi)}{\cos \varphi} \right] \left(1 - \frac{A}{2} \right) + r_o^2 \cos^2 \psi_o \right]^2 + r_o^2 \sin^2 \psi_o}, \quad (13)$$

where f – coefficient of seed friction on the blade;

ω – angular velocity, rad/s;

r_o – distance from the center of the disk to the point where particles are fed to it, m;

ψ_o – the angle between the blade and the radius drawn through the point where the particle is fed to the disk, deg;

φ – angle of friction, deg;

$$A = (1 + \sin \varphi) \exp \frac{1 - \sin \varphi}{\cos \varphi} \theta + (1 - \sin \varphi) \exp \left(- \frac{1 + \sin \varphi}{\cos \varphi} \theta \right), \quad (14)$$

θ – the angle of disc rotation from the moment the particle is fed to it, until the moment it escapes it, deg.

$$\text{Using dependencies: } r_o \sin \psi_o = R \sin \alpha_R, \quad (15)$$

$$r_o \cos \psi_o = \sqrt{r_o^2 - R^2 \sin^2 \alpha_R}, \quad (16)$$

where R – disk radius, m,

and assuming that $r = R$, we solve equation (13) with respect to r_o :

$$r_o = \sqrt{\left[\frac{2R \cos \alpha_R \pm (2-A)Rf \sin \alpha_R - \frac{fg}{\omega^2}(2-A)}{A} \right]^2 + R^2 \sin^2 \alpha_R} \quad (17)$$

$\frac{fg}{\omega^2}(2-A)$ is neglected due to its small value. In this case, equation (17) is greatly simplified:

$$r_o = R \sqrt{\left[\frac{2 \cos \alpha_R \pm (2-A)f \sin \alpha_R}{A} \right]^2 + \sin^2 \alpha_R} \quad (18)$$

Taking the radius drawn through the point of departure of the particle from the disk as the polar axis, and r_o as the polar radius, we determine polar angle ψ :

$$\psi = \theta \pm \left(\arcsin \frac{R \sin \alpha_R}{r_o} - \alpha_R \right), \quad (19)$$

Thus, the desired locus of points is determined by equations (15) and (16) in polar coordinates. For a positive angle α_R , a minus sign should be put in equation (15), and a plus sign in equation (16), and vice versa if α_R is negative.

It is convenient to use feed lines as boundaries for seed feeding on the centrifugal disc. The angle between homogeneous lines is feed angle β_n . As it was established, spreading angle β was related to the feed angle by the following empirical relationship:

$$\beta = 8 \cdot 10^{-5} \beta_n^3 - 0,017 \beta_n^2 + 1,67 \beta_n + 25,6, \quad (20)$$

At large values of β_n (over 100°), the spreading angle is practically equal to the feed angle.

The experiments have shown that if feed angle β_n does not exceed 30° ($\beta \leq 60^\circ$), then the distribution of seeds over the spreading angle is always close to the law of normal distribution. If $\beta_n > 30^\circ$, then the spreading by the spreading angle can take on a different form depending on the distribution of seeds at the place of feeding on the centrifugal disc. In this regard, the angles $\beta_n \leq 30^\circ$ and $\beta_n \leq 60^\circ$ are called elementary.

To implement a given distribution of seeds by the angle of spreading, a method for designing rational places for feeding fertilizers to the centrifugal disc was developed [9, 10].

On a scale, the curve of the optimal distribution of seeds by the scattering angle is plotted (Figure 3a), calculated based on the distribution accuracy, the scattering angle and the overlap of adjacent passes of the unit.

The area under this curve is divided by ordinates at intervals equal to the elementary feed angle ($\beta_n \leq 30^\circ$). On the model of the centrifugal disk (Figure 3b), the points of the required start A and end B of seed gathering are marked, and the arc between these points is divided into sections corresponding to the accepted interval. From the boundaries of the sections, the lines of the feed points are drawn, corresponding to the parameters of the disk and the material being developed.

a) the calculated curve of the optimal distribution of seeds by the angle of spreading; b) the layout of the centrifugal disc with the lines of the delivery points;
Fig. 3. Determination of rational places of feeding and distribution of seeds over them

In accordance with the design features of the spreader (type of conveyor, distance from the conveyor to the disc), the delivery point is selected in the area between extreme lines AC and BD so that its boundaries touch these lines. The point of delivery can be discontinuous, but the end of one section must be on the same line (for example, EF) with the beginning of the other.

To ensure the specified distribution by the spreading angle, it is necessary to distribute the seeds over the sections $M_1, M_2, \dots, M_i, \dots, M_n$ of the delivery point about the same ratio as the sites $S_1, S_2, \dots, S_i, \dots, S_n$ under the curve of the optimal distribution. This is provided by the design of the fertilizer guide.

When fine-tuning the design of the fertilizer guide, it becomes necessary to determine the expected distribution of seeds by the spreading angle. The problem is solved in the reverse order. In this case, it is taken into account that the distribution of seeds from individual areas $M_1, M_2, \dots, M_i, \dots, M_n$ is close to the law of normal distribution. The general distribution curve is obtained by summing the ordinates of the curves of the individual distributions.

Using this method, rational places for feeding seeds to the centrifugal disc were designed for a laboratory setup. According to the results of the design, a fertilizer guide was made. By feeding the seeds through it, the distribution by the angle of spreading can be

obtained, close to the optimal one (Figure 4). After that, the distribution of seeds across the working width was determined.

1 – optimal distribution; 2 - experimental distribution;
Fig. 4. Graph of seed distribution by the spreading angle

According to the calculation, the optimal working width should be 19 m with an uneven distribution of 9%. In fact, it turned out to be 18.5 m and 9.6%, respectively (Figure 5).

The proposed method was used to design and manufacture a prototype of the fertilizer guide for the serial spreader KSA-3. The refinement of the design of the fertilizer guide was carried out during laboratory-field experiments directly on KSA-3 spreader. The distribution of seeds by the angle of spreading was determined using a special device for this spreader, consisting of eight cells. Each cell covered an angle of 30 °. Fertilizers that got into the device were collected in easily removable trays.

1 – expected theoretical distribution; 2 - experimental distribution;
Fig. 5. Graph of seed distribution across the working width

In the centrifugal apparatus of the spreader, in addition to replacing the feed guide with a new one, the disc blades were installed radially, and their upper edges were sharpened.

Production tests in the educational and experimental farm ‘Kuban’ showed high efficiency of the converted spreaders when planting rice seeds.

According to technical and economic calculations, the productivity of the converted spreaders when planting rice increases by 1.5 times. The uneven distribution of rice seeds over the working width does not exceed 15%.

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