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Original article

Harrow with Turning Disc Section

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Abstract

Introduction. At present, there is widely used smooth plowing, which is moldboard plowing without back ridges and deep furrows.
Aim of the Article. The article deals with developing a new design of working tools for smooth soil plowing that ensure the fulfillment of the required quality of soil cultivation.
Materials and Methods. Based on the analysis of existing designs, the authors developed a harrow with a turning disc section, which is characterized by increased operational reliability by reducing energy costs for its adjustment. The range of change in the approach angle of the disk working bodies is 5–45°.
Results. It was found that the speed of movement and the inclination angle disks have the greatest influence on the tillage quality. To optimize the motion parameters with a turning disk section for the best smooth plowing quality, a two-factor experiment was carried out.
Discussion and Conclusion. As a result, it was found that at a speed of 9.113 km/h and approach angle of working disks of 32°, the quality of tillage is maximum and amounts to 86.1%.

Keywords: smooth plowing, disc harrow, angle of attack disks, two-factor experiment, response surface, optimization problem

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Оригинальная статья

Борона с поворотной дисковой секцией

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Аннотация

Введение. В настоящее время широкое распространение получила гладкая вспашка, представляющая собой отвальную обработку почвы без свальных гребней и глубоких борозд.
Цель статьи. Цель исследования – разработка новой конструкции рабочих орудий для гладкой вспашки земли, обеспечивающей необходимое качество обработки почвы.
Материалы и методы. На основе анализа существующих конструкций авторы разработали борону с поворотной дисковой секцией, отличающуюся повышенной эксплуатационной надежностью за счет снижения затрат энергии на ее регулировку. Диапазон изменения угла атаки дисковых рабочих органов составляет 5–45°.
Результаты исследования. Выявлено, что наибольшее влияние на качество обработки почвы оказывают скорость движения и угол наклона дисков. Для оптимизации параметров движения с поворотной дисковой секцией, обеспечивающих наилучшее качество гладкой вспашки, был проведен двухфакторный эксперимент.
Обсуждение и заключение. Максимальное качество обработки почвы 86,1 % получено при скорости движения 9,1 км/ч и угле наклона рабочих дисков 32°.

Ключевые слова: гладкая вспашка, дисковая борона, угол наклона дисков, двухфакторный эксперимент, поверхность отклика, задача оптимизации

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Introduction

A high yield of agricultural products largely depends on the moisture-saving and moisture-accumulating properties of the tilth top soil [1; 2]. Insufficient moistening of the tilth top soil can lead to 30–40% yield loss. Autumn-winter tillage plays an important role in the process of moisture accumulation in the seed layer [3; 4].

Plowing is the most important agrotechnical method of soil cultivation. It is the most energy-intensive point of soil preparation for the cultivation of grain crops. Plowing accounts for 30–40% of all agricultural energy consumption costs [5].

An even, well-loosened surface with complete incorporation of crop residues is the main requirement for plowing [6]. Moving the upper tilth top soil layer to the place of the lower one creates good conditions for the growth and development of plants. The yield depends on the incorporation of the fertile top layer to the depth of plowing.

Today, there is no consensus among specialists in the agricultural sector about the need for basic tillage and the preference for one or another method of its implementation.

Until recently, in our country, almost everywhere, moldboard plowing was used as the main one. It ensures the turnover of the soil layer, the crumbling of the soil, and the incorporation of crop residues, organic and mineral fertilizers.

Moldboard plowing is one of the most effective and environmentally friendly ways to control weeds, pests and pathogens. However, moldboard plowing technologies have a number of serious disadvantages. These include a high energy intensity of the process, horizontal displacement and mixing of soil layers, the formation of a “plow sole”, high ridgedness and clodiness of the field surface, especially in dry farming conditions.

The problem is the formation of a treated moisture-saving and moisture-accumulating soil layers in the conditions of insufficient moisture for reducing plant damage from Fusarium decease, due to which crop losses can be from 30 to 40%.

Non-moldboard tillage with chisel tools makes it possible to eliminate a number of these shortcomings and contributes to the accumulation of moisture while maintaining biological balance in the soil layer.

However, the currently existing non-moldboard tillage technologies are energy- and material-intensive, and need to be improved. Therefore, the development of innovative combined universal tillage products is a topical research area.

Recently, smooth plowing is widely used, which is moldboard tillage without dump ridges and deep furrows [7; 8].

The purpose of further research was to develop a new design of working tools for smooth soil plowing, providing the required quality of tillage, and characterized by increased operational reliability by reducing energy costs for its adjustment.

Literature Review

New technologies contribute to the development of new and continuous improvement of existing working tools of machine and tractor units [9–11]. Reversible plows are currently the most popular (Fig. 1).

F i g. 1. Reversible plow

A reversible plow eliminates unnecessary operations with a soil layer. Each subsequent pass of the plow across the field is carried out very close to the previous one. This reduces the cost of tilling by 10% and improves the conditions for using agricultural machinery for further harvesting.

Reversible plows are equipped with two sets of working bodies with an electromechanical reversing device [12–15]. Reversible plows are characterized by the complexity of the design, increased material consumption (2–3 times higher than traditional plows) and high cost [16]. All this contributed to the development of new technical means for the main tillage.

An alternative to reversible plows are two-row plows [17]. Their metal consumption is 1.5 times less than the metal consumption of reversible plows (Fig. 2).

a) b)

F i g. 2. Double-row harrows with (a) disk working bodies and (b) disk-chisel working bodies

The disc harrow (Fig. 2a) is equipped with two rows of disc harrows [18]. The approach angle of the working tools varies within 0–30° that which allows adjusting the unit for different types of soil. However, this design has a number of disadvantages:

– poor plowing quality (especially of hard clay soils);

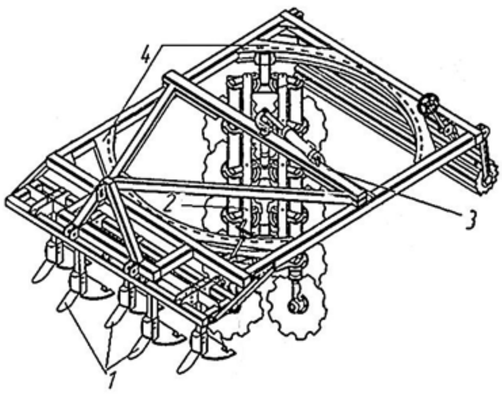
– need for frequent maintenance (need for cleaning);

– manual adjustment of the approach angles of the disc working tools (using a wrench).

The chisel-disk harrow is a combined soil-cultivating aggregate (Fig. 2b). It combines the functions of a heavy disc harrow and a chisel plow. This allows increasing the depth of soil tillage from 20 to 40 cm [19–21]. However, shortcomings in the adjustment and maintenance of the harrow remain.

To improve the regulation of the approach angles of discs, a plow with a turning beam was designed [22]. It includes a bar with chisel working elements1 and a turning block with disk working tools *2* (Fig. 3).

The rectangular welded section of the disk block *2* can move along the arcuate guide *4* with the help of a swing hydraulic cylinder *3*. The approach angle of the disks *2* is changed by means of additional rods separately for the right and left rows. This is a single frame design with a width of 2.3 m and a longitudinal dimension of 5.5 m. With a mass of 5 tons, this working tool is capable of working with the Kirovets K-742 (K-744 R4) tractor. The disadvantage of this design is the high time spent on setting up the disk block. To set the approach angle of the discs, it is necessary first to loosen the fastening of the cutting tools to the turning bar, and after adjusting to tighten them until they stop.

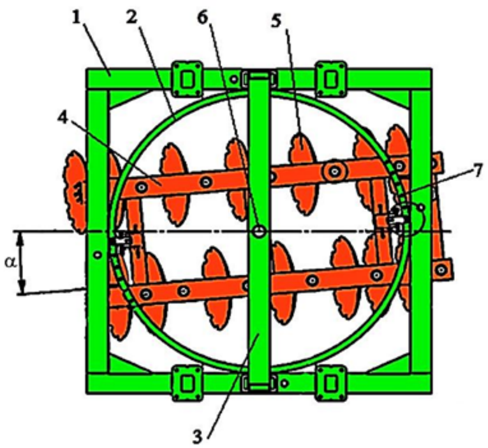


F i g. 3. Plow with swivel beam [22]

Materials and Methods

Object of research

To achieve this goal, the authors developed a harrow design with a turning disc section (Fig. 4).



F i g. 4. Harrow with a turning disc section [23]

It is a hinged connection of two sections: a fixed (green) and a movable turning (red). The fixed section is made in the form of a welded square frame *1* with a guide ring *2* and a middle beam *3*. The movable rotary section is made in the form of a rectangular frame *4*, on the side beams of which racks with cutting discs *5* are rigidly fixed in a staggered manner *5*. Initially, the working discs *5* are installed perpendicular to the beams of the movable frame *4*. When the beam frame rotats, the approach angle changes α = 15; 30; 45°. The inclination angle of the discs to the soil (the angle of obstruction) was 70°.

The movable frame rotates relative to the central kingpin *6* of the fixed section by an angleana α. The cutting disks *5* fixed on the frame *4* rotate at the same angle α relative to the fixed frame *1*. The rigid fastening of the disks on the movable frame eliminates the use of wrenches and simplifies the procedure for adjusting the approach angle of the cutting disks.

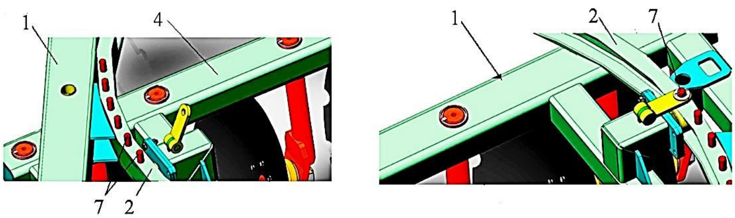
The rotary section is adjusted in a raised transport position. The approach angle α of the movable section is fixed with the help of thrust pins *7*, symmetrically welded on two opposite sides of the ring *2*. Additional fixation with a cotter pin is provided. The frequency of placement of thrust pins *7* is equal to five degrees (Fig. 5).

When the harrow moves, the discs *5* begin to rotate, due to which the soil is loosened and the roots of plants are cut. The combination with a chisel plow and a packer roller contributes to the required quality of the soil loosening.

The developed design of the harrow with a rotary section makes it easy to set approach angles from 5 to 45° [23]. The choice of the best adjustment depends on the soil resistance.

Optimization of the harrow operating modes

Field tests were carried out on the territory of the Krasnoarmeysky Rice Breeding Plant in the Krasnoarmeysky District of the Krasnodar Krai. The object of the experiment was a John Deere-7830 tractor with an experimental harrow with rotary disc section. Soil cultivation was carried out simultaneously with chisel and disc working tools without rollers (Fig. 6).



a) b)

F i g. 5. Rotary disc section in (a) unlocked and (b) locked position

The most significant factors affecting the soil cultivation quality according to agricultural requirements are [24]:

− v is speed of movement of the machine-tractor unit (km/h);

− α is approach angle of disc (degree).

A two-factor experiment was carried out on the basis of a symmetrical composition plan [25–27]. The levels of factors were chosen so that their optimal values were in the center of the variation interval. The speed of movement v of the unit varied from 6 to 12 km/h. The approach angle of disks α varied in the range of 15–45° (Table 1).

Factors were coded according to the expression:

$$x_i = \frac{x_i + x_{i0}}{\Delta_i}, \qquad (1)$$

where x_i is coded value of the i-th factor; x_i, x_{i0} are natural values of the i-th factor in the center of the experiment plan; Δ_i is factor variation interval; $i = 9$ is serial number of the experiment.

Mathematical processing of the experiment was carried out in the Mathcad program with subsequent approximation of the results by a second-order polynomial.

The quality of soil crumbling was determined according to GOST 33736–2016. Samples were taken from four points (repeatability) of the plot. Two samples were taken in the direction of movement of the unit and two samples were taken in the opposite direction.

Results

The results of experiments to ensure the required quality of soil cultivation, according to agro-technical requirements, are presented in Table 2.

The regression equation in coded form (according to the results of Table 2) is:

$$\bar{Y} = 85.872 + 1.464x_1 + 2.97x_2 - $$
$$-2.655x_1x_2 - 14.553x_1^2 - 10.39x_2^2, \qquad (2)$$

F i g. 6. John Deere-7830 tractor with experimental harrow in field trials

T a b l e 1

Factors, intervals and levels of variation

Variable factors	Coded designations x_i	Change interval Δ_i	Factor level		
			+1	0	–1
Movement speed	x_1, m/s	3	12	9	6
Disc angle	x_2, degree	15	45	30	15

Table 2

Experimental results

Experiment number	Factor		Response			
	x_1	x_2	Y_1	Y_2	Y_3	mean $\bar{Y}$
1	+1	+1	62.66	62.81	62.33	62.60
2	–1	+1	65.10	64.10	65.46	64.89
3	+1	–1	63.90	60.48	62.10	62.16
4	–1	–1	55.50	53.73	52.40	53.88
5	–1	0	73.00	72.50	72.80	72.77
6	–1	0	69.20	70.90	69.22	69.77
7	0	+1	77.50	78.90	78.50	78.30
8	0	–1	71.70	72.50	73.50	72.57
9	0	0	85.30	86.80	85.35	85.82

where $\bar{Y}$ is soil tillage quality according to agrotechnical requirements, %; x_1 is a coded value of the aggregate speed, km/h; x_2 is the coded value of the approach angle of discs (degree).

According to Student t-test, all regression coefficients are statistically significant [26]. According to the Fisher criterion, the adequacy of the equation (2) is confirmed [25].

To solve the optimization problem, we differentiated equation (2) for each of the variables:

$$\begin{cases} \dfrac{\partial \bar{Y}}{\partial x_1} = 1.464 - 2.655x_2 - 29.106x_1, \\ \dfrac{\partial \bar{Y}}{\partial x_2} = 2.97 - 2.655x_1 - 20.78x_2. \end{cases} \quad (3)$$

The coordinates of the extremum points of the response surface are obtained $x_1 = 0.0377$, $x_2 = 0.1381$ by equating the partial derivatives to zero (3). We have substituted the values x_1 and x_2 into the regression equation (2) and found the values of the optimization parameter at the extremum point of the response surface with a constant free term $\bar{Y}_{max} = 86.1\%$.

After moving the center to the point of extremum and rotation of axes in factor space by an angle of 16.26°, the regression equation (2) was reduced to the canonical form:

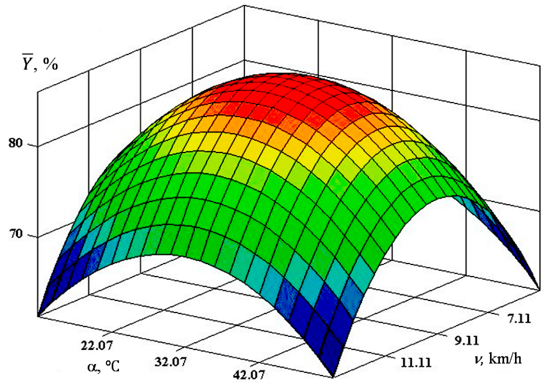
$$\bar{Y} - 86.1 = -14.94x_1^2 - 10.0x_2^2. \quad (4)$$

The same signs of the canonical equation coefficients (4) indicate that the response surface has the shape of a paraboloid of revolution. And their negative values indicate that at the point with coordinates $x_1 = 0.0377$, $x_2 = 0.1381$ is the maximum of the response function $\bar{Y}$. The conversion of the encoded factors x_1 and x_2 into real values (1) showed the values of the motion speed $v = 9.1$ km/h and the approach angle of disc $\alpha = 32°$, providing the maximum quality of tillage $\bar{Y}_{max} = 86.1\%$ (Fig. 7).

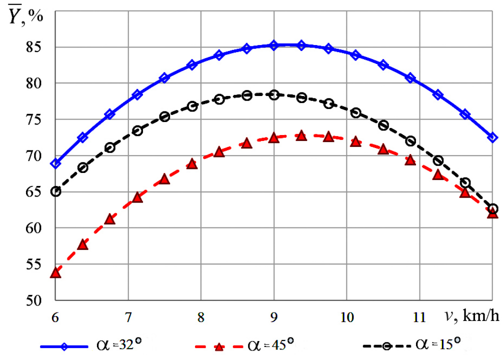
Next, using two-dimensional sections of the response surface $\bar{Y}$ a family of conjugate isolines in the form of hyperbolas was obtained near the optimal values of the factors (Fig. 8).

Dependences (Fig. 7) of the tillage quality $\bar{Y}$ on the motion speed v were obtained by approximation for different rotation angles of disks:

$$\alpha = 32°; \bar{Y} = -14.55^2 + 1.831 + 85.26;$$
$$\alpha = 45°; \bar{Y} = -14.55^2 + 4.119;$$
$$\alpha = 15°; \bar{Y} = -14.55^2 - 1.191 + 78.45.$$



F i g. 7. The response surface of the quality of tillage according to agricultural requirements $\bar{Y}$ to the motion speed v and the approach angle of disks α



F i g. 8. The dependence of the quality of tillage $\bar{Y}$ on the motion speed v at different approach angles of disks α

The nature of the isolines obtained as a result of the section of the response surface $\bar{Y}$ (Fig. 7), shows that the motion speed v has a greater impact on the quality of tillage than the disk approach angle α. The same conclusion confirms the smaller absolute value of the coefficient of the second factor x_2 canonical equation (4). The appearance of the treated soil in the experimental area of the field is shown in Fig. 9.

F i g. 9. Appearance of the soil after cultivating with an experimental harrow

Discussion and Conclusion

There has been developed a design of a harrow with a turning disc section confirmed by a patent of the Russian Federation [23]. The design excludes manual adjustment using wrenches, thereby ensuring an increase in operational reliability and a reduction in energy costs. The range of change of the approach angle of disk working bodies is from 5 to 45°.

It was revealed that the following factors have the greatest influence on the quality of tillage: the motion speed n and the approach angle of discs α. Based on a two-factor experiment, the optimal parameters of the harrow for high-quality smooth plowing are determined.

The maximum quality of tillage $\bar{Y} = 86.1\%$ was obtained at the speed of movement $v = 9.1$ km/h and the attack angle of working disks $\alpha = 32°$.

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I. P. Troyanovskaya – conducted a mathematical treatment of the experiment results, analyzing and drawing conclusions.

S. A. Partko – prepared and designed the material of the article.

S. A. Voinash – made a prototype of an experimental harrow.

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