Study of the kinematics of a disc-pin working body

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Abstract. Currently, there are a large number of tillage disc working tools. The article provides a detailed analysis of their designs. The main disadvantage of all structures is slippage during its interaction with the soil, which greatly reduces the quality of tillage. To eliminate this drawback, a new design of a soil-cultivating disc-pin working body was developed. The purpose of this study was to study the kinematics of a soil-cultivating disc-pin working body to ensure uniform operation without slipping. The rotation of the disk is ensured by a pin drum. During the forward movement of the trolley, the pins enter the soil, engage with it and turn the pin drum until, due to this rotation, they come out of the soil. A mathematical model of the movement of the ends of the pins in the plane of motion and taking into account the angle of attack has been compiled. Based on kinematics studies, the main parameters of the disc-pin working body are substantiated, the performance of which has been confirmed experimentally.

1 Introduction

The main purpose of surface tillage is: loosening the soil; leveling the top soil layer; destruction of soil lumps and surface crust; destruction of weed sprouts [1]. In recent years, rotary implements for surface tillage have attracted the greatest interest [11, 13]. To perform the technological operation of surface tillage, among all the working tools used, preference is often given to disc working bodies [6, 14].

Currently, there are many different types of disks with different design and geometric parameters. Disc tillage implements differ in the shape of the working parts and the shape of the blade; installation method on the shaft; type of location on the frame and rack [12]. To improve agrotechnical performance and reduce energy costs when cultivating the soil, each disc is located on an individual rack.

The disc body has the highest crumbling efficiency compared to other working bodies. It has high maneuverability in the presence of obstacles. Depending on the depth of cultivation and purpose, disc tillage machines are divided into:

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- Disc cultivators with a processing depth of 4...10 cm;
- Diskators with processing depth 6…16 cm;
- Disc harrows with processing depths from 10 cm (light) to 20 cm (heavy);
- Disc plows with a working depth of up to 30 cm.

Currently, there are a large number of different types of disc organs, having different design and geometric parameters. Tillage machines with disk working bodies installed in several rows on individual racks are widely known. The discs are equipped with a mechanism for adjusting the angle of attack for the entire row [15]. Installing a bearing unit for each disk or rack leads to a more complex design, which is a big disadvantage of these machines.

In this regard, the Russian Academy of Agricultural Sciences developed tillage sections with two or more discs on a stand. The design of the soil-cultivating double-disc section contains two discs of different diameters on one axis of the individual stand (Figure 1 a). This technical solution makes it possible to increase the stability of the implement under extreme soil conditions [17]. The disadvantage of the tool is the rigid fastening of the disc sections, which increases the likelihood of breakage when cultivating rocky soils.

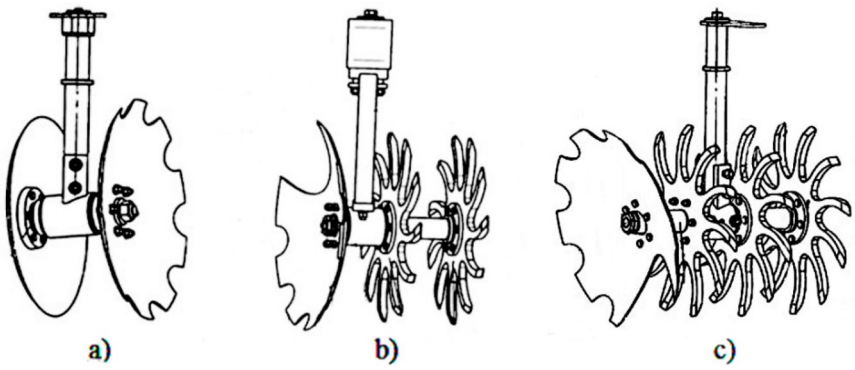

Fig. 1. Tillage sections: a) double-disc [17]; b) three-disc [18]; c) four-disc [19].

The three-disc section is equipped with two needle harrows and one spherical disc (Figure 1 b). The bearing unit is located between the spherical disc and the needle harrows. The design makes it possible to reduce erosion processes by creating alternating intermittent furrows. After treatment on the soil, there is an alternation of stripes with plant residues stored on the surface of the field and with plant residues embedded in the soil. This treatment is the most effective. Stubble strips accumulate snow well and provide wind resistance to its surface. Strips without mulch warm up faster in the spring. Holes and furrows retain water runoff and prevent erosion [18]. The disadvantage of this design is that the inter-disk spaces of the section become clogged with increased humidity and soil contamination.

The four-disc tillage section contains a bearing module, a shaft with three disc harrows and a larger diameter spherical disc (Figure 1 c). The plane of the disc harrows is perpendicular to the shaft axis. The plane of the spherical disk is located at an angle to the shaft axis. This design solution of the section makes it possible to reduce the number of racks and bearing units in the working tool [19]. However, a small angle of attack reduces the quality of tillage, which is a disadvantage of this design.

The shortcomings of existing designs predetermined the emergence of combined tillage tools. Patrick Colchester has developed a rotary disc device for incorporation of crop residues (Figure 2 b). It includes two rotating disks with a flat central area and many teeth extending from the central area. Each tooth has a profile with a concave first edge and a convex second edge. The complex profile of the teeth allows to minimize the distribution of plant residues

removed by the discs from the planting row. The disadvantage of this implement is its poor copying of the field surface and the inability to perform deeper tillage.

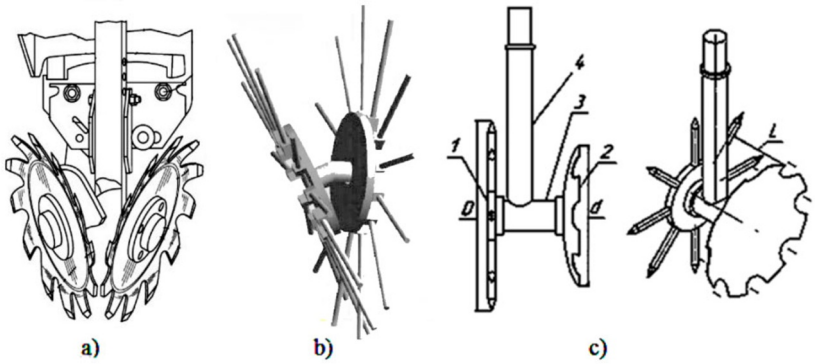

Fig. 2. Tillage organs: a) for embedding reaped residues (Patent US 20160066497A1); b) dentodiscal [8]; c) disco-pin.

Employees of the South Ural Agrarian University developed a tooth-disk rotary working body (Figure 2 b). The section disks are located at an angle to each other. When moving, the trajectory of the teeth of one disk intersects with the trajectory of the teeth of the other disk in the longitudinal and transverse directions. The tooth-disk rotary working body eliminates compaction and lumpiness of the soil along the tractor track at a depth of 15-20 cm simultaneously with other agricultural tillage operations [8]. The disadvantage of this design is that the rotary rippers become clogged with plant debris, which affects the quality of processing.

We have proposed a combined disc-pin working body (Figure 2 c), which makes it possible to improve the quality of surface tillage and reduce the traction resistance of the unit. The combined disk working body consists of a round rack 4, a bearing unit 3, a coaxially installed pin drum 1 and a spherical cut-out disk 2.

The pin drum is designed to ensure stable uniform rotation of the spherical disk with a constant angular velocity ω. During the forward movement of the unit, the pins enter the soil, engage with it, and rotate the pin drum until they exit the soil [10]. At the same time, the pin must carry out preliminary loosening of the soil by changing its position in the soil from the moment of entry to the moment of exit.

Several disc pins can be located on one shaft. In this case, they are fixed with a slight angular displacement of the adjacent disc pins. This will ensure high uniformity of operation of the unit without slipping [3].

To select the dimensions of the combined disc-pin organ, it is necessary to consider in more detail the kinematics of its movement. An adequate description of the interaction of the working body with the soil will allow choosing optimal operating modes [4, 2].

The purpose of the study is to study the kinematics of movement of the disc-pin working body in the process of its interaction with the soil.

2 Materials and methods

The pin drum performs a complex movement consisting of translational movement along with the axis and rotational movement around it in the vertical plane. The end of each pin describes a cycloid during movement (Figure 3).

To ensure uniform movement, it is desirable that there are 2...3 pins simultaneously in the deepening zone. From this condition, the minimum number of pins $n = 8$ was determined.

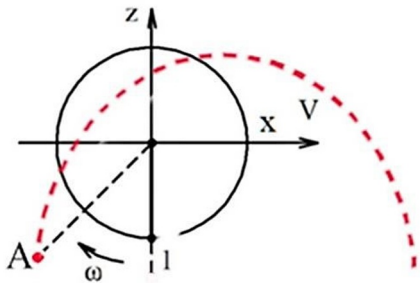

Fig. 3. Movement of the end of the pin drum in the vertical plane.

Let the first pin at the initial time $t = 0$ be directed vertically downwards. The coordinates of the end of the first pin are: $x = 0$; $z = -Rx$, where R is the radius of the pin drum. The equations of motion for the end of the pin have the form:

$$\begin{cases} x_1(t) = vt - R\sin(\omega t) \\ z_1(t) = -R\cos(\omega t) \end{cases}, \tag{1}$$

where v is the speed of translational movement of the center of mass of the pin; ω – angular speed of rotation of the pin drum.

The remaining pins are numbered counterclockwise. Each subsequent pin is shifted counterclockwise by an angle $\Delta\varphi = 2\pi/n = 45°$. The equations of motion for the end of each of them have the form:

$$\begin{cases} x_i(t) = vt - R\sin\left[\omega t - (i-1)\Delta\varphi\right] \\ z_i(t) = -R\cos\left[\omega t - (i-1)\Delta\varphi\right] \end{cases}, \tag{2}$$

where $i = 1...8$ – pin number.

Let us clarify the equations of motion of the ends of the pins in connection with the rotation of the pin drum relative to the plane of motion by the angle of attack α. Let us introduce a new coordinate system $x'y'z'$. The z' axis coincides with the vertical z axis. The x' and y' axes are rotated relative to the x and y axes by an angle of attack α (Figure 4). The dotted line indicates a strip processed by one pin drum. The width of the processed strip is $2R \sin \alpha$.

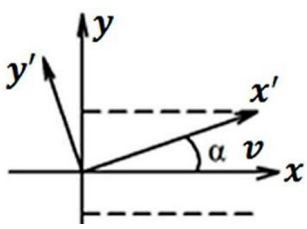

Fig. 4. Top view of the selected coordinate system.

The pin drum moves forward along the x-axis. The pin drum rotates in the $x'z$ plane. Formulas for transforming coordinates on a plane when one coordinate system is rotated relative to another by an angle α take the form:

$$\begin{cases} x = x'\cos\alpha - y'\sin\alpha \\ y = x'\sin\alpha + y'\cos\alpha \end{cases}. \tag{3}$$

Rotation equations (2) are valid for the $x'z$ plane of rotation of the pin drum. Taking into account the transformation of coordinates (3), the equations of motion of the end of the pins in space take the form:

$$\begin{cases} x_i = vt - R\cos\alpha \sin\left[\omega t - (i-1)\Delta\varphi\right] \\ y_i = -R\sin\alpha \cdot \sin\left[\omega t - (i-1)\Delta\varphi\right] \\ z_i = -R\cos\left[\omega t - (i-1)\Delta\varphi\right] \end{cases}. \quad (4)$$

The trajectories of the ends of the pins are ellipses elongated vertically. The resulting trajectory equations (4) made it possible to theoretically substantiate the design parameters of the working body [5, 9].

3 Results

Theoretical studies made it possible to determine the optimal ratio between the radius of the pin drum R and the radius of the spherical disk r. With the same radii $R = r$, the required loosening depth h will be provided only with the pin in a vertical position. At the moment the pin enters and exits the soil, the depth of loosening will be less. For normal operation of the pin working body, the radius of the pin drum R must be greater than the radius of the spherical disk r.

It is recommended to choose the distance between the spherical disk and the pin drum L equal to the radius of the pin drum $L = R$. The distance between the rows of racks is recommended to be 1.5 times greater than the distance between sections. The optimal ratio between the radius of the pin drum and the spherical disc was $R = 1.25r$.

Based on theoretically based dimensions, a prototype of a combined disc-pin working body was created (Figure 5).

Fig. 5. A prototype of a disc-pin working body.

To test the theoretically obtained kinematic relationships in the soil channel of the Kazan State Agrarian University, a laboratory experiment was conducted. The soil channel used was gray forest soil of medium loamy texture with an average humus content of 3.1%. Soil moisture in the surface layer 0...150 mm was 19.5%. Soil hardness varied from 1.7 MPa to 2.1 MPa.

The kinematics of the combined disc-pin working body was tested at three values of the translational speed of the trolley: 1.56 m/s; 2.1 m/s and 2.51 m/s. The experiment was carried out at three processing depths: 10.5 cm; 12.5 cm and 14.5 cm. For the experiment, a pin drum

of three different diameters was used: 515 mm; 565 mm or 615 mm. Comparative results of experimental studies of the disk and disk-pin working body are presented in Tables 1-2.

Table 1. Experimental data from laboratory tests of a soil-cultivating unit with a disk working body.

Pin drum diameter, mm	Processing depth, cm	cart speed, m/s								
		1.56			2.10			2.51		
515	10.5	0.93	1.05	0.99	1.35	1.50	1.63	2.12	2.16	2.13
	12.5	1.09	1.11	1.10	1.69	1.64	1.60	2.12	2.14	2.11
	14.5	1.23	1.16	1.26	1.86	1.80	1.78	2.09	2.16	2.11

Table 2. Experimental data from laboratory tests of a soil-cultivating unit with a disc-pin working body.

Pin drum diameter, mm	Processing depth, cm	cart speed, m/s								
		1.56			2.10			2.51		
		rotation speed of the disc-pin implement								
515	10.5	1.18	1.13	1.21	1.75	1.68	1.69	1.93	1.88	1.91
	12.5	1.36	1.37	1.34	1.87	1.88	1.89	2.17	2.20	2.21
	14.5	1.54	1.53	1.54	2.02	2.04	2.08	2.48	2.46	2.44
565	10.5	1.26	1.30	1.29	1.78	1.79	1.77	2.09	2.05	2.11
	12.5	1.36	1.37	1.39	1.88	1.90	1.89	2.19	2.21	2.20
	14.5	1.45	1.46	1.43	2.01	2.00	1.99	2.31	2.34	2.30
615	10.5	1.42	1.40	1.40	1.83	1.88	1.86	2.28	2.23	2.26
	12.5	1.38	1.38	1.38	1.91	1.92	1.88	2.22	2.20	2.21
	14.5	1.37	1.37	1.38	1.89	1.93	1.96	2.19	2.14	2.18

The kinematics of a disk working body without a pin drum is characterized by sliding, which reduces the quality of tillage. For a disc-pin working body, the best kinematics are observed in a pin drum with a diameter of 615 mm when processing at a depth of 10.5 cm and 12.5 cm. When deepened to a depth of 14.5 cm, a disc-pin working body with a pin drum diameter of 515 mm proved to be most effective.

The quality of soil cultivation was assessed by the ridgeness of the surface, measured by the lengthening of the cord when copying the topography of the soil surfaces. To do this, pegs were driven into the soil along the edges of the soil channel. A cord with measuring tape was tied to them. The length of the cord stretched across the direction of cultivation is 10 m. When the cord was released, its length between the pegs increased due to copying the surface of the arable land. The length of the cord was determined using a measuring tape. The ratio of the elongation of the cord to the stretched length (10 m) gives the percentage of ridgedness of the arable land [7, 16].

4 Conclusion

The presence of a pin drum makes it possible to eliminate slippage of the spherical disk working body, which has a positive effect on the quality of tillage and generally increases the productivity of the combined unit.

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