INTERACTION OF DISK WORKING BODY BLADE WITH FOREIGN BODY DURING CUTTING OF SOLID MEDIUM

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Abstract. Flat disc knives are widely used in agriculture. The aim of this study is to analyze the interaction between a disc knife blade and foreign bodies - specifically plant residues in the soil – during the cutting of a continuous medium in various operating modes. The research employs a method of determining isogonal curves intersecting with a family of circles. The interaction of the disc knife blade with plant roots and residues (foreign bodies) is examined for the following operating modes of the disc knife: braked state; disc rolling with sliding; disc rolling without sliding; disc rolling with slippage. When considering the interaction process between the disc knife blade and a foreign body, it was taken into account that the sliding of the foreign body along the blade is possible if the angle between the normal and the absolute velocity exceeds the maximum friction angle on the blade for the foreign body or the continuous medium being cut. Theoretical studies have yielded differential equations for isogonal trajectories, i.e. the movement paths of foreign body particles under the action of a disc knife blade, for various operating modes. Based on the analysis of the obtained equations for the movement trajectory of body particles under the action of the disc knife blade during continuous medium cutting, it was established that slowing the disc knife rotation, i.e. when the kinematic operating mode indicator (ratio of the circular speed of the disk knife to its translational speed) $\lambda < 1$ leads to its clogging with plant residues.

Keywords: soil, foreign object, disc knife, blade.

Introduction

For soil cultivation, various designs of general and special-purpose plows, subsurface tillers, and disc tillage implements operating under different technological influences on the soil and plant mass are widely used [1-3]. The vast majority of these implements are equipped with disc-type working elements, on which the quality and energy efficiency of the specified tools depend [4; 5]. The main distinguishing feature of disc blades is their reduced clogging with weeds and various plant residues found in the soil and on its surface, due to their superior cutting ability [6]. A significant number of works by various researchers have been dedicated to studying the interaction of flat discs with soil: V. Goryachkin [7], B. Mirzaev [8-10], N. Aldoshin [11; 12], S. Nurushev [13], Z. Kogut [14], F. Mamatov [10; 11], K. A. Sokht [15], and others. These studies pay great attention to various approaches for determining soil cutting reactions, as theoretical and experimental research indicates that the main soil reaction to the disc blade under various operating conditions is concentrated in the blade zone. For instance, in the classical works of V. Goryachkin [7], the cutting reactions of a disc blade in free rotation mode were determined. Nurushev [13] and others justified the parameters and modes of operation of the disk knife. Theoretical studies have established that cutting conditions worsen with the decrease of the kinematic parameter. F. Mamatov [10-12] investigated the process of soil cutting with disc knives and the influence of their main parameters on the traction resistance and qualitative performance indicators of the plow. Z Kogut [14] and others studied the components of traction resistance of the disk depending on its design parameters, G. Golub studied the influence of the disk blade on the performance of the plow [16; 17]. It is established that when installing disk knives on the plow, the depth of plant residues embedding is maximum, and fuel consumption becomes minimal. V. Konovalov obtained analytical expressions that allow to determine the qualitative indicators of the disk working organ depending on the design and technological parameters [18; 19]. He established the influence of the shape and design-mode parameters of disk operation on the qualitative and energy indicators of the implements. He revealed the regularities of interaction of the disk blade with the soil-plant mass in the unstressed (natural) and stressed (stretched) state [15]. Kobyakov studied the main factors affecting the efficiency of disc working elements in soil cultivation implements [20; 21]. He evaluated the energy consumption and quality of the disc performance. A Soyunov and E. Demchuk [5] examined the process of interaction between the disc working element and soil, deriving analytical expressions that establish the dependence of horizontal and vertical components of the resistance force of the disc soil cultivation implement as functions of the volume of the cut soil layer.

The aim of the research is to analyze the interaction of the disc knife blade with a foreign body - plant residues – during the cutting of a continuous medium (soil) in various operating modes.

Materials and methods

The cutting of plant residues on the field surface and in the soil depends on the operating modes of the disc blade. Therefore, it is necessary to examine the interaction of the disc blade with roots and plant residues (foreign bodies) located in the soil (continuous medium) under different operating modes of the disc blade. Let us consider the process of interaction between the disc blade and a foreign body, taking into account that the sliding of a foreign body along the blade is possible if the value of the angle α between the normal and the absolute velocity exceeds the maximum value of the friction angle φ for either the blade, the foreign body itself, or the continuous medium being cut [11; 12], i.e. $\alpha > \varphi$. For simplicity, we assume $\varphi_{max} = \varphi$. We also assume that the blade is completely blunt and no cutting of the foreign body occurs. Depending on the kinematic mode indicator of the disc blade operation, i.e. the ratio of the circumferential velocity of the disc blade $\upsilon_o=\omega r$ to its translational speed υ_m (Fig. 1), four cases are possible: 1 – braking state, $\lambda = 0$; 2 – disc rolling with sliding, $\lambda < 1$; 3 – disc rolling without slipping, $\lambda = 1$; 4 – disc rolling with skidding, $\lambda > 1$.

Case 1. The disc knife operates in a stationary state ($\lambda = 0$), and two zones can be distinguished on its blade in the direction of foreign body particle movement V_p (Fig. 1): Zone 1 (arc AB), where υ_p coincides with the direction of the absolute velocity V_α of the blade points, since $\alpha < \varphi$. A particle located in this zone will not slide along the blade and will remain on it. Zone 2 (arc *BC*), where υ_p deviates from the normal towards υ_α by an angle φ. A particle located in this zone, sliding along the blade, will leave it after the disk's center has traveled a certain path, which must be determined by knowing the particle's displacement equation. As is known [22], the equations of such trajectories are found using the method of determining isogonal curves intersecting a family of circles. To find the differential equation of isogonal trajectories, i.e. particle trajectories, it is necessary to eliminate the constant from the equations of the family of circles**:**

$$f(x,y,C)=(x-C)^2+y^2-r^2 \tag{1}$$

and

$$\frac{df(x,y,C)}{dx}+\frac{\alpha f(x,y,C)}{dy}y'=(x-C)+yy'. \tag{2}$$

The equation

$$y'=\frac{\sqrt{r^2-y^2}}{y} \tag{3}$$

obtained after excluding *C*, needs to be replaced with

$$\frac{y'-k}{1+ky'}. \tag{4}$$

Then

$$y^1=\frac{ky-\sqrt{r^2-y^2}}{y+k\sqrt{r^2-y^2}}. \tag{5}$$

Here

$$k=tg(\gamma_1-\gamma)=\text{ctg}\,\varphi, \tag{6}$$

where r – radius of the disc knife, cm;
γ_1 – angle between the *x*-axis and the direction of movement, degrees;
γ – angle between the *x*-axis and the tangent to the family of circles, degrees.

After substituting the value of *k* and replacing *y*’ with *dy*/*dx*, equation (5) takes the following form

$$x = \int_{y_0}^{y_1} \frac{y - ctg\varphi\sqrt{r^2 - y^2}}{yctg\varphi - \sqrt{r^2 - y^2}}\,dy. \tag{7}$$

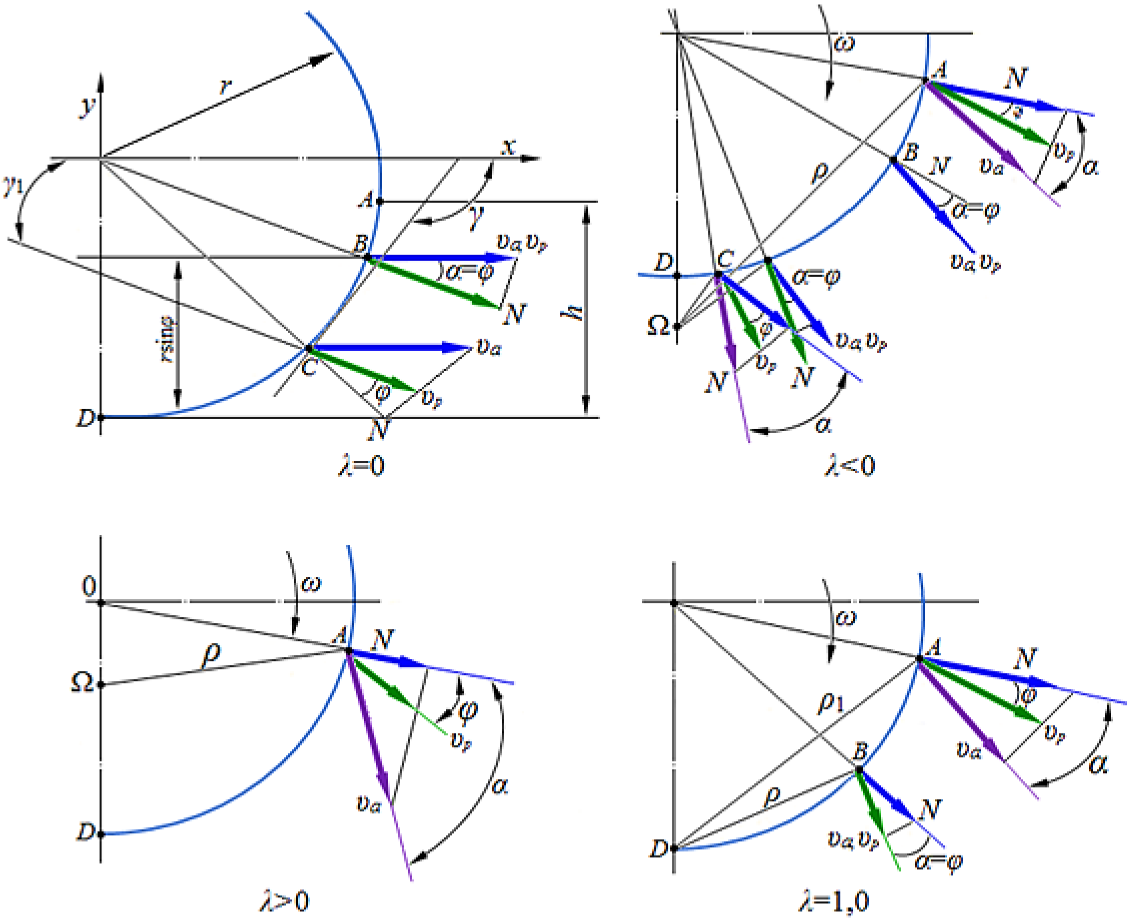

Fig. 1. **Diagram for determining the trajectory of particle displacement under the action of a disc knife blade**

Having calculated the integral, we obtain

$$x = r\cos\varphi \ln\left[\frac{\mathrm{ctg}\left(\dfrac{\arcsin\dfrac{y_1}{r} + \varphi}{2}\right)}{\mathrm{ctg}\left(\dfrac{\arcsin\dfrac{y_0}{r} + \varphi}{2}\right)}\right] + \sqrt{r^2 - y_1{}^2} - \sqrt{r^2 - y_0{}^2}. \tag{8}$$

In the *BC* arc zone, for the particle to detach from the blade, the disk must travel a distance equal to $x_d = x = x_0$. Taking into account $y_1 = -r$ and $y_0 = -(r-h) \le -r\sin\varphi$ we have

$$x_d = r\cos\varphi \ln\left[\frac{\mathrm{ctg}\left(\dfrac{3\pi}{4} + \dfrac{\varphi}{2}\right)}{\mathrm{ctg}\left(\dfrac{1}{2}\arcsin\dfrac{r-h}{r} + \dfrac{\varphi}{2}\right)}\right], \tag{9}$$

where *h* – depth of the disk immersion into the soil, cm.

Case 2. On the blade of the disc (Fig. 1), which is without slipping, two zones can be distinguished. The equation of the trajectories of particle movement in the first zone (arc *AB*) is found similarly to the first case. Since in this zone υ_p is deviated from the normal to the rotation side by an angle φ υ_p then

$$k = \mathrm{ctg}\varphi, \tag{10}$$

$$y = -r\cos 2\varphi = -r\sin(\frac{\pi}{2} - 2\varphi). \tag{11}$$

Therefore

$$x_{d1} = r\cos\varphi \ln\left[\frac{ctg(\frac{\arcsin\frac{y}{r} - \varphi)}{2}}{ctg(\frac{1}{2}\arcsin\frac{y-r}{2} - \frac{\varphi}{2}}\right]. \tag{12}$$

The first zone ends at point *B*, for which

$$y = -r\sin\frac{\pi}{2} - 2\varphi \cdot$$

Therefore, the foreign body particle will leave the first zone of the knife blade after the disc has traveled a certain distance.

$$x_{d1} = r\cos\varphi \ln\left[\frac{ctg(\frac{3\varphi}{2} - \frac{\pi}{4}}{ctg(\frac{1}{2}\arcsin\frac{h-r}{2} - \frac{\varphi}{2}}\right].$$

In the second zone (*BC* arc), the direction of the particle movement V_p coincides with the absolute velocity, since $\alpha < \varphi$. The trajectory of the particle movement in this zone is an ordinary cycloid, whose equations in the adopted coordinate system have the form

$$x_1 = r\arccos\frac{y}{r} - \sqrt{r^2 - y^2}. \tag{13}$$

If a foreign body particle is located in the first zone, it will come off the blade after the disk has traveled its path.

$$x_d = x_{d1}\Bigg|_{y_0 = -(r+h)}^{y_1 = -r\cos 2\varphi} + x_{d2}\Bigg|_{y_1 = -r\cos 2\varphi}^{y_2 = -r} = r\cos\varphi \ln\left[\frac{ctg(\frac{3\varphi}{2} - \frac{\pi}{4})}{ctg(\frac{1}{2}\arcsin\frac{y-r}{2} - \frac{\varphi}{2}}\right] - 2r\varphi. \tag{14}$$

Case 3. The disc knife rolls with sliding, and on its blade three zones can be distinguished in the direction of foreign body particle movement.

The direction of displacement υ_p deviates from the normal by an angle φ in the first zone (arc *AB*) towards the direction of rotation, and in the third zone (arc *CD*) in the opposite direction. In these zones, the equation of particle trajectories is analogous to equations (8) and (12).

In the second zone (*BC*), the particles move in the direction of absolute velocity, as $\alpha < \varphi$. Therefore, the trajectory of particle movement in this zone is a shortened cycloid, that is,

$$x = (r + \delta)\arccos\frac{y}{r} - \sqrt{r^2 - y^2}, \tag{15}$$

where δ – is the distance from the instantaneous axis of rotation to the lowest point of the blade along the ordinate axis.

Case 4. When the disk rolls with slippage, the absolute velocity of all blade points is deflected in the direction of rotation, so the foreign body particles move in a direction deviated from the normal towards the rotation. The equation of particle trajectories is analogous to equation (14). Substituting $y_1 = r$ and $y_0 = -(r-h)$ into (12), we have:

$$x_d = -r\cos\varphi \ln\left[tg\left(\frac{\pi}{4}-\frac{\varphi}{2}\right) ctg\left(\frac{\arcsin\frac{h-r}{2}-\varphi}{2}\right)\right]. \tag{16}$$

Results and discussion

Figure 2 shows the dependencies of the path traveled by the disk (at which particles, sliding along the blade, will come off it) on the depth of the foreign body particle location for various rolling cases. From the graphs, it can be seen that at the value of the kinematic operating mode indicator $\lambda = 0$, particles located higher will not slide along the blade or on it (Fig. 3), and with an increase in λ, the disk's path (xd) shortens. However, when the disk operates, plant roots and residues continuously enter its blade. Therefore, when λ decreases, the number of foreign body particles coming off the blade becomes smaller, consequently, the number of particles on it increases. This leads to the disk knife being clogged with plant roots and stems. Thus, as soon as the disk rotation slows down or stops, the disk immediately becomes clogged and its resistance increases.

Studies [11; 16] have established that flat smooth discs, when cultivating sodded soils heavily overgrown with vegetation, as well as those with a large amount of plant residues (e.g. long straw) on the soil surface, handle cutting well as long as they continue to rotate. As soon as the knife's free rotation stops, they immediately become clogged. Therefore, when cultivating such soils, it is necessary to use a disc knife with a wavy edge, which, receiving forced rotational motion from the soil, does not slow down.

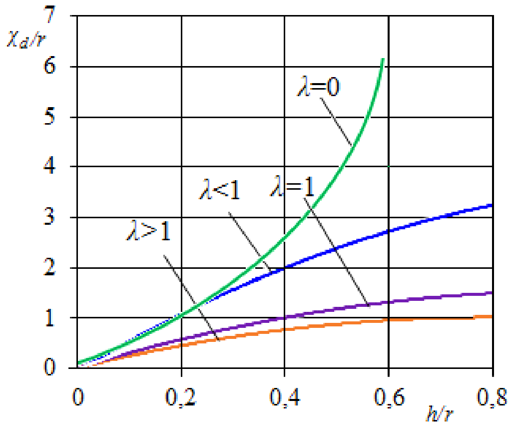

Fig. 2. **Dependencies of the path traveled by the disk (at which a foreign body particle will leave the blade) on the kinematic parameter and the disk's depth of penetration**

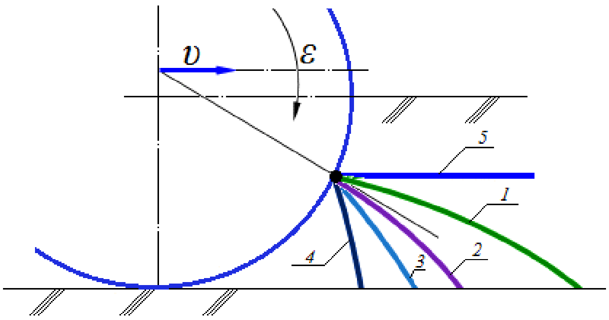

Fig. 3. **The trajectory of material particle movement under the influence of a disc knife:** 1 – the particle moves in a direction deviating from the normal in the opposite direction of rotation by the angle of friction; 2 – the particle moves in the direction of the normal; 3 – the particle moves in a direction deviating from the normal in the direction of rotation by the angle of friction; 4 – the particle moves in the direction of absolute velocity; 5 – the particle remains on the blade, where $\alpha < \varphi$ and $\lambda = 0$

Conclusions

Theoretical studies have yielded differential equations for isogonal trajectories, that is, the movement paths of foreign body particles under the action of a disc knife blade for various operating modes. Based on the analysis of the obtained equations describing the trajectory of particle movement under the influence of the disc knife blade when cutting through a continuous medium, it has been established that a decrease in the disc knife's rotation speed, specifically when the kinematic operating mode indicator - the ratio of the disc knife's circumferential velocity to its translational velocity $\lambda < 1$, leads to its clogging with plant residues.

Author contributions

Conceptualization, F. M., X. F., and I. I.; data curation, N. R, and D. Ch; formal analysis, F. M., S. O., O. M., and A. S; funding acquisition, M. B.; investigation, F. M., X. F, N. R., and A.S.; methodology, F. M., X. F, and N. R; software, F. M.; supervision, F. M., and X. F.4 validation, M. B., and O. M.; visualization, F. M. and X.F.; writing – original draft preparation, F.M. and X.F.; writing – review and editing, F. M., D. Ch., A. S., I.I., N. R, S. O., O. M., M. B. All authors have read and agreed to the published version of the manuscript.

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