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Application of Kinematic analysis in rational selection of parameters and operation modes

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Abstract

The aim of this study is to conduct a kinematic analysis of the BROU to derive the a priori conditions for the rational selection of its design parameters and operation modes via simulation in a mathematical model as methodology. By studying the results of the study we can conclude that the kinematic analysis of the blade rotary operating unit makes it possible to find the cutting angle of a random elementary section of straight and curved cutting edges with regard to the turning angle of the operating unit, its dimensions, and parameters of its operation mode.

Key words: Rotary Operating Units, Blade, Tillage.

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Aplicación del análisis cinemático en la selección racional de parámetros y modos de operación

Resumen

El objetivo de este estudio es realizar un análisis cinemático del BROU para derivar las condiciones a priori para la selección racional de sus parámetros de diseño y modos de operación mediante simulación en un modelo matemático como metodología. Al estudiar los resultados del estudio, podemos concluir que el análisis cinemático de la unidad operativa giratoria de la cuchilla permite encontrar el ángulo de corte de una sección elemental al azar de los bordes de corte rectos y curvos con respecto al ángulo de giro de la unidad operativa. Sus dimensiones, y parámetros de su modo de operación.

Palabras clave: Unidades de operación rotativas, cuchillas, labranza.

1. INTRODUCTION

The optimal parameters and operation modes of rotary operating units of tillage machines and tools ensure high-quality tillage at minimized specific energy expenditures. To find this optimal combination, it is necessary to analyze the interaction of the operating units with the soil. This task is quite difficult, and the designers often have to confine themselves to their kinematic analysis and study the motion of rotary operating units without considering effective forces. Sometimes, even this relatively simple analysis allows one to justifiably select the design and process parameters of such operating units by reducing the region of permissible values of these parameters (Akimov and Konstantinov, 2015).

The first step of kinematic analysis is to determine the motion laws of rotary operating units, their elements, and points. Some authors confine themselves to deriving these laws. The derived motion laws of the points of such units make it possible to draw the motion paths of these points. The analysis of these paths makes it possible to draw important conclusions about the quality of tillage and, in particular, determine the relation of the groove bottom roughness to the parameters of the operating unit and select these for meeting agrotechnical requirements. In addition, this analysis and the analysis of speeds and accelerations of various points of the rotary operating unit make it possible to rationally select design and mode parameters of rotary operating units and ensure their more efficient impact on the soil, while reducing the specific energy expenditures on tillage (Chatkin, 1986).

A new blade rotary operating unit (BROU) protected by inventor's certificate no. 1083940 was proposed as an alternative to available rotary operating units to improve the quality of tillage and reduce its energy intensity. The invention showed itself to good advantage in various agricultural engineering operations (Vasilenko, 2017). Tillage machines with these BROU heap the soil aside and can also be used with success in the primary soil cultivation in propulsor mode. With the drum (rotor) of 500--600 mm in diameter, the primary soil cultivation can reach a depth of up to 22 cm. That said, it is natural to expect that the reduced wheel slip losses of energy-saturated wheeled tractors will mean much lower specific energy expenditures on secondary tillage without aggravating the soil quality. In view of the foregoing the study of the operation of this operating unit bears not only purely theoretical importance but major practical importance as well. Work Goryachkin (1968) considered the kinematics of the BROU used as an active skim colter. In works [15-18] the proposed mathematical model of BROU-soil interaction was used to elaborate the techniques of determining various power characteristics of this operating unit. However, the rational selection of its dimensions and mode parameters remained understudied (Pervushin and Salimzyanov, 2008). The purpose of this work is to conduct a kinematic analysis of the BROU to derive the a priori conditions for the rational selection of its design parameters and operation modes (Mirasova, 2018).

2. MATERIALS AND METHODS

Figure 1a shows a BROU of four blades made by cutting an ellipsoid disk along its semiaxes and symmetrically fixed on the hub. The minor semiaxes of the operating unit in motion lie in one and the same vertical plane, whereas the major semiaxes deviate from this plane at one and the same angle $\beta = \arccos(r/c)$, where r is the minor semiaxis and c is the major semiaxis of the disk. That said, the projection on the longitudinal vertical plane of the BROU is a circle with a radius equal to the minor semiaxis of the disk. The blades mounted in this manner allow attaining a more uniform depth of tillage in the face plane of the operating unit. The rotation imparted to the BROU hub allows the blades to penetrate the soil top-down. That is why, the horizontal component of the total soil reaction to the BROU is directed along the unit's trajectory (Gaynutdinov, 2016). Thus, in addition to executing the main function, i.e., high-quality tillage, the BROU also works as a propulsor. Each of the blades tills the soil with its surface, minor semiaxis blade, and curved blade (Kazakov and Kazakov, 2016).

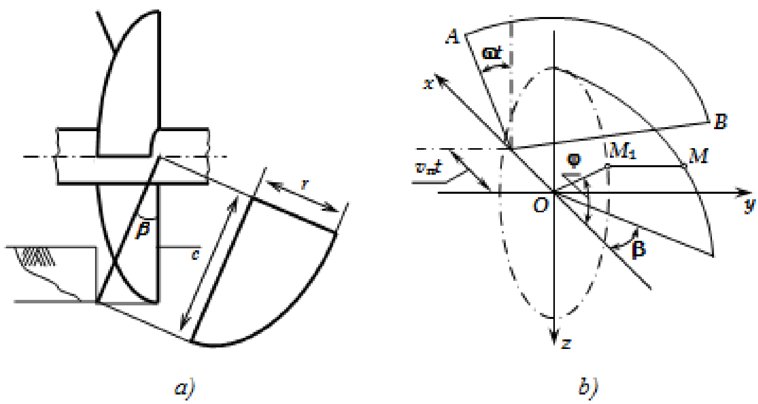

Fig. 1. Blade rotary operating unit for tillage: design (a) and initial and current positions relative to the axes of reference (b)

Relying on the analogy of the plane wedge, Kanarev (1983) proposed to evaluate the soil mellowing capacity of an elementary area of the dumping surface of the operating unit by the angle θ between the normal vector to this area and the absolute speed vector of any point of the considered area. They justified their proposal on the assumption that the concentration of stresses in the soil goes down with the reduction in the given angle; therefore, the soil destructibility becomes more possible. According to their data, that angle varies within 45±9° in the most common plow designs and within 90±9° in the rotary cultivators that have gained the most widespread practical use (Khodabakhshi1 et al., 2013).

3. ANALYSIS AND DISCUSSION

Let us determine the variation limits of θ for the BROU. If the minor blade semiaxis is vertical at any initial moment t=0, then the law of motion in the *Oxyz* stationary frame of reference (Fig. 1b) of a random point of the blade, the position of which is determined by the angle φ (0≤φ≤90°) and the distance from the rotary axis ρ (0≤ρ≤r), is recorded as

$$\begin{cases} x = -\rho\cos(\phi + \omega t) + v_{fwd} t, \\ y = \rho\cos\phi tg\beta, \\ z = -\rho\sin(\phi + \omega t); \end{cases} \quad (1)$$

Where v_{fwd} is the forwarding speed of the tillage machine and ω is the angular rotation speed of the BROU.

By differentiating in time motion law (1) of the blade point determined by the curvilinear coordinates φ and ρ, it is easy to determine the absolute speed vector ***v*** as

$$\boldsymbol{v} = (\rho\omega\sin(\varphi + \alpha) + v_{п})i - \rho\omega\cos(\varphi + \alpha)k, \quad (2)$$

Where $\alpha = \omega \cdot t$ is the angle by which the blade turns for the time t.

Thus the speed vector of a random point of the blade is the 2π periodic function of α. That is why, since the diurnal soil surface is usually below the *xOy* plane of reference, it will be enough to consider the change in this vector in a range from 90 to 360°.

The operation mode of the BROU is characterized by the kinematic parameterλ. It is equal to the relation of the circular speed of points on the cutting edges of the curved blade to the forwarding speed of the tillage machine, i.e., $\lambda = \omega r/ v_{fwd.}$ The speed vector projections for the points on the instantaneous rotation axis of the BROU are equal to zero. Taking account of (2) and proceeding from $v_z = 0$, cos (φ+α) = 0. Since $\varphi + \alpha > \pi/2$, then $\varphi + \alpha = 3\pi/2$ and sin (φ +α) =–1. That is why, proceeding from the second condition, $v_x = 0$, $\rho = v_{fwd}/\omega = r/\lambda$. The instantaneous rotation axis of the BROU blades lies in the vertical plane passing through the rotation axis of the hub. It lies below the axis of the hub at the distance r/λ at which the instantaneous rotation axis of the flat disk knife lies at the distance from its rotation axis given that the knife runs at the same forward ($\boldsymbol{v}_{fwd}$) and angular (ω) speed Ponomarev (2014) as the BROU.

Assume that h is the maximal depth to which the BROU tills the soil. It is clear that, from the standpoint of attaining the maximal motive force and high-quality execution of process operations, the instantaneous rotation axis of the BROU must not be lower than the diurnal soil surface, i.e., such in equations must hold as $\frac{r}{\lambda} \leq r - h$ or

$$\lambda \geq 1/(1-\xi), \quad (3)$$

Where $\xi = h/r$ is the maximal relative blade embedment.

In equation (3) imposes the condition on λ and ξ that set the rational operation modes of the BROU. Note that this equation coincides with the similar condition attained by V. I. Medvedev for the flat disk propulsor. Condition (3) can be used as a functional restrictor in optimizing the parameters and operation modes of the BROU.

Since the coordinates of extreme point A ($\rho=r$; $\varphi=\pi/2$) on the minor blade semiaxis and extreme point B ($\rho=r$; $\varphi=0$) on the main blade semiaxis (Fig. 1b) in the $Oxyz$ frame of reference are, by virtue of (1), A ($r\sin\alpha + v_{fwd}t$; 0; $-r\cos\alpha$) and B ($-r\cos\alpha + v_{fwd}t$; $r\text{tg}\beta$; $-r\sin\alpha$) and the BROU hub crosses its rotation axis (ρ=0) in point O ($v_{fwd}t$; 0;

0), then the normal to the blade from untilled soil is determined by the following vectorial product:

$$n = \mathrm{O}A \times \mathrm{O}B = r^2(\cos\alpha \,\mathrm{tg}\beta\, i + j + \sin\alpha\,\mathrm{tg}\beta\, k), \qquad (4)$$

Where *i*, *j* and *k* and the unitary vectors of the *Oxyz* frame of reference.

If to use θ for denoting the angle between *v* and *n* and introduce the dimensionless parameter

$\zeta=\rho/r$, $1-\xi \le \varsigma \le 1$ (because $r-h \le \rho \le r$), the result from (2) and (4) will be

$$\cos\theta = \frac{\boldsymbol{v}\cdot\boldsymbol{n}}{v|\boldsymbol{n}|} = \frac{\sin\beta(\lambda\zeta\sin\varphi + \cos\alpha)}{\sqrt{(\lambda\zeta)^2 + 2\lambda\zeta\sin(\varphi+\alpha) + 1}}. \qquad (5)$$

Formula (5) coincides with the formula from Mukhametshin and Valiev (2016) with an accuracy to the symbols.

The main semiaxis (φ=0) of the first blade to penetrate the soil can lie in it depending on ξ at turning angle values of $180^\circ \le \alpha \le 360^\circ$. In addition, as it appears from (5) θ is blunt at φ=0 and $180^\circ < \alpha < 270^\circ$. Consequently, the blade section adjoining the major blade semiaxis has an insufficient soil crumbling efficiency.

The equation derived for the points of the cutting edge of the minor semiaxis upon substituting $\varphi=90^{\circ}$ to (5) is

$$\cos\theta = \frac{\sin\beta(u+\cos\alpha)}{\sqrt{(u+\cos\alpha)^2+\sin^2\alpha}}, \qquad (6)$$

Where $u = \lambda\zeta$. Since $\theta'_u \leq 0$ at any u and α, then $\theta'_\lambda = \zeta\theta'_u \leq 0$, and $\theta'_\zeta = \lambda\theta'_u \leq 0$ at any λ, ζ, α, and the crumbling efficiency of the cutting edge section adjoining the minor semiaxis starts to improve with increasing λ and ζ at any α because θ decreases in the process.

The minor semiaxis of the first blade to penetrate the soil can be positioned in it depending on ξ at the turning angle values of $90^{\circ} \leq \alpha \leq 270^{\circ}$. Figure 2a shows the graphs of the θ/α relation for three points of the minor semiaxis (ζ = 0.4; 0,5; 1) and the characteristic value $\lambda=3$. In this figure the three upper and the three lower curves correspond to $\beta = 20^{\circ}$ and $\beta = 60^{\circ}$, respectively. What is more, the unbroken thin and thick curves are drawn for $\zeta=0.4$ and $\zeta=0.5$, respectively, and the dashed curves are drawn for $\zeta=1$. It follows therefrom that the blade section adjoining the minor semiaxis shows the highest soil crumbling efficiency at the groove bottom, and this efficiency decreases with the approximation to the diurnal soil surface at any α but for $\alpha = 180^{\circ}$ at which the crumbling efficiency is constant. The angle $\theta < 80^{\circ}$, i.e., less than in tillage milling cutters is observed even for $\beta = 20^{\circ}$. At $\beta = 60^{\circ}$ this angle takes on values close to θ in plows. Thus the soil crumbling efficiency of the given blade section at this value of β is close to the soil crumbling efficiency of plows.

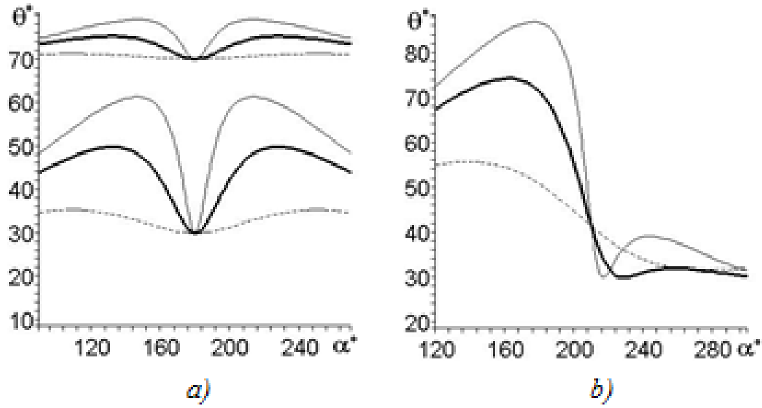

Fig. 2. Relation of the angle θ to the blade turning angle α for the points of the minor blade semiaxis (a) and the points of the blade line φ=60° (b)

The part of the considered blade adjoining the line φ=60° interacts with the soil at turning angles of 120° ≤ α ≤ 300°. That said, θ for λ=3 and β=45° varies according to the graphs presented in Fig. 2b. What is more, the unbroken thin and thick curves correspond to ζ=0.4 and ζ=0.5, respectively, and the dashed curve corresponds to ζ=1. In the greater part (byζ) of the given section of the blade this angle is much smaller than θ for tillage milling cutters. What more, the values is of θ become close to its values for plows from the start of the soil removal from the groove bottom.

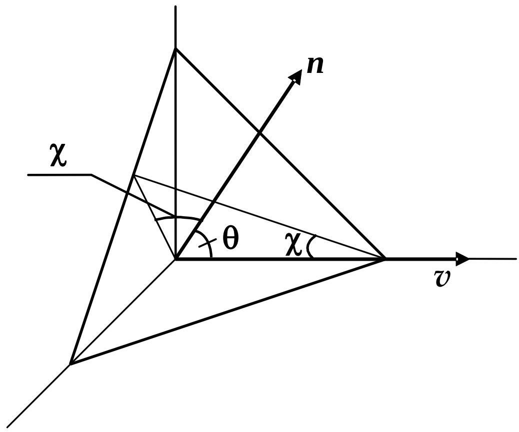

Fig. 3. Determining the cutting angle χ of the three-face wedge

According to Kanarev (1983), the χ angle of soil cutting by the trihedral wedge is the angle between the motion course of the soil along the wedge and the direction opposite to the trajectory of the wedge. In the compressible soil stratum model χ is supplementary to the angle between the normal to the wedge plane and the wedge forwarding speed vector to the angle of π/2 (see Fig. 3).

The blade sections adjoining the curved cutting edge can be treated as elementary trihedral wedges with the common normal that is normal to the blade. However, these wedges move at various absolute speeds. The first researcher to present this approach was (Akimov, 2001). In Akimov (2006) it was used to study cutting angles of elementary lines of flat disks of hoeing plows and the derived conclusions were well in line with the known results of experimental works for such disks.

Since the cutting angle is $\chi = \pi/2 - \theta$ and $\rho = r$ for the points of the curved cutting edge, then the cutting angle of an elementary section of this cutting edge determined by φ is found from (5) at ζ=1:

$$\sin\chi = \frac{\sin\beta(\lambda\sin\varphi + \cos\alpha)}{\sqrt{\lambda^2 + 2\lambda\sin(\varphi+\alpha)+1}}. \qquad (7)$$

Figure 4a shows the graphs of the relation of the cutting angle χ to the blade turning angle α at φ=0 for λ=2, 3, and 6. The graphs are drawn for 180°≤α≤360° for which the major blade semiaxis can lie in the soil because, usually, $h \le r$. It follows from these graphs that at any depth of tillage the cutting angles of the curved blade section adjoining the major blade semiaxis (φ=0) will be negative until the maximal embedment of this semiaxis is attained at α=270°.

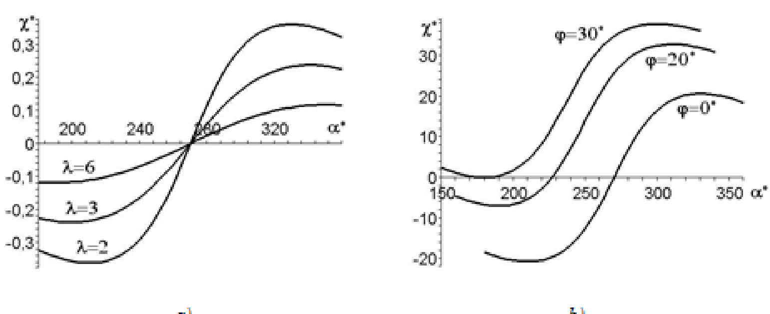

Fig. 4. Relation of the cutting angle χ for the points of the curved cutting edge to the blade turning angle α at different λ (a) and φ (b)

At negative cutting angles the elementary sections of the curved cutting edge interact with the soil as obtuse two-face wedges, which increases nonproductive energy expenditures and aggravates the quality of tillage. Figure 4b shows the graphs of the considered relation in the spaces of possible interaction of the elementary parts of the cutting edge with the soil for $\lambda=2$ at $\varphi=0°$, $\varphi=20°$, $\varphi=30°$. It follows therefrom that, according to α, the spaces with negative cutting angles at minor λ and small φ can be quite significant. That said, high nonproductive losses of energy at a much worse quality of tillage are also possible.

It follows from (7) that the cutting angle for all the sections of the curved cutting edge will be other than negative only at $\lambda\sin\varphi + \cos\alpha \geq 0$. The condition sufficient to meet this inequation is

$$\sin\varphi \geq 1/\lambda, \qquad (8)$$

Because in this case $\lambda\sin\varphi \geq 1 \geq -\cos\alpha$. On the other hand, condition (8) is also necessary for the non-negativity of cutting angles because at $\varphi = \pi/2$ and $\alpha = \pi$ $\lambda\sin\varphi + \cos\alpha = \lambda - 1 \geq 0$, $1/\lambda\leq 1$, i.e., $\sin(\pi/2) \geq 1/\lambda$. The latter inequation coincides with condition (8) at $\varphi = \pi/2$. Thus inequation (8) is the necessary and sufficient condition for the absence of negative cutting angles on the curved blade of the BROU. It is well in line with the graphs given in Fig. 4.

On top of that, to fulfill condition (8), the cutting angles for the points of the curved cutting edge can be made fairly small by selecting such dimensional parameter as the angleβ, which additionally makes it possible to reduce the specific energy expenditures on executing the processing functions of the BROU. With condition (8) fulfilled, in equation

$$\frac{\lambda \sin\varphi + \cos\alpha}{\sqrt{\lambda^2 + 2\lambda \sin(\varphi + \alpha) + 1}} \le 1, \qquad (9)$$

is equivalent to the evident inequation $(\lambda\cos\varphi+\sin\alpha)^2\ge 0$. Therefore, inequation (9) holds for any α and φ that meet (8). But then it follows from (7)-(9) that $\sin\chi \le \sin\beta$ for all the points on the curved cutting edge, which means that $\chi \le \beta$. In other words, the non-negative cutting angles of the points of the curved cutting edge do not exceed β at $\sin\varphi \ge 1/\lambda$.

The formula for the points of the cutting edge of the minor semiaxis is

$$\sin\chi = \frac{\sin\beta(\lambda\varsigma + \cos\alpha)}{\sqrt{(\lambda\varsigma + \cos\alpha)^2 + \sin^2\alpha}}. \qquad (10)$$

The necessary and sufficient condition for attaining the non-negative cutting angles of the points of the minor semiaxis is $\lambda\zeta$ +

cosα ≥ 0. To satisfy this inequation at any α and ς meeting the inequation 1–ξ ≤ ς ≤ 1, it is enough to require that condition (3) λ ≥ 1/(1–ξ), be met because in this case λζ ≥λ(1–ξ) ≥1 ≥ –cosα.

It is obvious that at λζ + cosα ≥ 0 the inequation

$$\frac{\lambda\varsigma + \cos\alpha}{\sqrt{(\lambda\varsigma + \cos\alpha)^2 + \sin^2\alpha}} \leq 1$$

Holds for allα; therefore, χ ≤ β is also fulfilled by virtue of relation (10) for all the points of the cutting edge of the minor semiaxis that lie in the soil at any position of the blade. Consequently, the non-negative cutting angles for the points on the cutting edge of the minor semiaxis do not exceed β either.

4. CONCLUSION

The kinematic analysis of the blade rotary operating unit has made it possible to determine the angle between the normal to the blade and the speed vector of a random point of the blade and elementary cutting angles of various sections of the straight and the curved cutting edge, and also draw the following conclusions:

1) The θ angles attainable by selecting the blade incidence angle β are much smaller than in milling cutters and close to the

respective angles in plows; in other words, it is possible to attain a high soil crumbling efficiency of the BROU;

2) To achieve a higher quality of tillage with lower specific energy expenditures, it is enough to select the operating unit mode meeting $\lambda \geq 1/(1-\xi)$ and ensure that $\sin\varphi \geq 1/\lambda$ holds by cutting the parts of the blades adjoining directly to their major semiaxes.

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