RATIONALE OF THE OPTIMAL SHAPE AND PLACEMENT ANGLE VARIATION PATTERN OF THE TILLAGE ROTARY BLADE

ՀՈՂԱՄՇԱԿ ՖՐԵԶԻ ԴԱՆԱԿԻ ՕՊՏԻՄԱԼ ՁԵՎԻ և ՏԵՂԱԿԱՅՄԱՆ ԱՆԿՅԱՆ ՓՈՓՈԽՄԱՆ ՕՐԻՆԱՉԱՓՈՒԹՅԱՆ ՀԻՄՆԱՎՈՐՈՒՄ

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ABSTRACT
The article addresses the issue of reducing the energy consumption and minimizing the ejection of loosened soil mass from the cultivated zone in gardening tillage rotary machines with a vertical rotation axis. Generally, rotary tilling machines with a horizontal rotation plane are characterized by high energy consumption. Additionally, during the rotary tilling process, there is an undesirable phenomenon of soil mass ejection caused by the blade, resulting in exposed areas and furrows in the already cultivated zone. This results in a disruption of the technological quality of soil cultivation. Considering that both the resistance moment of the rotor and the intensity of soil mass ejection are significantly influenced by several structural-technological and soil physico-mechanical factors, the comprehensive and simultaneous identification of these influences remains a relevant challenge. The solution to the problem is based on the theory of adjusting the angular positioning of rotary tiller blades and the results obtained. The theoretical solution to the issue of soil mass ejection from the cultivated area relies on the model of oblique impact between two bodies under viscous friction conditions. As a result, expressions were derived that allow determining an optimal angular positioning pattern for the tiller blades and an optimal shape of the blade body. These ensure that the technological process is carried out with minimal energy consumption and the least possible soil mass ejection.

ԱՄՓՈՓԱԳԻՐ
Հոդվածում դիտարկվում է ուղղաձիգ պտտման առանցքով այգեգործական հողամշակ ֆրեզի էներգատարրողության և մշակման գոտուց փխրեցված հողազանգվածի արտաշպրտման նվազեցման հիմնախնդիրը: Ընդհանուր առմամբ հորիզոնական հարթության մեջ պտտվող հողամշակ ֆրեզ-մեքենաներին ներհատուկ է բարձր էներգատարրողությունը, բացի այդ, հողի ռոտացիոն մշակման ընթացքում դիտվում է դանակի կողմից մշակված հողային զանգվածի շպրտման անցանկալի երևույթ, որի պատճառով արդեն իսկ մշակված հողային գոտում ի հայտ են գալիս որոշ մերկացած տեղամասեր և ակոսներ, որոնց հետևանքով խաթարվում է հողի մշակման տեխնոլոգիական որակը: Հաշվի առնելով, որ ինչպես ռոտորի դիմադրության մոմենտը, այնպես էլ հողազանգվածի արտաշպրտման ինտենսիվության վրա որոշիչ ազդեցություն են թողնում մեքենայի կառուցվածքա-տեխնոլոգիական և հողի ֆիզիկա-մեխանիկական հատկություններով պայմանավորված մի շարք գործոններ, որոնց ամբողջական ու միաժամանակյա ազդեցության բացահայտումը մնում է ակտուալ խնդիր: Խնդրի լուծման հիմքում դրված է հողամշակ ֆրեզի դանակների տեղակայման անկյան կարգավորման տեսությունը և ստացված արդյունքները: Մշակվող տարածքից հողազանգվածի արտաշպրտման խնդրի տեսական լուծման հիմքում դրված է երկու մարմինների շեղ հարվածի մոդելը մածուցիկ շփման պայմաններում: Արդյունքում ստացվել են արտահայտություններ, որոնք հնարավորություն են տալիս սահմանել ֆրեզի դանակների տեղակայման անկյան կարգավորման այնպիսի օրինաչափություն և դանակի իրանի օպտիմալ ձև, որոնց դեպքում տեխնոլոգիական գործընթացն իրականացվում է նվազագույն էներգածախսումներով և հողազանգվածի հնարավոր քիչ արտաշպրտմամբ:

INTRODUCTION
Nowadays, the rotary tillers equipped with active operating parts have been widely used in the process of soil cultivation, in particular in the orchards and vineyards, to ensure the highest quality of the soil tillage

processes, weed control as well as to provide relevant agrotechnological requirements *(Acharya et al. 2019*; *Manaenkov et al, 2017; Panov and Tokushev, 2005*; *Schjønning and Rasmussen, 2000*).
The cutting angles of the blade in the separate locations of its movement trajectory significantly exceed the defined optimal cutting angles of the common operating parts of the rotary tiller with the vertical rotation axis *(Sineokov and Panov; 1977; Koval, 2010*; *Kupryashkin and Gusev, 2020; Panov and Tokushev, 2005).* The mentioned factor not only increases the energy consumption of the technological processes, but also negatively effects on the technological quality of the soil cultivation. The high energy consumption of the rotary tiller is connected also with the quite high cutting speeds of the soil's tillage process (5,0÷10,0) $\frac{m}{s}$, in the course of it the technological characteristics of the interactions between the working part and cultivated soil changing significantly (*Panov and Tokushev, 2005*; *Sineokov and Panov, 1977)*. This creates additional dynamic resistance, not only due to the soil cutting process but also due to the scattering of the cultivated soil mass. The aforementioned significant drawback is inherent in tillers with a vertical rotation axis *(Kupryashkin and Gusev, 2020; Konstantinov, 2019)*.

Unlike the horizontal tillers, where the soil's cutting is a periodic process, in the case of the vertical tillers it is continuous and the knives are in the dense soil environment throughout the technological process.

In the case of the rigid fixation of the blade of the tiller with vertical rotation axis, the installation angles were selected by considering the fact that in the frontal area which is the most overloaded part of the knife's trajectory, the cutting angle was within the range of optimal values: $\beta = (20-30)^0$ *(Akimov A.P. et al, 2013; Akimov A.P. et al, 2018; Grigoryan and Altunyan, 2021, Tarverdyan et al, 2022).*

With this approach, the cutting angle almost doubles along the rest of the blade's movement trajectory, particularly in the tiller's rear area. As a result, highly undesirable processes such as scattering and scraping of the cultivated soil mass by the inner surface of the blade's handle are observed, negatively impacting technological quality. It is also important to note that changes in the cutting angle over such a wide range generate vibrations to the rotating parts, particularly the vibration of the tiller rotor, which is an undesirable phenomenon to ensure reliable machine operation.

The energy consumption of the technological process of the rotary tiller has been mainly defined by the geometric shape, location as well as the mutual positioning of the knives. This has been approved by many research studies and our own experiments *(Panov, 2005; Koval, 2010; Konstantinov, 2019; Vorobyov and Marchenko, 1990; Chatkin, 2008; Mandal et al, 2013; Matin & Fielke, 2014; Raparelli et al, 2021; Grigoryan and Altunyan, 2021).*

In addition, by considering the fact that the operational reliability of the existing machines is relatively low, especially in the types of terrain in the Republic of Armenia, which are characterized with the high content of stones and gravels, self-regulating blades for angular positioning were designed and developed, specifically for rotary tilling machines with a vertical rotation axis.

The patterns of variation in cutting angles and the conditions for maintaining them constant, in the case of a fixed positioning angle of the blade in a soil-cultivating rotary tiller with a vertical rotation axis, are detailed in the previous study *(Tarverdyan A.P. et al, 2023).*

In the study mentioned, an important conclusion was reached based on the review and analysis of scientific literature in the field. It highlights that the inherent shortcomings of soil-cultivating rotary tillers with a vertical rotation axis—namely, high energy consumption and the ejection of loosened soil from the cultivation zone—can be minimized. This can be achieved by optimizing the blade shape and adjusting the blade positioning angle throughout one rotation of the rotor.

The article aims to study the inherent drawbacks of rotary tillers with a vertical rotation axis, specifically high energy consumption and soil mass ejection from the cultivated zone, and to develop and justify an optimal blade body shape and a theoretical calculation for adjusting the angular positioning of the blades during one rotation of the rotor.

MATERIALS AND METHODS

As already mentioned, the high energy consumption and soil mass ejection of rotary tilling machines with a vertical rotation axis are primarily and mainly due to changes in the cutting angle of the blades during one rotation of the rotor, which, in turn, is related to the fixed angular position of the blades *(Akimov A.P. et al, 2013, Damanauskas et al., 2019).*

It is evident that a stable cutting angle during the operation of the tiller can only be ensured through the non-rigid fixation of the blades and the corresponding adjustment of their angular positioning.

The issue has been thoroughly discussed and resolved by us in *(Tarverdyan A.P. et al, 2023)*, where analytical expressions were derived that substantiate the possibility of maintaining a constant cutting angle of the blades during one rotation of the rotor. Since this work also addresses the problem of blade angular positioning and, in particular, the optimal shape, it is necessary to present certain provisions and results from the mentioned work here.

During the operation of the rotary tiller when the rotor rotates at an angular speed ω $(\varphi = \omega t)$ and makes a forward movement in the direction of the X axis at a speed of V_F (Fig. 1), an arbitrary point C of the rotary tiller draws an elongated cycloid (trochoid), the appearance of which is determined by the kinematic parameter of the rotary machine:

$$\lambda = \frac{V_C}{V_F} > 1, \quad (V_C = \omega R)$$

where V_F is the forward velocity of the machine [m/s] and V_C is the circumferential velocity of the blade [m/s], R - the rotation radius of the C point of blade, [m], ω - angular speed of the tiller blade, [min^{-1}].

In parametric form, the equation of C point motion in the XOY coordinate system is as follows in Eq. (1):

$$\left.\begin{aligned} x &= V_F t \pm R sin\omega t, \\ y &= R cos\omega t. \end{aligned}\right\} \tag{1}$$

where V_F is the velocity of forward movement of the aggregate [m/s], R - rotation radius of blade point (e.g. C point) [m], ω - angular speed of the tiller blade [min^{-1}]

The movement of the blade attached to the rotor during one full rotation is analyzed and it is assumed that the conventional starting point is the moment when the cutting edge of the blade crosses the y-axis (M point, Figure 1). The M point draws the MCANBF cycloid during one rotation, and since the blade is fixed to the rotary tiller disk at a constant angle γ with respect to the radius (OM), the cutting angles characterizing the technological process of soil cutting mass are constantly changing during the rotation.

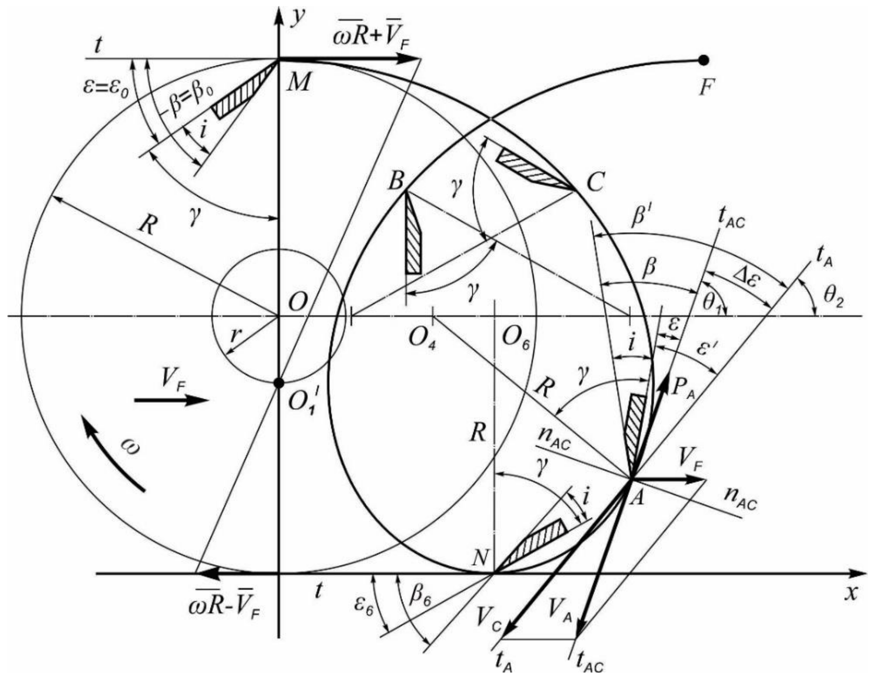


Fig. 1 - The changing scheme of the trajectory and cutting angles of the tiller's blade during one rotation of the rotor

The installation angle of the blade in an arbitrary position A of the trajectory - the angle γ - formed by the back plane of the knife arm and the radius $O_4A=R$ in that position is constant and unchanged, β_4' is the front cutting angle; it is the angle formed by the tangent t_A of the front plane of the blade and the tangent at point A to the circle with radius $O_4A=R$, ε' is the angle formed by the back part of the blade and t_{AC} tangent, β_4 - real front cutting angle, it is the angle formed by the front plane of the blade and cycloidal tangent t_A across the A point, i - sharpening point of the blade.

The diagram (Figure 1) attests, that:

$$\beta' = \varepsilon' + i; \quad \beta = \varepsilon + i; \quad \beta = \beta' - \Delta\varepsilon; \quad \varepsilon = \varepsilon' - \Delta\varepsilon, \tag{2}$$

where $\Delta\varepsilon$ is the angle made by the cycloidal tangents (t_A and t_{AC}) to the circle at the given point (A).

Since the discussed objective seeks to provide the possible constant values of the blade's cutting angles during one rotation of the tiller, the only possible case is to reach the equilibrium of the changes of moment loads generated from the factors of the resistance forces applied on the rotor's shaft. It is obvious that in that case the blade installation angle γ has to be changed or adjusted.

As a result of the study of an arbitrary point trajectory on the tiller blade and the kinematic analysis of the drive mechanism, an analytical expression was derived for the precise determination of the change in the cutting angle of a rigidly fixed blade during one rotation of the rotor *(Tarverdyan A.P. et al, 2023)*.

$$\Delta\varepsilon = \pm arccos\frac{\lambda \pm cos\varphi}{\sqrt{1+\lambda^2 \pm 2\lambda cos\varphi}}: \tag{3}$$

Since, according to the condition of the discussed problem, the cutting angle of the blade must remain as constant as possible, the relationship between the blade's angular positioning γ and the change in the cutting angle Δε must be taken into account.

$$\gamma = \frac{\pi}{2} - \beta + i - \Delta\varepsilon, \tag{4}$$

The specified condition can only be met if the change in γ follows the same pattern.

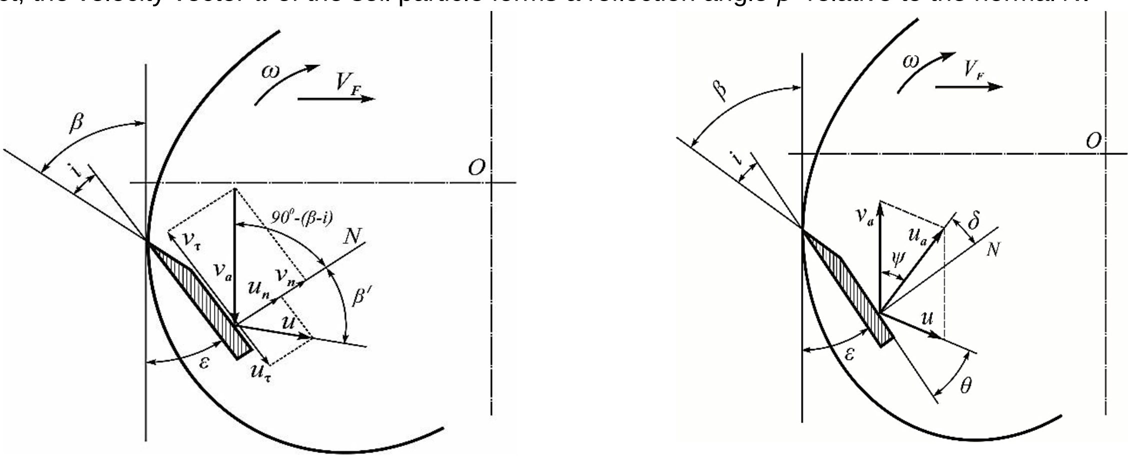
The other essential aim of the discussed problem is to exclude or minimize the throwing process of the cultivated soil mass from the cultivated zones by the tiller's blade.

A straight flat blade of a rotary tiller with a vertical axis was chosen as the object of study.

When determining the angle of soil displacement and the relative and absolute velocities, it was assumed that the interaction between the blade and the soil is of impact nature under conditions of viscous friction.

The impact process between an individual soil particle and the vertical surface of the blade is considered. The blade has a cutting angle β, an inclination angle *i*, and an absolute velocity v_a (Fig. 2).

In the case of reversibility of the impact process, it can be assumed that the soil particle strikes the stationary blade with a velocity v_a at an angle of $90^o - (\beta - i)$ relative to the normal *N* of the blade vertical surface (Fig. 2a shows the pre-impact velocity v_a and the post-impact velocity *u* of the soil particle). After the impact, the velocity vector $\bar{u}$ of the soil particle forms a reflection angle β' relative to the normal *N*.



a) b)

Fig. 2 - The case of a soil particle impact on the vertical flat surface of the blade:
a) scheme for determining the relative velocity,
b) scheme for determining the angle of the absolute velocity of particle displacement.

According to the classical theory of oblique impact for inelastic bodies, there is the following relationship between the normal components of the pre-impact and post-impact velocities of the particle *(Ivanov A.P., 1992)*:

$$\mu = \frac{u_n}{v_n}, \tag{5}$$

where μ is the coefficient of restitution of the impacting body, $0 \le \mu \le 1$, v_n and u_n - the normal components of the pre-impact and post-impact velocities [m/s]. Moreover, the values $\mu = 0$ correspond to an absolutely inelastic impact, and $\mu = 1$ to an absolutely elastic impact.

Between the tangential components of the velocities, according to the hypothesis of viscous friction, the following relationship exists.

$$u_\tau = (1-\varphi)v_\tau, \tag{6}$$

where v_τ and $u_\tau$are the tangential components of the pre-impact and post-impact velocities [m/s], and φ- the instantaneous coefficient of friction during the impact.

After the impact, the relative velocity of the soil particle's motion, according to the scheme shown in Fig. 2a, will be:

$$u = \sqrt{u_\tau^2 + u_n^2}.$$

Considering that $u_\tau = v_a(1-\varphi)cos(\beta - i)$ and $u_n = v_a\mu \cdot sin(\beta - i)$, after certain transformations it will be obtained:

$$u = v_a\sqrt{(1-\varphi)^2cos^2(\beta - i) + \mu^2sin^2(\beta - i)}. \qquad [\mathrm{m/s}] \tag{7}$$

Regardless of which hypothesis is accepted for oblique impact - viscous or dry friction - the post-impact velocity of a material point after an oblique impact is determined as follows *(Blekhman I.I., 1979):*

$$u = v_a\mu \cdot \frac{cos(\beta - i)}{sin\beta'}. \tag{8}$$

According to the viscous friction hypothesis *(Blekhman I.I., 1979)*, the angles of reflection β' and impact $[90-(\beta - i)]$ are closely related by the following expression (Fig. 2a):

$$tg\beta' = \frac{1-\varphi}{\mu}tg[90-(\beta - i)]. \tag{9}$$

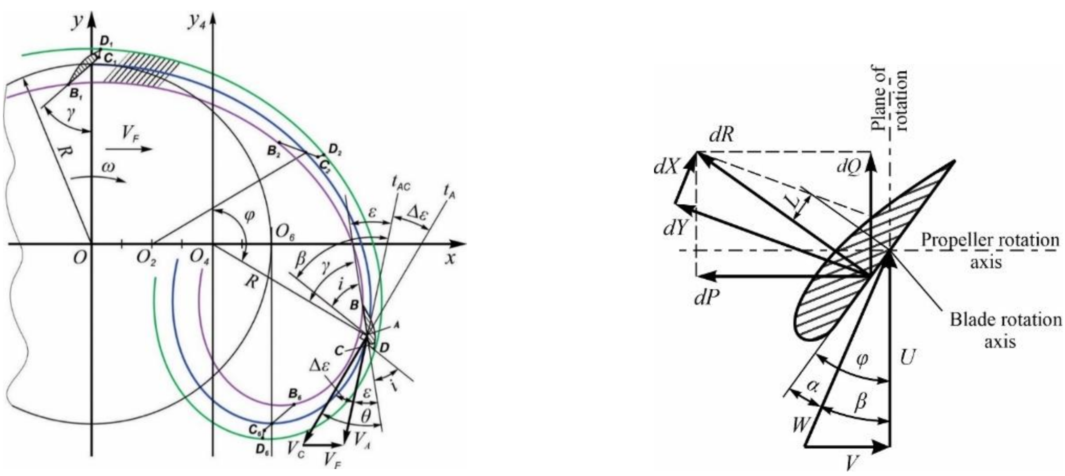
Since the blade is actually moving, and the soil particle is initially at rest before the impact, after the impact, the motion will also be transmitted to the soil particle in the direction of the impact. Therefore, the post-impact absolute velocity u_a of the soil particle will be determined as the vector sum of the translational velocity v_a and the relative velocity u (Fig. 2b).

$$u_a = \sqrt{u^2 + v_a^2 - 2uv_a cos(90 + \beta - i - \beta')}. \tag{10}$$

The high values of the post-impact absolute velocity (u_a) of the soil particle are responsible for the ejection of the soil mass and also for the significant forces acting on the blade *(Akimov A. P. et al, 2018)*. It should be noted that these factors are determined not only by the blade positioning angle but also by the geometric shape of the blade cross-section. Therefore, the blade positioning angle and the shape of its cross-sectional surface should be such that $u_a$is minimized.

RESULTS AND DISCUSSIONS

The process of the soil cutting, the cinematic and dynamic traits are characterized by the presented parameters in the arbitrary A point along with the trajectory (Fig.1 and 3).



a) b)

Fig. 3 - The scheme of the cutting angles changes of the tiller's blade with the streamlined form (a) The scheme of the propeller location angles (according to Alexandrov V.L) (b)

During these investigations the goal is to elaborate certain scheme of the knife location to allow the cutting angles β and ε, by characterizing the main tillage procedure, to remain constant during one rotation and the location angle γ to be subjected with the designed adjusted changes, in respect with the Equation (11) *(Tarverdyan A.P. et al, 2023)*

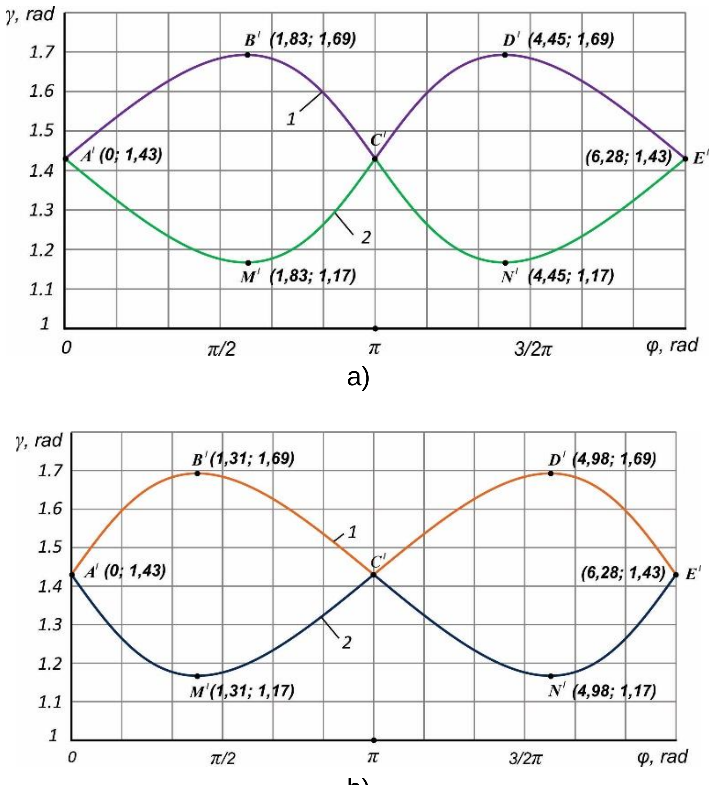
$$\gamma(\varphi) = \frac{\pi}{2} - \beta + i \mp arccos\left(\frac{\lambda \pm cos\varphi}{\sqrt{1+\lambda^2 \pm 2\lambda cos\varphi}}\right), \tag{11}$$

where i is the sharpening angle of the blade, it is constant in each specific problem; it is assumed that β is also constant as a precondition and hence assigning $K = \frac{\pi}{2} - \beta + i$ it can be written:

$$\gamma(\varphi) = K \mp arccos\left(\frac{\lambda \pm cos\varphi}{\sqrt{1+\lambda^2 \pm 2\lambda cos\varphi}}\right). \tag{12}$$

whereas $\mp arccos\left(\frac{\lambda \pm cos\varphi}{\sqrt{1+\lambda^2 \pm 2\lambda cos\varphi}}\right)$ member exhibits itself the changes of the cutting angles during one rotation period $\Delta\varepsilon$.

As it is known *(Tarverdyan A.P. et al, 2023)*, the variation pattern of γ may depend on the rotor's rotation angle (φ) having the following form (Fig. 4):



1. $\gamma = 1{,}43 + arccos\left(\frac{\lambda+cos\varphi}{\sqrt{1+\lambda^2+2\lambda cos\varphi}}\right)$,
2. $\gamma = 1{,}43 - arccos\left(\frac{\lambda+cos\varphi}{\sqrt{1+\lambda^2+2\lambda cos\varphi}}\right)$

1. $\gamma = 1{,}43 + arccos\left(\frac{\lambda-cos\varphi}{\sqrt{1+\lambda^2-2\lambda cos\varphi}}\right)$,
2. $\gamma = 1{,}43 - arccos\left(\frac{\lambda-cos\varphi}{\sqrt{1+\lambda^2-2\lambda cos\varphi}}\right)$

Fig. 4 - The diagram of $\gamma = f(\varphi)$ function during one rotation of the rotor in case of constant cutting angles ($\lambda = 3,85$)

By following the presented pattern to ensure changes in the cutting angles, the tiller will operate stably and without vibrations. In this direction the research experiments continue to enhance the efficiency and productivity of the machine work.

However, it is essential to note, that the primary objective of the presented research is to solve the issue related to the soil throwing from the cultivated zone during the tillage. In fact, as it is mentioned, efforts were made to strengthen and ensure the streamlined shape of the blade.

Field experiments have revealed the fact that the high value of the absolute velocity (V_A) of the soil particle after hitting the surface of the knife determines the throwing of the soil mass as well as the high resistance forces of the knife *(Grigoryan and Altunyan, 2021; Akimov A.P., 2018; Tarverdyan A.P. et al, 2024; Konstantinov Yu.V., 2019; Raparelli T., 2021)*.

Considering equations 7 and 10, the post-impact absolute velocity of the soil particle is obtained:

$$u_a = v_a\sqrt{1 + m + 2\sqrt{m} \cdot \sin(\beta - \beta' - i)}, \qquad [\mathrm{m/s}] \tag{13}$$

where $m = (1 - \varphi)^2 \cdot \cos^2(\beta - i) + \mu^2 \cdot \sin^2(\beta - i)$:

Expression (13) implies that, in the case of a constant cutting angle, the absolute velocity of the post-impact soil particle remains approximately unchanged during one rotation of the rotor.

It must be considered that these factors have been related not only to the installed angles of the blade but also to the geometrical shape of its body plane. This indicates that its study and optimal configuration as well as the determination of its parameters becomes a vital issue.

It is important to define the exact knife shape (contours) for the required surface of the transverse incision of the blade to cause small resistance forces while moving in the soil and to have such a ratio of the tangential components and normal velocities of the different parts of the surface to result in a minimized throwing of the soil mass.

In the context of hydrodynamics and aerodynamics' similar problems, the movement of the bodies with streamlined abilities in the environment is considered *(Landau and Lifshitz, 2001).*

Research has defined that it is essential that the particles' detachment from the surface occur at the back edge of the body, where the "stormy" movements of the particles are minimal.

It is significant to mention that the field experiments and operation practices of the tiller have demonstrated that the amount of the soil thrown during its cultivation, is primarily connected with the physico-mechanical characteristics of the soil and its moisture content. In particular, the extent of throwing soil is minimal or completely absent in the wet and silty soil, whereas it is maximum in the dried soil that is characteristic for most orchards in Armenia.

Thus, the discussion refers to the example described above, and the behavior of dry, pulverized bulk soil mass can be assessed with the above mentioned analogy.

According to the prominent provisions of this analogy, it should be given such a form to the blade plane that the growing environmental resistance would occur slowly and smoothly along with its edge length.

The solution is to give elongated form to the plane of the blade so that that the streamlined surfaces gradually approach the cleaning direction by creating a sharp edge at the junction. In fact, the frontal part should have a rounded shape.

The mentioned conditions are totally provided by the prominent streamlined shape of plane (Figure 5).

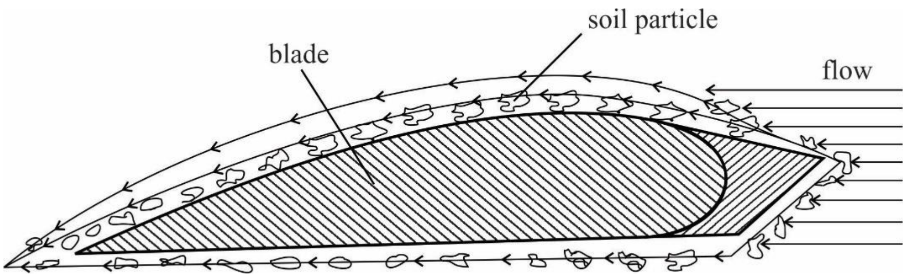


Fig. 5 - The scheme of the streamlined plane of the rotary tiller's blade

It is obvious, that the streamlined shape is related to the entire length of the blade body where the cutting edge should be fixed at the rounded part of the blade in the cutting zone of the soil layer.

Since the basis of the objective is to maintain the constant values of the cutting front and, consequently, the rear angles of the blade ($\beta = const$ or $\varepsilon = const$) during one rotation of the tiller rotor by regulating the angle of the knife location (Y), it is explicit from Equation (14) that:

$$\varepsilon = \frac{\pi}{2} - \gamma \pm \Delta\varepsilon = const. \tag{14}$$

In respect with the above mentioned analogy, it can be defined that during complex movement of the streamlined body in the resisting environment (e.g. air, water), the best streamlined ability of the body with the smooth movement of particles without removal from its surface, and their minimal "stormy" movement is ensured if the following conditions exist *(Aleksandrov V.L., 1951):*

$$\alpha = \varphi - \beta = const \tag{15}$$

The dimensions are demonstrated in the scheme given in Fig. 3b, where the location angles of the propeller and the forces exerted on it are represented.

By comparing the schemes depicted in fig. 3a and 3b it is clear, that in the mentioned case α is equivalent to ε, β is equivalent to $\pm\Delta\varepsilon$ and to φ, to θ or to the same like: $\frac{\pi}{2}$-γ.

In two different fields, the elaborated problems with nearly almost identical objectives and varying principles of solutions have shown substantial similarities. This allows assuming that in the discussed case, the obtained equilibriums and formulas can serve as the basis for the practical solutions of the mentioned objectives.

It is quite remarkable and interesting to mention that determining the optimal and favorable values of the location and cutting angles the tiller knife, in the perspective of the equality and minimum *(Akimov A.P. et al, 2018; Ivanov A.P., 1992; Blekhman I.I., 1979)* conditions of the resistance forces and on the basis of the streamlined ability and exclusion of throwing away the soil mass particles, leads to the same result for the stability of the cutting angles of the knife and with a very specific pattern of the changes for the location angle.

To verify and evaluate the results of the theoretical research, a laboratory soil-cultivating rotary tiller with a self-regulating blade positioning angle was designed and developed. The results and analyses of its testing will be presented in future studies.

CONCLUSIONS

1. The resistance moment or energy consumption of the rotor of a rotary tiller with a vertical rotation axis and the volumes of soil mass displacement from the cultivated area are interrelated and, under stabilized technological-kinematic parameters, are primarily determined by the angular positioning of the blades and the shape of their cross-sectional profile.

2. A significant reduction in the resistance moment of the rotary tiller and the velocity and volume of soil mass displacement is achieved during one rotation of the rotor by ensuring the stability of the cutting angle and using a streamlined cross-sectional shape of the blade body. The stability of the cutting angle is maintained through the adjustment of the angular positioning, according to the derived expression and established pattern. The streamlined cross-sectional shape of the blade body, in the case of complex motion, ensures the smooth movement of soil particles without detachment from the body surface until their separation at the sharp rear end. The pattern of the surface curve will be determined in future studies.

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