Methodology for designing tillage working bodies of a stubble cultivator-flat-cutter based on agricultural biomechanics

L F Babitsky¹, I V Sobolevsky¹,², V A Kuklin¹

¹ V.I. Vernadsky Federal University, 4, Vernadskogo Prospekt, Simferopol, 295007, Russia
² Research Institute of Agriculture, 150, Kievskaya Street, Simferopol, 295493, Russia

E-mail: sobolevskii-ivan@mail.ru

Abstract. The article presents an engineering design technique based on agricultural biomechanics. This technique made it possible to theoretically substantiate the main parameters of the model of the working bodies of the cultivator-flat-cutter for tillage on the stubble using two bionic prototypes - the fan-shaped jaw of the scarab beetle (Scarabaeus) and the burrowing foot of the common dung beetle (Geotrupes stercorarius). The model of the working body of the cultivator-flat-cutter allows you to preserve the top stubble and ensure the anti-erosion resistance of the soil in the soil-protective agriculture system for the “Mini-till” technology. The results of experimental studies are presented, confirming the decrease in the traction resistance of the proposed models of the working bodies of the cultivator of the flat cutter for processing on the stubble with the preservation of its structure in the upper soil layer.

1. Introduction

The strategy for the development of agricultural production should be aimed, first of all, at increasing soil fertility in order to ensure higher yields of field crops and the quality of the resulting crop products. The annual use of plows, heavy cultivators, with them heavy tractors, in combination with multiple passes of the units across the field entails high costs for fuel, depreciation of equipment, and also has a detrimental effect on the soil and the environment. For the southern regions of Russia, with insufficient average annual precipitation, it is typical to use the minimum mini-till technology for the cultivation of grain crops. The mini-till cycle assumes the use of deep tillage only once every few years, the rest of the time the soil is cultivated by cultivators, rotary working bodies (verti-till technology) and harrows to a depth of 8 cm [1-3].

The analysis of the existing designs of the working bodies of cultivators and theoretical studies of the process of their work showed that the main theoretical developments are associated with the study of soil deformation under the influence of tillage working bodies [4, 5]. The influence of the shape and geometric parameters of the cutting blade on the energy intensity and quality of processing was determined on the basis of the methods of theoretical mechanics and continuum mechanics, soil mechanics and experimental methods. We have found that the shape of the working surfaces of most existing tillage working bodies is not always optimal, and the previously used theoretical methods and approaches do not make it possible to fully explain and take into account all the main phenomena that arise in the soil during mechanical processing. The use of the mechanical-bionic approach [1] will
allow one to analytically describe the shape and parameters of the working organs of the cultivator-flat-cutter with fundamentally new resource-saving methods of influencing the processed environment and meeting modern agrotechnical requirements.

The purpose of the research is the development of theoretical prerequisites for the substantiation of the parameters of the working bodies of the cultivator-flat-cutter for tillage on the stubble on the basis of agricultural biomechanics.

2. Materials and methods
In agricultural biomechanics, one of the main research methods is bionic modeling based on a systems approach. The objects under study were two natural models of biological prototypes: the fan-shaped jaw of the scarab beetle (Scarabaeus) and the burrowing foot of the common dung beetle (Geotrupes stercorarius). As a physical model for joint comparative studies of living systems and machines, the working bodies of the cultivator-flat-cutter were used for tillage on the stubble.

3. Results
The issue of using the methods of theoretical research with the use of the regularities of the systemic structure and functioning of objects of living nature still remains unresolved. As the analysis shows, the most relevant, in relation to the solution of this issue, is the use of the multi-contact action of the working bodies on the soil. Applying a systematic approach, taking into account the biological system "soil-plant-atmosphere", it is possible to substantiate the optimal geometric shapes of the working organs of the cultivator of the flat cutter for tillage on the stubble, giving them some properties, as well as the characteristics of living organisms [6].

The object of theoretical research is the technological process of interaction of the working bodies of the cultivator-flat-cutter with the soil on the stubble.

The biological prototype of the scarab beetle (Scarabaeus) [7] (Figure 1) is of particular interest for the bionic comparison of the working organs of the cultivator-flat-cutter in terms of the nature of their vital activity.

The design of the profile of the working surface of the cultivator of the flat cutter and the substantiation of the geometric parameters of this tillage working body are based on the patterns revealed in the study of the structural features of the bionic prototypes discussed above.

The common dung beetle with its first pairs of legs 1 with notches, shown in Figure 2, dig tunnels up to 2 meters deep.
The initial data for substantiating the parameters of the working body of the cultivator-flat-cutter are: the depth of the working body \( a \); the angle of friction of the soil against steel \( \phi \) and the angle of internal friction of the soil \( \phi_0 \).

The main working elements in the design of the working body of the cultivator-flat-cutter are the working surface of the chisel and the cutting edges of the wings.

It was found that the best soil crumbling is provided by rippers with a lateral profile made in the form of a logarithmic spiral, which is confirmed by an analysis of the structure of the lateral projection of the head of the scarab beetle (Scarabaeus). When constructing the working surface of the bit, we use the conjugate segments of the logarithmic spiral. To do this, we draw auxiliary lines 2-2 and 3-3 parallel to the \( OX \) axis, as shown in Figure 3. Through point \( C \) on line 2-2 at an angle \( \alpha_{\text{max}} = 90° - \phi \) to the \( OX \) axis, we draw a line 4-4 and a perpendicular 5-5 to the \( OX \) axis. In this case, the height of the working body \( h \) determines the place of points \( K' \) and \( O \), point \( C \) lies in the middle, and line 4-4 is a tangent to the section of the logarithmic spiral at point \( C \). Then, through points \( K' \) and \( K \) at an angle \( \alpha_1 \) to the \( OX \) axis, we draw tangents. In this case, the angle of installation of the working body \( \alpha_1 \) to the bottom of the furrow corresponds to the minimum possible angle:

\[
\alpha_1 = \alpha_{\text{min}} = 45° - \frac{\phi_0}{2}.
\]  

According to the formula \( Q = 90° - (\phi + \alpha_{\text{min}}) \) [8], we find the angle \( Q \), which determines the first section of the logarithmic spiral for the part of the chisel of the working body of the cultivator-flat-cutter, which cuts the soil layer.

**Figure 2.** Front burrowing leg of the common dung beetle (Geotrupes stercorarius)
Figure 3. Justification of the profile of the working surface of the cultivator-flat-cutter chisel

The initial radius vector $\rho_0$ of the section of the logarithmic spiral of the bit surface, the working body of the cultivator-flat-cutter, is determined by the known [9] dependence:

$$\rho_0 = \frac{a}{\cos Q \cdot \tan \varphi},$$

(2)

where $Q$ is the angle that determines the first logarithmic part of the profile of the working surface of the chisel of the working body of the cultivator-flat-cutter;

$\varphi$ is the angle of friction of the soil against steel;

$b$ is the depth of tillage.

We postpone the calculated value of the initial radius vector $\rho_0$ from point $C$ in both directions along the ray $P-P$. The resulting point $O_1$ is something other than the pole of a logarithmic spiral. It is also the undercutting part at the working surface of the chisel of the working body of the cultivator-flat-cutter we are designing. Then we draw a perpendicular to the $OX$ axis through the $O_1$ pole. We divide the angle $Q$ by rays into 7 parts with an interval of $9^\circ$.

We find the values of the intermediate radius vectors by the expression [1]:

$$\rho_i = \rho_0 \cdot e^{Q_i \cdot \tan \varphi_0},$$

(3)

where $\rho_i$ is the current radius vector;

$\rho_0$ is the initial radius vector;

$Q_i$ is the current polar angle;

$e$ is the base of the natural logarithm;

$\varphi_0$ is the angle of internal friction of the soil.

We postpone the found values of the radius vectors $\rho_i$ from the $O_1$ pole on the corresponding rays and connect the obtained points with a smooth curve. Thus, the first part of the working surface of the working body of the cultivator-flat-cutter is built.
In the upper second part of the surface of the cultivator-flat-cutter chisel, we draw a vertical straight line, which is a continuation of both the rack and the chisel of the working body of the cultivator-flat-cutter.

We determine the height of the chisel of the working body of the cultivator $h_{ch}$ according to the formula:

$$h_{ch} = K'O = \frac{2 \cdot \tan \alpha \cdot b}{e^{\alpha \cdot \gamma \phi_0}}. \quad (4)$$

The height $\Delta h$ of the chisel chest of the working body of the cultivator-flat-cutter is calculated by the formula:

$$\Delta h = \frac{h_{ch}}{2} = \frac{2 \cdot \tan \alpha \cdot b}{e^{\alpha \cdot \gamma \phi_0}} \cdot 2 = \frac{b \cdot \tan \alpha}{e^{\alpha \cdot \gamma \phi_0}}. \quad (5)$$

We find the outreach $L$ of the toe of the chisel of the working body of the cultivator-flat-cutter relative to the rack according to the equation:

$$L = l_1 + l_2 = \frac{2 \cdot \tan \alpha \cdot b \cdot \tan \theta}{e^{\alpha \cdot \gamma \phi_0}} + \frac{2 \cdot b}{e^{\alpha \cdot \gamma \phi_0}} = \frac{2 \cdot b}{e^{\alpha \cdot \gamma \phi_0}} \left( \frac{\tan \theta \cdot \tan \alpha}{1} + 1 \right). \quad (6)$$

To construct the projection of the wavy cutting edge of the wings of the cultivator-flat-cutter, on the basis of the front burrowing leg with the serrated dung beetle (Geotrupes stercorarius), we build the contour of its wavy cutting edge as shown in Figure 4. For this purpose, from the toe $O$ of the working body of the cultivator-flat-cutter at an angle $\gamma = 90^\circ - \varphi$, from the condition of descent with sliding of soil with plants, we draw a straight $OK$, which is equal to the length $L$ of the contour of the cutting edge of the blade of the wavy wing of the cultivator working body, found from equation (6).

The half-width of the grip $B_L/2$ of the working body of the cultivator of the cultivator-flat-cutter is determined by the formula:

$$B_L = L \cdot \sin \gamma = L \cdot \sin(90 - \varphi). \quad (7)$$

We find the number of protrusions $Z$ on the cutting edge of the cultivator working body wings using the equation:

$$Z = \frac{L + S - 2a}{S}. \quad (8)$$

We divide the $L$ value by the number of protrusions $Z$ and we obtain segments $OA, AB, BC, SD, DK$, which are equal to the width of $2a$, with a step $S$ of the protrusions.

Studies show that burrowing limbs of the biological prototype of the common dung beetle deserve special attention.
There are cavities between the teeth located on the beetle’s burrowing limbs, as shown in Figure 2. The shape of the cavity between adjacent teeth has the shape of a logarithmic curve described by the function \( f(x) \). To create a blade with a similar logarithmic shape, taking into account its “golden ratio”, we inscribe Kepler’s right-angled triangle \( \triangle A_1B_1C_1 \), which is shown in Figure 4. The peculiarity of a right-angled triangle is that the lengths of its sides make up a geometric progression corresponding to the golden ratio \( \Phi = 1.618 \) [10]. If a bisector \( B_1O_1 \) is drawn from the right angle of the base of two legs, then it will divide the hypotenuse into segments of a certain length \( b_1 \) and \( b_2 \). Measurements have shown that the ratios of the lengths of the larger \( O_1C_1 = b_2 \) segment to the small one \( A_1O_1 = b_1 \) are in the range of 2.1...2.9. Further, along the points of the triangle, we inscribe a segment of the logarithmic curve and get the outlines of the cutting edge of the wings of the cultivator-flat-cutter.

On the basis of the obtained theoretical prerequisites for the bionic substantiation of the parameters of the working organs of the flat cutter cultivator based on the prototypes of the fan-shaped jaw of the scarab beetle (Scarabaeus) and the burrowing foot of the common dung beetle (Geotrupes stercorarius), the design presented in Figure 4 has been developed.

![Figure 4](image)

**Figure 4.** Determination of the parameters of the cutting edge of the working body of the cultivator-flat-cutter

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![Figure 5](image)

**Figure 5.** Tillage working body of the cultivator-flat-cutter in bionic likeness: a - general view of the design development; b - a full-scale sample of the working body of the cultivator of the flat cutter when tested in the soil channel
The proposed tillage working body of the cultivator contains an elastic stand 1, a chisel 2, wavy side wings 3 and a striker 4 (Figure 6). The results of laboratory tests showed that the traction resistance of the proposed working body is 16.5% less than the traction resistance of the serial sample of the CFA-3.8 working body. This is due to the fact that the wavy wing blades and the profile of the bit reduce the traction resistance of the implement during stubble cultivation.

The use of the proposed tillage working bodies of the cultivator-flat-cutter with improved chisels and side wings will allow one to reduce the traction resistance and at the same time to increase the efficiency of surface loosening of the stubble of the soil in width and depth with the formation of a mulching layer, as well as to increase soil fertility with an increase in the degree of crumbling of soil aggregates during its stubble cultivation.

4. Conclusion
In accordance with the biosystem approach, as well as on the basis of the functional diagram improved as a result of theoretical studies, a design methodology and a new design of the working body of the stubble cultivator-flat-cutter have been developed. Based on the analysis of the structural features of the bionic fan-shaped jaw of the scarab beetle (Scarabaeus) and the burrowing foot of the common dung beetle (Geotrupes stercorarius), the following are analytically substantiated: the profile of the chisel and the wavy shape of the lateral wings of the working bodies of the cultivator-flat-cutter allow one to reduce the traction resistance by 16.5% and increase the efficiency of surface loosening of the soil on the stubble with the formation of a mulch layer.

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