Bionic modelling of the working bodies of machines for surface tillage

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Abstract. The article presents the methods and results of bionic modeling in agricultural mechanics, which made it possible to justify models of working bodies adapted to the soil environment: a tillage ring-cutting roller using modeling of a digging foot of the rhinoceros beetle; a spring soil leveler, where the burrowing limbs of the mole cricket (Gryllotalpa) are used; a stubble cultivator, in the likeness of the forms of a burrowing limb of the scarab beetle (Scarabaeus). The analysis of the results of the tests shows that all the models of working bodies of machines for surface tillage, created by the method of bionic modeling, show a significant decrease in traction resistance in comparison with serial working bodies.

1. Introduction

In the farming system of non-destructive loosening of the soil for the technology of minimal cultivation, the main components are continuous cultivation, harrowing and rolling. They are used to destroy weeds and loose the soil without wrapping it when caring for fallows and preparing the soil for sowing, with the creation of a moisture protective layer with an optimal density [1-3]. This technology of tillage to a depth of 16 cm contributes to the preservation of moisture and nutrients in a form that is available for absorption by plants [4].

Existing rigid suspension tillage tools used in minimal tillage technologies have a high metal consumption, as well as elements of active influence on soil aggregates with their low adaptation, which often leads to their failure, especially on stony soils. Therefore, it is necessary to further improve the working bodies for minimal tillage, taking into account the requirements of environmentally friendly principles of exposure and the search for original technical solutions that will be aimed at preserving the agricultural background and soil fertility. One of the original and new solutions for improving working bodies is the use of the bionic approach [5-7].

Wildlife reveals a significant number of examples of adaptation or fitness of organisms to the variation of various living conditions. To justify the principle of action of the working bodies of tillage machines, it is necessary to consider the features of the functioning of living organisms, selected as biological prototypes. Existing soil cultivation tools mainly experience increased resistance from soil sticking to their surface. Soil adhesion and friction significantly increase energy consumption and degrade the quality of work of tillage tools. Soil animals are well adapted to the soil environment [8, 9].

At a certain stage of evolutionary development, two different adaptations to the soil occurred in soil-forming animals: passive and active. Passive adaptation characterizes animals with short or extra limbs, the body becomes smaller, thinner. However, stronger digging limbs were the result of active adaptation for beetles burrowing into the ground [10].

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In bionic studies, it is necessary to select prototype organisms whose functions correspond to the purpose of the created mechanical system of tillage working bodies. For the working bodies of tillage machines used in the system of cultivation of non-destructive loosening of the soil for minimal tillage technology, it is necessary to minimize significant energy costs. This can be achieved by creating them according to the bionic prototype of those animal organs that are optimally adapted to the conditions of functioning in the environment that surrounds them.

The relevance of the studied problem lies in the need to justify rational parameters and operating modes of the working bodies of machines for surface tillage based on the biosystem approach for their subsequent adaptation in the soil environment while maintaining its fertility.

2. Materials and methods
During the research, the main bionics method was used - modeling of biological organisms, presented in the form of a structural and functional diagram in Figure 1.

![Figure 1. Structural and functional diagram of the modeling of biological organisms of animal diggers for tillage working bodies.](image)

In the research process, three types of modeling were used: physical, mathematical, and imitation. Physical modeling was based on functional mock-ups of biological prototypes - digging animals for reproduction of the basic geometric and physical characteristics of a living organism. Mathematical modeling described biological prototypes as an object of research, a system of mathematical expressions and operators. The simulation method is characterized by performing multiple modeling of digging limbs of biological prototypes with their approximation to new structural elements of the working bodies of tillage machines.

As the study material, we used animal digging animals such as: the mole cricket (Gryllotalpa) shown in Figure 2 (a), the scarab beetle (Scarabaeus) shown in Figure 2 (b) and the common rhinoceros beetle (Oriectes nasicornis) shown in Figure 2 (c).

The general structure of digging limb elements of the selected biological prototypes was studied using a microscope of the HT-60S model shown in Figure 3 (a), with a magnification of 1 to 500. The obtained digital photos of the ground beetles and elements of their limbs were processed in the Hotviewer software. In this case, the basic geometric parameters of the digging limb elements were measured, which are shown in Figure 3 (b) and (c).
Figure 2. General types of bugs of excavation under a microscope: a - mole cricket (Gryllotalpa); b - scarab beetle (Scarabaeus); c - common rhinoceros beetle (Orietes nasicornis).

Figure 3. Investigation of the general structure of digging elements of the limbs of animal diggers: a - microscope model HT-60L; b - determination of the angle of the back support foot; c - determination of the ratio of the corners of the cloves at the apron of digging legs.

The obtained values were compared with similar parameters of existing working bodies of tillage machines for surface tillage. These parameters include: geometric parameters of structural elements, dynamic and functional characteristics of the working bodies. Then the approximation was performed - the reconstruction of the existing geometry of the working bodies under the geometry of the biological prototype in the KOMPAS 3D program.

According to the working drawings, models of the working bodies of machines for surface tillage, such as a tillage ring-cutting roller, were made; spring leveling soil; stubble cultivator.

Figure 4. Experimental setup: a - platform for recording equipment; b - sensors for working with the experimental working body.

The manufactured experimental models were tested in the soil channel in order to determine their qualitative and energy performance indicators in comparison with the performance of serial working bodies.
To determine the energy indicator - traction resistance of the force, the method of tensometry was used. In this case, measurements were made over a period of time of the maximum applied load, depending on the depth of tillage \( h \) and the speed of movement \( V \) of the working body. The values shown in Figure 4 (a) and (b) were calculated using a Lenovo ideapad 310-15 IAP - 1 laptop, ZET 017-T8 - 2 strain gage, ZET017-U2 - 3 analyzer, TS21-T2 - 4 strain gage and two piezoelectric accelerometers BC 110 - 5.

3. Results

3.1. Bionic substantiation of the structural elements of the working bodies of the ring-cutting tillage roller

The object of research is the technological process of interaction of ring-cutting working bodies of the roller with soil. As applied to the loosening working bodies of the ice rink, exploratory studies have established that the common rhinoceros beetle (Orictes nasicornis) performs efficient movement in the soil with front paws with teeth of \( b \) width and located with a certain step \( S \), one of which is shown in Figure 5 (a). The ring-cutting roller model proposed in Figure 5 (b) also contains ripping elements 2 located with a certain step \( S \) on the rotary disks 3 [11].

![Figure 5](image-url)

**Figure 5.** Bionic substantiation of the model of ring-cutting working bodies of the ice rink: a - the digging limb of the common rhinoceros beetle (Orictes nasicornis); b is a side view of the model of ring-cutting working bodies of the roller.

The ripping elements 2 of the rotary discs 3 of the ring-cutting roller model 1 have the shape of truncated cones, the lateral surface of which is made along the length of the logarithmic spiral \( f(x) \), as can be seen in Figure 5 (b).

Experimental verification of traction resistance of the ring-cutting roller model shown in Figure 6 (a), in comparison with the 3KSh-6 serial roller, performed in the experimental field of V.I. Vernadsky of Crimean Federal University, confirmed the feasibility of its use. During field trials, soil moisture was 15 ... 17\%, soil hardness \(-38.9 \ldots 51.4\ N / cm^2\), deformation index \(-2.8 \cdot 10^{-7} \ldots 3.5 \cdot 10^{-7} m^2 / N\), soil type - southern black earth.

Figure 6 (b) shows the graphical dependence of the traction resistance of the ring-cutting roller model on the speed of movement in comparison with the serial model 3RSR-6.

The experimental model of the ring-cutting roller reduces traction resistance by 12 ... 14\% compared with that of the production model 3RSR-6. This is ensured by the vibrational action of the ripping elements on the soil. The optimal soil density after the passage of the experimental model of the ring-cutting roller creates more favorable conditions for the accumulation and preservation of moisture and increase soil fertility.
3.2. Bionic substantiation of the structural elements of the working bodies of the spring soil leveler

Exploratory studies of existing biological prototypes of animal excavators have shown that the shock process in combination with the multi-contact form of the working bodies, which leads to the principle of multi-contact and shock action on the soil, deserves special attention [12].

The model of the working body of the spring soil leveler, created in accordance with the second postulate of the general theory of systems, for periodic compression and cleavage of soil blocks should ensure the implementation of the main rheological features based on the rheological model of the Shvedov body and perform a vibration-pulse effect, destroying soil aggregates.

Of particular interest is a study of the behavior of the mole cricket (Gryllotalpa) and its dentate burrowing organs, adapted to vibration-pulse movement. It made it possible to establish that in the course of movement in the soil, the mole cricket can generate four types of vibration with a frequency from several units to one thousand Hertz, both for the purpose of transmitting information and with the goal of reducing the friction force on the soil [13].

The main functions of loosening in the mole cricket (Gryllotalpa), shown in Figure 7 (a), are performed by strongly modified forearm digging legs, which are well adapted to digging and moving in the soil layer. As can be seen in Figure 7 (b), the extended hands of the front ripper legs have teeth of width b located in increments S. An analysis of the kinematics of the process of loosening the soil with the brushes of the front ripper legs shown in Figure 7 (b) showed that due to their massive hips, they are performed simultaneously two types of motion: reciprocating with a semicircular.

![Figure 6](image1)  ![Figure 7](image2)

**Figure 6.** Tests of the model of a ring-cutting roller: a - general view of a field installation; b - graphical dependence of the specific traction resistance of the model of a ring-cutting roller on the speed of movement.

**Figure 7.** General view of the mole cricket (Gryllotalpa): a - photo of the mole cricket; b - longitudinal projection of the movement of the front burrowing foot of the mole cricket; c - the brush of the anterior hardening leg.
This physical phenomenon made it possible to adapt the structural elements of the front loosening legs of the mole cricket (Gryllotolpa) to justify the structural scheme of the model of the working body of the spring leveling soil. The scheme of the working body of the spring soil leveler, shown in Figure 8 (a), consists of a frame 1 with working bodies 2 on a C-shaped spring strut 3 [14].

The cutting edges 4 of the working bodies 2 have protrusions 5 and depressions 6 in the form of a logarithmic curve with a positive convexity of curvature inside the depressions, creating the effect of sliding cutting and elastic impact in the soil, which reduces the energy consumption of the process of crumbling lumps of blocks and destruction of the soil crust. In the inner cavity of the C-shaped spring strut 3 fixed lower drummer 7 and upper drummer 8.

![Figure 8](image)

**Figure 8.** Experimental model of the working bodies of the spring soil leveler: a - structural design; b - general view of the experimental model; c - graphical dependence of the traction resistance of the spring equalizer model of the soil on the speed of movement.

Joint shock pulses of two impactors 7 and 8 change the intensity, depending on the physical and mechanical composition of the soil and its density.

An experimental check of the traction resistance of the model of the working bodies of the spring equalizer of the soil in comparison with the serial model of the equalizer ESM-5.6A shown in Figure 8 (b), performed under the conditions of the soil channel of the experimental laboratory, confirmed the feasibility of their use. The type of leveled soil is southern carbonate medium loamy chernozem. During the experiment in the soil channel, the soil moisture was in the range of $W = 13 \ldots 17\%$.

Figure 8 (c) shows the graphical dependences of the traction resistance of the model of the working bodies of the spring equalizer of the soil on the speed of movement in comparison with the serial model.

An experimental model of the working bodies of the spring soil leveler provides a decrease in traction resistance by $7 \ldots 8\%$ and increases the stability of the course in depth 1.54 times. The lumpiness of the soil layer decreases 2.3 \ldots 2.4 times, and the loosening ability is higher by $23 \ldots 25\%$ in the model of the working bodies of the spring soil leveler, in comparison with ESM-5.6A.

### 3.3. Bionic substantiation of structural elements of the working bodies of the stubble cultivator

As shown in Figure 9 (a), the biological structure of the head of the prototype scarab beetle (Scarabaeus) by the nature of vital activity is of significant interest for the bionic substantiation of the working bodies of the stubble cultivator.
Figure 9. Approximation of the head of the scarab beetle (Scarabaeus) and the model of the working body of the stubble cultivator: a - projection of the head in front; b - working body of the stubble cultivator, top view.

One of the main functions of loosening in a scarab beetle (Scarabaeus) is performed by the fan shape of the front of the head. The fan-shaped structure of the head of the scarab beetle shows the presence of two pairs of burrowing teeth: central and lateral. Burrowing teeth are located symmetrically with respect to the longitudinal axis. The geometry of the structure of the teeth is characterized by three indicators: the width of the teeth $b_1$ and $b_2$, their spacing factors $k_1$ and $k_2$, with certain steps of the spacing $S_1$ and $S_2$, as can be seen from Figure 9. Measurement of the geometry of digging teeth showed that their placement coefficients for the central $k_1$ and lateral $k_2$, respectively, are 0.3 and 0.22. Moreover, the ratio of the width of the central teeth to the extreme will be $k_1 = \frac{b_2}{b_1} = 1.17$.

The obtained geometric features of the physical structure of the head allow us to adapt its elements to the working bodies of the stubble cultivator. The main structural elements of the model of the working bodies of the stubble cultivator are a C-shaped rack 1 with a chisel 2 and two wings 3, shown in Figure 10 (a). In figure 9 (b) the bit 2 is made expanding from the bottom up and has in its active part a cutting edge 4 with four longitudinal protrusions 5 and three longitudinal hollows 6 of a rounded shape. Two wings 3 have cutting edges 7, which are made in the form of four teeth 8 and three depressions 9, as shown in Figure 9 (b) made in the form of a sinusoïd [15].

Reducing the energy costs of cutting the soil layer provides a serrated shape at the surface of the cutting edge of the bit of the working bodies of the stubble cultivator, where the tops of the teeth become stress concentrators and, with much less pressing force, cause processes of soil deformation and destruction. When designing, it is necessary to take into account that the teeth on the working surface of the cultivator bit are located along its cutting edge, which is an arc of a circle of length and radius, as can be seen from Figure 9 (b). The length of the arc of a circle can be represented by an equation of the form:

$$\Delta l = 2S_1 + S_2 + b_1,$$

where $S_1$ and $S_2$ are the tooth pitch.

Equation (1) makes it possible to determine the number and width of the teeth depending on the length of the cutting edge of the bit.

The length of the arc of the circumference of the cutting edge of the bit is described by the curved shape of the eccentric circle, which is characterized by the constancy of the angle between the normal and the radius vector, and the value of this angle is equal to the angle of internal friction of the soil, which allows the soil and plant residues to slip with minimal energy consumption.
The nature of the interaction of the experimental model of the working body of the stubble cultivator with the soil, in comparison with the working body of the serial cultivator CFA-3.8, was investigated during experimental passes in the soil channel.

Figure 10 (c) shows the graphical dependence of the traction resistance of the experimental model of the working body of the stubble cultivator on the speed of movement in comparison with the serial analog cultivator CFA-3.8.

The analysis of experimental data presented in the form of graphical dependence showed that the traction resistance of the proposed model of the working body of the stubble cultivator is less by 16.5% than the traction resistance of the serial cultivator CFA-3.8. This is due to the fact that in the process of work, the toothed shape of the surfaces of the cutting edges of the bit and the wings of the paws reduces the traction resistance of the experimental model of the working body.

4. Conclusion

The new scientific direction in agricultural mechanics was further developed, which consists in a bio-system approach to the creation of low-energy working bodies of machines for surface soil treatment on the basis of bionic modeling using the regularities of the structure of digging limbs of shrews.

Based on the analysis of the peculiarities of the burrowing limb of common rhinoceros beetle (Orictes nasicornis) substantiates the model ring-cutting working bodies of the rink (RU patent № 173240), which allows one to loosen and to compact the soil surface and is based on the principle of compensation of the disturbing vibration effects that occur during processing.

Based on the study of the longitudinal projection of the movement of the front digging legs bionic prototype of mole crickets (Gryllotalpa), and geometry shapes of its wrist, the model of the working bodies of the spring equalizer of the soil has been developed (RU patent № 2697546). Based on the analysis of the structural features of the fan-shaped elements of the front part of the head of the bionic prototype of the scarab beetle (Scarabaeus), the model of the working body of the stubble cultivator (RU patent № 173203) is substantiated.

Analysis of the results of the tests showed that all models of working bodies of machines for surface tillage, created by the method of bionic modeling, show a significant decrease in traction resistance in comparison with serial working bodies.

5. Acknowledgments

The reported research was funded by the Russian Foundation for Basic Research and the Ministry of education, science and youth of the Republic of Crimea, grant № 18-48-910001.
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