INVESTIGATION AND JUSTIFICATION OF WORKING BODY PARAMETERS OF COMBINED SOIL TILLAGE IMPLEMENT SCREW SECTION

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Abstract. An analysis has been conducted of the working bodies of combined soil tillage machines and recommendations provided in the article regarding the drawing of a layout diagram. There is substantiated the design of a helicoidal working element for surface tillage of the soil, the surface of which differs from another widely known helical ruled surface – a helical conoid. There are given parametric equations of an expanded helicoid with a horizontal axis of rotation. Differential equations of a particle motion on the surface of a helicoid were compiled, and on their basis the trajectories of the motion of the soil particles on the surface of the helicoid were obtained. Regardless of the point of entry of the particle onto the surface, it slides along it, approaching the inner periphery of the surface, and with an increase in the particle arrival speed on the helicoid surface from 1.9 $m \cdot s^{-1}$ to 2.5 $m \cdot s^{-1}$, this approximation increases approximately 2 times. The difference between the angular velocities of the soil particles, moving along the helical surface with friction coefficients $f = 0.3$ and $f = 0$, is insignificant and reaches a value of up to 8.5%. A design of a working body with a lattice shaft that will additionally perform the function of a roller is proposed.

Keywords: helicoid, combined machine, helical surface, working body (element), lattice shaft.

Introduction

In modern agriculture soil tillage is an important technological process. For many years various methods of mechanical impact upon the soil have appeared in order to increase its fertility by creating better conditions for the development and growth of cultivated crops. One of the contemporary methods of surface treatment is the use of the combined soil tillage equipment which most often has disk working bodies, screw working bodies and different types of paws (single-sided flat-cutting, arrow-shaped flat-cutting, universal, loosening chisel-shaped, etc.), which ensure the processing of the soil surface to different depths, and the entire process is usually completed by rollers (wedge-shaped, ribbed, toothed, ring-spur, etc.) loosening. But despite the large selection of the working bodies that can be installed on a combined harrow, it is not always possible to achieve satisfactory quality of tillage, so the development of new progressive working bodies is an urgent task.

Due to mechanical processing the structure of the soil changes – the arable layer acquires a fine-grained structure, which ensures good and rapid germination of the seeds of the plant. In addition, the conditions of the soil, in particular thermal, air, and water, change. During the tillage the soil is cleared of pests, weeds and pathogens which cause infectious diseases of the plants. As a result of the tillage many useful microbiological processes are activated, and, in addition, fertilizers are introduced deep into the soil. Surface tillage has been actively applied throughout the world for many centuries. One of the modern methods of tillage is the use of the combined soil cultivation equipment, which most often has disc working bodies, screw working bodies, and various types of paws that ensure surface cultivation [1; 2]. In most cases discs are fixed in modern machines using rubber elements (dampers), which first appeared in the designs of the Väderstad machines. Approximately the same principle of fastening the working parts, using leaf springs is used on the Heliodor harrows from Lemken [3].

However, springs and rubber dampers do not fully compensate for the lateral displacement of the angled disks and the screw working elements. To compensate for the lateral tilt, two rows of disks are installed with an inclination in the opposite direction, and for the screw working bodies, helicoids with right and left windings of the screw surface are used [4-6]. The design parameters of the disks or the screw working element are related to their technological properties. On the one hand, it is necessary to reduce the diameter D of the working element for its better penetration into the soil, and, at the same time, to reduce the radius R of the sphere, or to increase the angle of inclination of the generatrix of the helical surface for better turning over the soil and mixing it with the plant residues. However, this can lead to the fact that the surface of the chamfer will crush the soil and prevent the immersion of the working element. To prevent this, the sharpening angle δ must be taken such that it ensures the presence of the so-called rear angle in the area of action of the working element, that is, the angle δ must be taken as small as possible. Yet, it can be reduced to a certain limit since this reduces the sharpening angle of the working element, which cannot be less than the maximum value (the sharpening angle is taken within the range of 12°...25°). The angles of attack of the working body also influence the determination of the sharpening angle δ at a given back angle (3°…5°), which prevents the soil from being crushed by the surface of the chamfer, similar to how the soil is crushed by the back surface of the working element at improper angles of its installation.

In addition, to prepare the seedbed, for example, after the autumn ploughing, a levelling bar is installed on some implements in front of the first row of the discs or screw working bodies.

Arrow paws are also one of the main working parts included into the combined machines for soil tillage. The width of the paws and their number determine the intensity of the machine and the size of the lumps. Their wide paws and long stride leave behind large clods of earth that can only be broken up with considerable effort [7; 8]. The working depth and width of the paws are very closely related to each other. The heavier the soil, the greater the working depth and the smaller the pitch of the paw track, the narrower the paw itself. The shape, width and working depth affect the result of the work, the fuel consumption and the material wear. Universal arrow-shaped paws have proven themselves well when cultivating the soil to a depth of 6 to 14 cm.

As a rule, the process of soil cultivation by a combined tillage unit ends with the soil compaction and destruction of large soil lumps. These operations are performed by rolling working bodies. The rollers level the soil surface, which ensures better uniformity of seed germination, break up the soil lumps and crust, and compact the surface layer. These technological operations are performed by rollers of different designs, which allows of the listed operations to be performed better than others and determines the use of rollers of a certain type. Therefore, the article proposes a design for a combined soil-cultivating tool with sections that have helical working bodies.

Materials and methods

Based on the above, we have developed a design and conducted research on a combined soil tillage tool, the diagram of which is presented in the form of three modules: a module with the disk or the screw working bodies; a soil loosening module; a module for compacting and levelling the soil surface (Fig. 1).

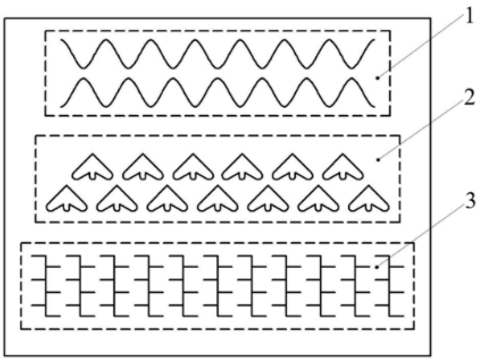

Fig. 1. **Diagram of a combined soil tillage implement**: 1 – module with the disk or the screw working bodies; 2 – loosening module; 3 – compacting and levelling module

In addition, the main conditions for such a combination of this working body will be as follows:

- a module with the disk or the screw working bodies, the type and appearance of which will depend on particular soil conditions;
- the loosening module is presented by different types of paws, the choice of which also depends on the soil conditions, depth of cultivation, weed cutting conditions, etc.;
- the compaction and levelling module consists of one or more sections of rollers of any type, and in some machines, it also performs a support function.

In solving the problems of modern agriculture, the priority direction of research was obtained on the basis of the results of scientific research, carried out under the conditions of long-term field experiments. It has been established that any agricultural technique or method will have a large agricultural and economic effect only if they are applied in a specific system. The further development of mechanical processing will depend on the improvement of the agricultural machinery, tools and their working bodies.

We have proposed a screw working element for surface tillage in the form of an unfolding helicoid, the surface of which will differ from another widely known ruled screw surface – a screw conoid (auger). If the rectilinear generating surfaces of a screw are perpendicular to its axis, then in the deployed helicoid they form a certain angle with the axis. The diagram of the unfolded helicoid as a soil-cultivating working body, in particular its frontal projection, is presented in Fig. 2.

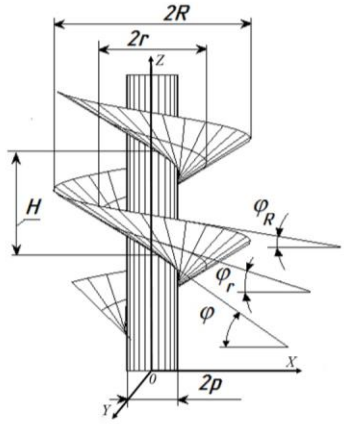

Fig. 2. **Frontal projection of the helicoid**

This diagram shows the basic linear and angular dimensions, and also the spatial coordinate system *XOYZ*, the vertical axis *Z* which coincides with its longitudinal axis. The design parameters of the working surface are the radius *r* of the inner edge, the radius *R* of the outer (cutting) edge, the pitch *H*, and the angle of inclination of the straight-line generatrices. The outer and inner edges are helical lines with the rise angles φ_R and φ_r . The angle of inclination φ of a rectilinear generating surface is determined by the angle of elevation of the helical line of the minimum possible radius *p*, which is called the turning edge. It is the presence of the angle of inclination of the rectilinear generatices that facilitates the immersion of the surface into the soil, if its axis is positioned horizontally and at an angle to the direction, perpendicular to the direction of *V* movement of the aggregate.

If the helical surface of the helicoid is rotated by 90° around the horizontal axis *OY*, then the parametric equations of the unfolded helicoid with a horizontal axis of rotation, parallel to the axis *OX*, have the following form:

$$\left.\begin{aligned} X &= h\alpha - u\cdot\sin\varphi; \\ Y &= p\sin\alpha - u\cos\varphi\cdot\cos\alpha; \\ Z &= p\cos\alpha + u\cos\varphi\cdot\sin\alpha, \end{aligned}\right\}, \tag{1}$$

where α, u – variable parameters of the surface, and α is the angle of rotation of a point around the axis of the surface as it moves to the current point on the helical line, located on a cylinder of the radius *p*;
u – length of the straight line from the current point on the helical line to the point on the surface;
h – constant value (screw parameter) by which the surface pitch is determined – $H = 2\pi\cdot h$;
φ – angle of inclination of the rectilinear generators of the helicoid.

If we take as constant *A* the following value $A = \sqrt{p^2 + h^2}$, then the system of equations (1) may be written in the following, more compact, form:

$$\left.\begin{aligned} X &= (A\alpha - u)\sin\varphi; \\ Y &= (A\sin\alpha - u\cos\alpha)\cos\varphi; \\ Z &= (A\cos\alpha + u\sin\alpha)\cos\varphi. \end{aligned}\right\} \qquad (2)$$

Next, there was considered the surface of the helical screw working body, turned at an angle of attack $\gamma = \beta + \varphi_R$ relative to the direction of the movement of the aggregate V_a (Fig. 3, a). Its lower part within the depth of processing will be in the soil. On the horizontal projection this part of the surface is limited by straight lines, parallel to the axis, and is depicted by dashed lines. The lowest point of the surface *A* (the cutting edge) is in contact with the soil at the bottom of the furrow. Point *B* of the edge is in contact with the soil on the field surface. If the aggregate moves with a forward speed V_a, then with the same speed V_p the soil particle enters the surface of the helicoid. This speed, as a vector quantity, can be decomposed into two mutually perpendicular equal components: $V_t = V_p \cdot \cos(\beta + \varphi_R)$ and $V_n = V_p \cdot \sin(\beta + \varphi_R)$. The angle of attack $\gamma = \beta + \varphi_R$ for a helicoid is variable and depends on the depth of the cutting edge point in the soil. This is also due to the variable value of the angle φ_R. The limits of variation of this angle are relatively insignificant $\varphi_R \ldots \varphi_r$, therefore it is assumed to be constant and equal at the lowest point of the cutting edge of the helicoid: $\varphi_R = \arctan(h \cdot R^{-1}) = \arctan(A \cdot \sin\varphi \cdot R^{-1})$.

To simplify the calculations, we will not turn the helicoid by the angle β (Fig. 3, b) but assume that the soil is moving towards it at the speed V_p at $\beta = 0$ (Fig. 3, c). This will allow to describe the surface of the helicoid in a simplified manner without turning the angle β, replacing the turn of the helicoid with a turn of the velocity vector of the aggregate. This allows to use the parametric equations (2) of the helicoid without complicating their turn at the angle β.

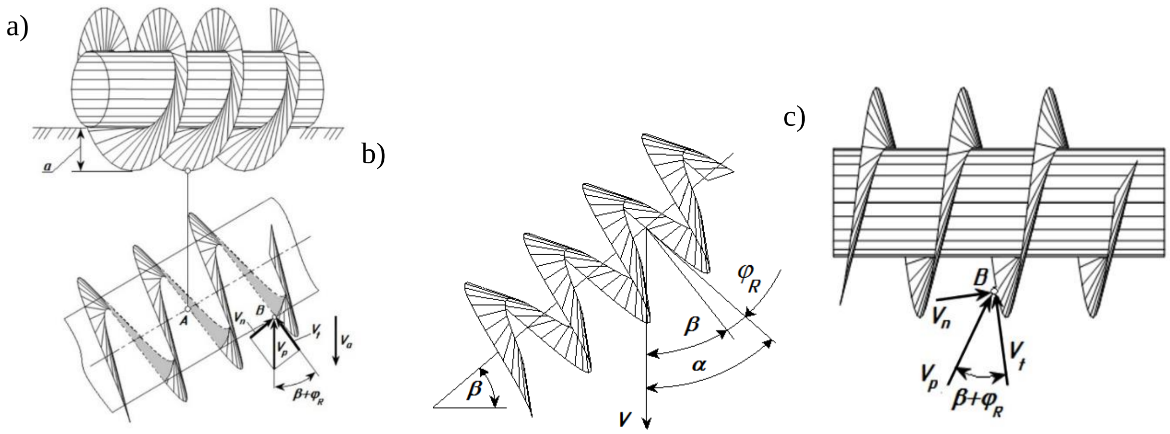

Fig. 3. **Schematic diagram of the surface of the screw implement:** a– contact helicoid with soil; b – helicoid is turned at an angle β; c – helicoid with vectors without rotation

With a transverse velocity V_n, the particle arrives at the surface of the helicoid, and the angular velocity of its rotation depends on the longitudinal velocity V_t. Based on the condition that the cutting edge of the helicoid rolls along the bottom of the furrow in the direction of the movement of the aggregate without slipping, we can therefore write $V_t = R \cdot \omega$, where ω is the angular velocity of rotation of the helicoid. This expression is not exact since the cutting edge is a helical line, not a circle, yet we will assume that it is acceptable for practice. From here the value of the angular velocity ω is found:

$$\omega = \frac{V_p \cdot \cos(\beta + \varphi_R)}{R} = \frac{V_p \cdot \cos\left(\beta + \arctan\dfrac{A\sin\varphi}{R}\right)}{R}. \qquad (3)$$

The value of the transverse velocity V_n, as well as the angular velocity of rotation ω of the helicoid, will be taken into account in the numerical integration of the differential equations of the relative motion of a soil particle along a helical surface.

The vector equation $m \cdot w = F$ in projections onto the axes of the coordinate system has the form:

$$\left.\begin{aligned} &mX'' = -N\cdot\cos\varphi - fN\frac{\left(A\alpha' - u'\right)}{\sqrt{\left(A\alpha' - u'\right)^2 + u^2\cdot\alpha'^2\cdot\cos^2\varphi}}\cdot\sin\varphi;\\ &mY'' = N\cdot\sin\varphi\cdot\cos\alpha - fN\frac{u\alpha'\cdot\sin\left(\omega t - \alpha\right) + \left(u' - A\alpha'\right)\cdot\cos\left(\omega t - \alpha\right)}{\sqrt{\left(A\alpha' - u'\right)^2 + u^2\cdot\alpha'^2\cdot\cos^2\varphi}}\cdot\cos\varphi;\\ &mZ'' = -mg + N\cdot\sin\varphi\cdot\sin\left(\omega t - \alpha\right) - fN\frac{u\alpha'\cdot\cos\left(\omega t - \alpha\right) - \left(u' - A\alpha'\right)\cdot\sin\left(\omega t - \alpha\right)}{\sqrt{\left(A\alpha' - u'\right)^2 + u^2\cdot\alpha'^2\cdot\cos^2\varphi}}\cdot\cos\varphi. \end{aligned}\right\} \tag{4}$$

After the simplifications were carried out, the following system of equations was obtained:

$$\left.\begin{aligned} &\alpha'' = \frac{\left[2u' + A(\omega - \alpha')\right]\cdot(\omega - \alpha')\cdot\cos\varphi - g\cdot\cos\left(\omega t - \alpha\right)}{u\cdot\cos\varphi} -\\ &-f\cdot\alpha'\cdot\sin\varphi\cdot\frac{u(\omega - \alpha')^2\cdot\cos\varphi + g\cdot\sin\left(\omega t - \alpha\right)}{\sqrt{\left(A\alpha' - u'\right)^2 + u^2\cdot\alpha'^2\cdot\cos^2\varphi}};\\ &u'' = g\cdot\cos\varphi\cdot\sin\left(\omega t - \alpha\right) - fu'\cdot\sin\varphi\frac{u(\omega - \alpha')^2\cdot\cos\varphi + g\cdot\sin\left(\omega t - \alpha\right)}{\sqrt{\left(A\alpha' - u'\right)^2 + u^2\cdot\alpha'^2\cdot\cos^2\varphi}} +\\ &+\frac{2Au'(\omega - \alpha')\cos\varphi - Ag\cdot\cos\left(\omega t - \alpha\right) + (\omega - \alpha')^2\cdot\left(A^2 + u^2\cos^2\varphi\right)\cos\varphi}{u\cdot\cos\varphi};\\ &N = m\cdot\sin\varphi\cdot\left[u\cdot(\omega - \alpha')^2\cdot\cos\varphi + g\cdot\sin\left(\omega t - \alpha\right)\right]. \end{aligned}\right\} \tag{5}$$

Having solved the first two equations of system (5), the variable parameters α, u of the movement of a soil particle along the surface of the helicoid were determined. From the third equation of system (5) the reaction N of the helicoid surface was found by substituting the known variable parameters α, u.

Results and discussion

The system of the first two equations (5) is solved by numerical methods in the *Simulink* environment of the *MatLab* software product. A condition is assumed that the helicoid, the design parameters of which were given earlier, moves with a speed of V_a = 9 km·h^{-1} ($V_a = V_p$ = 2.5 m·s^{-1}). The installation angle of the kelicoidal working body β = 40°, the coefficient of friction f = 0.3. Baseds on these data there were determined the following kinematic parameters: $V_t = V_p\cdot\cos(\beta + \varphi_R)$ = 1.62 m·s^{-1}; $V_n = V_p\cdot\sin(\beta + \varphi_R)$ = 1.9 m·s^{-1} Consequently, $\omega = V_t\cdot R^{-1}$ = 6.5 s^{-1}.

Initial integration conditions were chosen, based on the point at which the soil particle enters the surface of the cutting edge. This point can be selected within the values of the depth, and the immersion of the surface into the soil is set by initial coordinates u_o and α_o. For the cutting edge u_o = 0.276 m. To find the value of the variable α_o, it was necessary to solve the last equation (1) with respect to it:

$$\alpha_0 = -\text{Arccos}\frac{Az + u\sqrt{\left(A^2 + u^2\right)\cdot\cos^2\varphi - z^2}}{\left(A^2 + u^2\right)\cdot\cos^2\varphi}. \tag{6}$$

The surface of the field corresponds to the value z = – 0.15 m, but the bottom of the furrow corresponds to z = – 0.25 m. Substitution of these values into expression (6) made it possible to find the following values, respectively: α_o = – 0.94 and α_o = – 1.83. Therefore, the initial value of u_o during integration will be equal to u_o = 0.276 m, and the initial value of α_o depends on the depth of the cutting-edge point in the soil. For the soil surface α_o = – 0.94, for the furrow bottom α_o = – 1.83. Other values of α_o from this range correspond to a certain depth of the cutting-edge point in the soil. By choosing the parameter α_o from the indicated boundaries, we select a point on the blade at different immersion depths.

The initial value of the first derivatives u_o' and α_o' determines the direction of arrival of the soil particle onto the surface of the helicoid.

The derivative α_o' denotes the angular velocity of sliding of a soil particle at the moment it enters the blade. If the helicoid rotated but the particle remained in place, then the sliding speed along the blade would be stable, opposite to the direction of rotation of the helicoid and equal to $\alpha_o' = -\omega$. However, this happens only at the moment when the particle reaches the blade, and then it is carried away by the surface, moving along it, and the angular velocity of its sliding decreases.

The derivative u_o' means the linear velocity of the particle movement along the surface along the coordinate line (rectilinear generatrix) u. The linear velocity u_o' uo' along a rectilinear generating surface depends on the component V_n, which is equal to 1.9 m·s^{-1}. However, the direction of the component V_n does not coincide with the direction of the rectilinear generatrix. In addition, when the helicoid rotates, a component of the velocity of the movement of its points along the axis of rotation arises. The particle arrives at the surface with the velocity V_n and additionally the surface, due to the rotation "runs into" the particle. Taking this into account, the initial value u_o' was taken to be $u_o' = V_n = -1.9$ m·s^{-1} (the "minus" sign means that the particle moves along the rectilinear generating surface in the opposite direction of its counting), and then the pattern of the particle sliding was investigated with an increase in this value. Fig. 4 shows the trajectories of the particle motion, based on the results of numerical integration of differential equations (6).

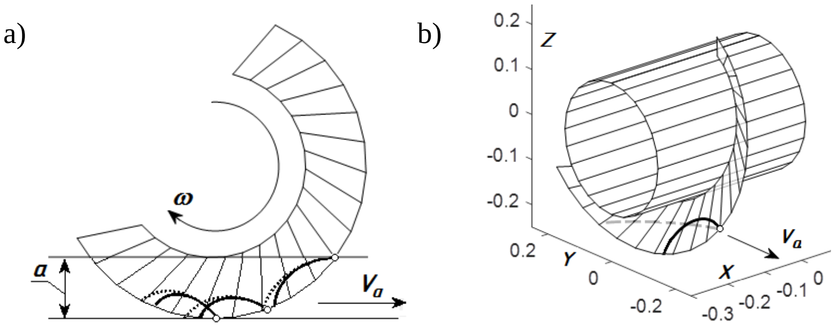

Fig. 4. **Trajectories of movement of a soil particle along the surface of a helicoid:**
a – at the speed of feeding the particle onto the surface of the helicoid V_n = 1.9 m·s^{-1};
b – at the speed of feeding the particle onto the surface of the helicoid V_n = 2.5 m·s^{-1}

Fig. 4 (view a) shows a helical surface, depicted in such a way that its axis is projected onto a point. The trajectories of sliding are constructed when the particle of the soil arrives at the surface at three points: on the surface of the field (the far-right position), at the bottom of the furrow (at the bottom) and in an intermediate position (in the middle between the previously indicated points). The solid line shows the movement of an individual soil particle without interaction with others. However, in the real process it interacts with other particles. There arise forces of support of the adjacent particles which force the particle to move along the surface, and it can be assumed that this force of support is equal to the friction force, and, therefore, we take the friction coefficient $f = 0$. Also, in Fig. 4 (view a) the relative trajectories of the particles at $f = 0$ are shown by a dashed line, and, as it can be seen, the difference between the trajectories is actually insignificant.

Regardless of the point at which the soil particle enters the surface, it slides along it, approaching the inner periphery of the surface, that is, the cylindrical shaft. The forward speed of the aggregate increasing, this approximation increases. For example, the graph presented in Fig. 4 (view b) shows the trajectory of a soil particle sliding along the surface of a helicoid, presented in a three-dimensional space with coordinate axes X, Y, Z and their given dimensions. The speed of delivery of a soil particle to the surface of the helicoid increases from $u_o' = -1.9$ m·s^{-1} to $u_o' = -2.5$ m·s^{-1}. The trajectory of sliding of the particle of soil at a certain moment approaches the cylindrical shaft. At even higher feeding rates of the soil particles the cylindrical shaft will act as an obstacle for them, which will contribute to their unwanted accumulation. Therefore, it is proposed to use a lattice shaft for this working element.

While sliding along the surface, the soil particle is additionally thrown back due to its turning. The sum of these two movements forms the absolute trajectory. If the blade is in the soil, the lower soil particles press onto the upper ones, and the cylindrical shaft becomes an obstacle to their movement. In the area where the screw surface adjoins the shaft, the soil will stick. To prevent this phenomenon, the shaft must be latticed (Fig. 5).

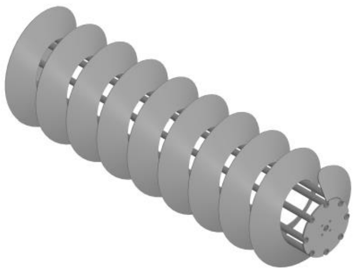

Fig. 5. **General view of a helicoid with a lattice shaft**

Using a program of calculation, developed on PC, we constructed graphical dependencies of the kinematic characteristics of the movement of the soil particles along the working part of the helicoid. Thus, Fig. 6 and Fig. 7 show the characteristics of the movement of a soil particle, entering the surface of a helicoid at the top point, that is, at the level of the soil surface (Fig. 4, a) for a friction coefficient equal to: $f = 0.3$ and $f = 0$. Fig. 6 shows a graph of the change in the angular velocity of a soil particle, sliding along a helical surface, and Fig. 7 shows a graph of the change in the relative and absolute velocity of a soil particle.

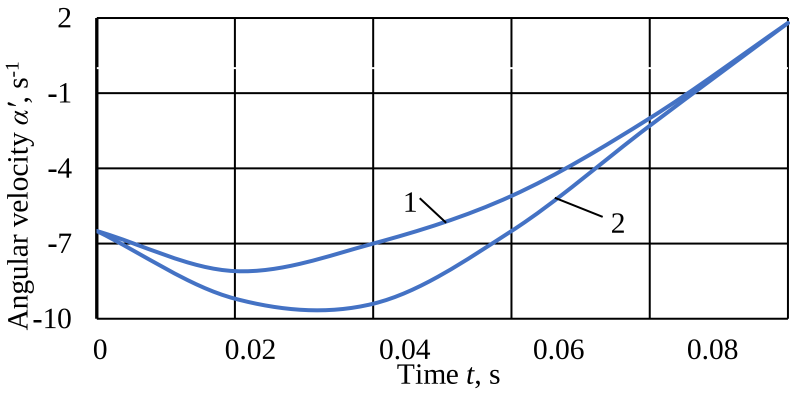

Fig. 6. **Dependence of the change in the angular velocity of sliding of a soil particle along a helical surface upon the coefficient of friction:** 1 – $f = 0.3$; 2 – $f = 0$

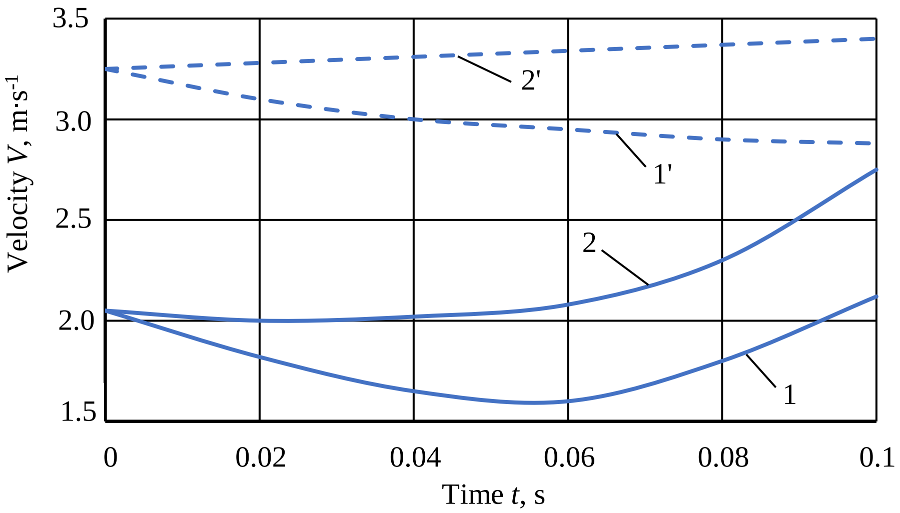

Fig. 7. **Dependence of the change in the relative (the solid line) and absolute (the dashed line) velocity of a soil particle on the friction coefficient:** 1 – $f = 0.3$; 2 – $f = 0$

The obtained graphical dependencies made it possible to establish that the angular velocity of sliding of a soil particle, arriving on the surface of the helicoid from the initial value of 6.5 s^{-1}, initially decreases due to friction against the surface of the helicoid, and then increases, as the soil particle moves downward. As it is evident from the graphs, the difference between the angular velocities of the movement of the soil particles at the coefficients of friction $f = 0.3$ and $f = 0$ is insignificant, and it amounts only to 8.5%.

The graph of the change in the relative and absolute velocities of the soil particle along the surface of the helicoid, shown in Fig. 7, indicates that the initial value of the relative velocity of the soil particle is 2.1 $m \cdot s^{-1}$, then its velocity decreases due to friction forces and increases, as the particle moves downwards. The velocity graph displays the time interval, equal to ($t = 0.1$ s) from the moment the soil particle enters the helicoid's helical surface until it leaves this surface.

The designs of the helical working bodies of the soil-cultivating implements and their experimental research are presented in several scientific papers. In particular, work [9] presents the design and results of experimental studies of the depth of soil cultivation depending on the angle of attack of the working bodies and the speed of movement of a harrow with helical working bodies. In work [10], optimization of the design of the helical working bodies was carried out. Work [11] presents the results of an investigation of the qualitative indicators of soil cultivation (the structural-aggregate state of the soil, the soil density and hardness, the soil structure coefficient) when working with a harrow having helical working bodies. Also in work [12] the results of the research of energy indicators of soil cultivation by helical working bodies are presented. The results of these studies confirm the basic provisions of the theoretical results of movement of the soil particles along the helical surface of the new working element of the helical harrow proposed by us.

Conclusions

1. The article contains analysis of the working bodies of combined soil-cultivating machines and provides recommendations for constructing a layout diagram.
2. There is substantiated a design of a helicoidal working body for surface cultivation of the soil. There are provided parametric equations of an expanded helicoid with a horizontal axis of rotation. Differential equations of motion of a soil particle on the surface of a helicoid are compiled, and on their basis the trajectories of motion of soil particles on the surface of a helicoid are obtained. It is established that, regardless of the point of entry of a soil particle onto the screw surface, it slides along it, approaching the cylindrical shaft. To prevent the phenomenon of soil sticking, the shaft must be latticed.
3. A design of a working body is proposed with a lattice shaft that will additionally perform the function of a roller.
4. There are constructed graphs of the change in the angular velocity of sliding of a soil particle along a helical surface and a graph of the change in the relative and absolute velocities of the movement of a soil particle, entering the surface of the helicoid at the field level. It was found that from the moment of entry onto the screw surface, the velocities decrease and then begin to increase. They reflect the time interval ($t = 0.11$ s) from the moment of entry of the soil particle onto the screw surface until its descent from the surface.

Author contributions

Conceptualization, V.B.; methodology, O.T., O.G. and V.N.; software, V.V.; validation, V.V. and I.B; formal analysis, V.B. O.T. and A.R.; investigation, V.B., I.B., V.V. and A.R.; data curation, A.A., V.B. an M.K.; writing – original draft preparation, V.B.; writing – review and editing, A.A. and A.R.; visualization, O.G., V.N.; project administration, V.B.; funding acquisition, A.R. All authors have read and agreed to the published version of the manuscript.

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