Kinematics and parameters for spiral-helical machinery unit used for secondary tillage

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Abstract. To improve the quality of pre-sowing/secondary tillage, the Kazan State Agrarian University has developed a soil-tillage machinery unit that, unlike other tools, contains a helical spiral and needle ellipsoid disks coaxially mounted on a horizontal shaft. A passive helical spiral creates a compacted seed bed at the depth of seed placement. Needle-shaped ellipsoidal disks are active and they provide mulching of the surface soil layer. The paper presents the parametric equations (derived in the analytical way) of some motion points that are placed on the cutting blade of a helical spiral. Also, we introduce the equations applied to determine the velocity of the motion points and accelerations, which together allow us to analyze how the machinery working body interacts with soil. Theoretical connections are also given to substantiate the main structural parameters of a spiral-helical machinery unit.

1. Introduction

Corresponding Member of the Russian Academy of Sciences, the academician Mazitov N.K. [1], based on the works of academician T. S. Maltsev, starting from the 80s of the last century, noted that secondary tillage should mainly ensure the creation of compacted seed at the depth of seeding a bed and a finely lumpy mulch layer on the surface. The compacted bed provides better seed contact with moist soil, therefore, accelerated starting growth of plants and the creation of a mulched layer on the surface prevents the evaporation of moisture since the capillary connection between the soil layers is interrupted.

Due to their universality, rotary machinery units with spiral-helical working bodies are widely used for secondary tillage. The universality of these tools lies in combining in one design the inclination angle of a working body to the vertical and the angle of its installation to the line of translational motion (angle of attack).

In Kazan State Agrarian University, the work on development of rotary implements (or machinery units) with spiral-helical working bodies was started back in 1979. On the basis of Agricultural Machinery Department, the researchers Gaynanov Kh.S. and Galiullin Sh. R. [2] developed a rotary tool with spiral-belt working bodies, which, when mowing peas, simultaneously loosens the surface soil layer.

Later, in different years, Gaynanov H.S. [3], Ermolko E.V. [4], Mazitov N.K. [1], Matyashin Yu. I. [5], Abdrakhmanov R.K. [6], Kozyrev B. M. [7], Naumov L. G. [8], Yakimov Yu. V. [9], Bulgarev G. G. and Yunusov R. G. [10], Yakhin S. M. and Valiev A.R. [11, 12] continued the theoretical research and developed a series of new spiral-helical rotary tillage tools.

Along with the scientists of Kazan State Agrarian University, Marmalyukov V.P. [13], Chatkin M.N. [14], Kuzmin M.V. [15], Shubin A.V. [16], Izbasarova Z. I. [17], Putrin A. S. [18], Golubev D.
A. [19], Padaltsin K. D. [20], Golubev V. V. [21] and others contributed to the development of spiral-helical tillage machinery tools and implements.

The aim of the study is to determine the parametric equations of motion of the spiral-helical working body of the proposed rotary tool in space, as well as to give, as evidence, the justification for its optimal design parameters.

2. Materials and methods

The methodology of theoretical research was based on the knowledge of analytical geometry and laws of classical mechanics.

The rotary tillage implement/tool which we developed, unlike other designs, contains a helical spiral and needle ellipsoid disks coaxially mounted on a horizontal shaft. The tillage implement (Figure 1a) consists of a welded frame 1 and a linkage mechanism 2. A horizontal shaft 4 is mounted on the frame 1 on the bearings 3.

On the shaft 4 on the bearings 5 are mounted horizontal disks 6, on which a helical spiral 7 of rectangular cross section (strip) with left and right windings is symmetrically connected to the linkage ring 8. The large side of the spiral 7 is inclined to the generatrix of the cylindrical surface, which describes the working body at the angle \( \delta \) (Figure 1d). In order to ensure the stable operation of the machinery unit, as well as to create an additional rolling effect, the turns of the spiral 7 are interconnected, as well as with the disks 6 and ring 8 through the spiral rods 9 (Figure 1b) of a square section, symmetrically with left and right windings related to the ring 8. The rods 9 are facing the field surface with their ribs. On the shaft 4, needle-shaped ellipsoid disks 10, equipped with a drive mechanism, for example, a hydraulic motor 11, are also coaxially rigidly fixed. The design parameters of disks 10 are found with the equation \( a = D / (2 \sin \alpha) \)

\( b = D / 2 \)

where \( a \), \( b \) are the major and minor axes of the ellipses, \( D \) are the diameters of the disks in the projection onto a profile plane, \( \alpha \) – the angle of disks’ fastening on the shaft. Needles 12 of the disks are mounted on a clip 13 with an inclination backward at the angle of \( \beta \) (Figure 1c). The tool also contains support wheels 14 with a screw mechanism 15 for adjusting the depth of tillage.

With the translational movement of the machinery unit, the helical spiral 7 plunges into the soil to a predetermined depth and, due to the sliding friction force on the soil, rotates around the horizontal shaft 4 and freely rolls around the field. As a result of the simultaneous and active impact of the spiral 7 and the rods 9 on the soil, the lumps are destroyed and, most importantly, a compacted seed bed is created at the depth of the seed placement.

At the same time, the hydraulic motor 11 drives the needle ellipsoidal disks 10 into rotation. Due to the design feature, the ellipsoidal disks 10, in addition to the rotational movement, make an additional oscillatory movement in the longitudinal-transverse plane. Therefore, the soil is intensively mulched, and the surface is effectively leveled.

It is well known that a helix is a spatial curve. When studying the kinematics of spiral helical tillage working bodies, the authors [4, 10, 19] choose the beginning and direction of the axes of a spatial rectangular coordinate system arbitrarily.

Considering the fact that the spiral-helical (sh) working body of the proposed tool is made as a passive one, the translational velocity \( V_{e(sh)} \) of an arbitrary point \( M \) of the cutting edge (Figure 2) is equal to its peripheral velocity \( V_{o(sh)} \):

\[ V_{e(sh)} = V_{o(sh)} = D_{sh} \omega_{sh} / 2, \]

where \( D_{sh} \), \( \omega_{sh} \) is the diameter and angular velocity of rotation of the spiral-helical working body.
Figure 1. Structural diagram of the proposed rotary tool

The time of movement of this point is found according to the well-known connection: 
\[ t_m = \frac{\varphi}{\omega_{sh}} \]  
(\( \varphi \) – the angle of rotation of the working body, radian).

For given values of the diameter of the helical spiral and translational velocity of the machinery unit, the angular velocity is found by the formula:

\[ \omega_{sh} = \frac{2V_{sh}}{D_{sh}} \]  
(2)

To balance the lateral reactions of the soil, the helical spiral of the working body is made of two halves with the same parameters, moreover, with right and left windings symmetrically relating to the vertical axis of symmetry.
Figure 2. Scheme to study the kinematics of a spiral-helical working body

The parametric equations of motion of the arbitrary point $M$ (Figure 2) of the cutting blade of the helical spiral, executed with the right coiling in the three-dimensional rectangular coordinate system $OXYZ$ look as:

$$\begin{align*}
X_M &= V_0 t_M - D_{sh} \sin \varphi / 2 = D_{sh} (\varphi - \sin \varphi) / 2, \\
Y_M &= - D_{sh} \varphi \tan \varepsilon / 2, \\
Z_M &= - D_{sh} \cos \varphi / 2 .
\end{align*}$$

(3)

where $\varepsilon$ – the angle of the slope of the helical spiral (helix angle), degree.

As far as the motion of the arbitrary point $R$ of the cutting blade of the helical spiral, executed with the left coiling, is concerned, the parametric equations of motion in this case remain without any change, only the mathematical sign before the equation to determine the ordinate of the point changes.

Thus, the parametric equations of the motion of the points $M$ and $P$ in the general case will be presented as follows:

$$\begin{align*}
X_{MP} &= D_{sh} (\varphi - \sin \varphi) / 2 \\
Y_{MP} &= \mp D_{sh} \varphi \tan \varepsilon / 2 \\
Z_{MP} &= - D_{sh} \cos \varphi / 2 .
\end{align*}$$

(4)

The extent of the movement of the considered points in the space for the same interval is equal to each other and is found with the equation:

$$S_{MP} = \sqrt{\left(X_{MP}\right)^2 + \left(Y_{MP}\right)^2 + \left(Z_{MP}\right)^2} = D_{sh} \sqrt{\varphi^2 (1 + \tan^2 \varepsilon) - 2 \varphi \sin \varphi + 1} / 2,$$

(5)
The main kinematic characteristics that determine the intensity of the impact of the helical spiral on the tilled soil and accordingly affect the energy performance of the work are the value and direction of the velocity and acceleration of the points of the cutting blade.

The projections of the velocity of the cutting blade points can be calculated by differentiating equations (4) with respect to time:

\[
\begin{align*}
V_{M,P}^X &= dX_{M,P}/dt = D_{sh}\omega_{sh}\left(1 - \cos\varphi\right)/2, \\
V_{M,P}^Y &= dY_{M,P}/dt = \mp D_{sh}\omega_{sh}\ t g\varepsilon/2, \\
V_{M,P}^Z &= dZ_{M,P}/dt = D_{sh}\omega_{sh}\sin\varphi/2.
\end{align*}
\]

The absolute value of the absolute velocity of the studied points, i.e., the rate of soil cutting by the cutting blades of the helical spiral, is found with the equation:

\[
V_{M,P} = \sqrt{(V_{M,P}^X)^2 + (V_{M,P}^Y)^2 + (V_{M,P}^Z)^2} = D_{sh}\omega_{sh}\sqrt{2\left(1 - \cos\varphi\right) + t g^2 \varepsilon}/2.
\]

Differentiation of equations (6) in time gives the projection of the acceleration of the studied points of the cutting blade:

\[
\begin{align*}
a_{M,P}^X &= dV_{M,P}^X/dt = D_{sh}\omega_{sh}\sin\varphi/2, \\
a_{M,P}^Y &= dV_{M,P}^Y/dt = 0, \\
a_{M,P}^Z &= dV_{M,P}^Z/dt = D_{ch}\omega_{ch}\cos\varphi/2.
\end{align*}
\]

The absolute acceleration of the points is found with the formula, which looks as:

\[
a_{M,P} = \sqrt{(a_{M,P}^X)^2 + (a_{M,P}^Y)^2 + (a_{M,P}^Z)^2} = D_{sh}\omega_{sh}\sin^2\varphi/2.
\]

The direction of the velocity vectors and acceleration of the points of the cutting blade in space is found through the direction cosines:

\[
\begin{align*}
K_{X}^{V_{M,P}} &= V_{M,P}^X/V_{M,P} = (1 - \cos\varphi)/\sqrt{2\left(1 - \cos\varphi\right) + t g^2 \varepsilon}, \\
K_{Y}^{V_{M,P}} &= V_{M,P}^Y/V_{M,P} = \mp t g\varepsilon/\sqrt{2\left(1 - \cos\varphi\right) + t g^2 \varepsilon}, \\
K_{Z}^{V_{M,P}} &= V_{M,P}^Z/V_{M,P} = \sin\varphi/\sqrt{2\left(1 - \cos\varphi\right) + t g^2 \varepsilon}.
\end{align*}
\]

\[
\begin{align*}
K_{X}^{a_{M,P}} &= a_{M,P}^X/a_{M,P} = \sin\varphi, \\
K_{Y}^{a_{M,P}} &= a_{M,P}^Y/a_{M,P} = 0, \\
K_{Z}^{a_{M,P}} &= a_{M,P}^Z/a_{M,P} = \cos\varphi.
\end{align*}
\]

The analysis of the kinematic connections (4) shows that the points of the cutting blade of the helical spiral of the proposed tool during translational movement of the machinery unit make a complex movement in space. The velocity and acceleration components of the studied points, as
shown by equations (6) and (8), are variable parameters, and this contributes to active crumbling of the soil and lumps' destruction.

One of the main parameters that determine the operability of the proposed tool and also affect the energy performance of the machinery unit is the diameter of the helical spiral.

Note that the spiral-helical working bodies belong to non-traditional machinery units [15], since they differ from other designs not only with curvature, but also with torsion of their cutting elements (Figure 3).

![Figure 3. Characteristics of individual points of a helical spiral](image)

Each point of the cutting blade of the spiral is characterized by the main normal \( n \), which is directed to the center of the circle of the curvature, tangent \( t \), which is perpendicular to the main normal, and the binormal \( b \), i.e., the normal which is perpendicular to the contacting plane. A contacting plane is a plane that passes through the tangent \( t \) and the main normal \( n \). What is characteristic, the binormal vector \( b \) forms a constant angle with the axis \( OY \) equal to the angle of inclination of the spiral \( \varepsilon \). At the same time, the binormal \( b \) periodically changes its direction through the angle of rotation of the spiral \( \theta \), equal to 45 degrees.

Studies by Ermolko E.V. [4] assumed that the maximum depth of tillage that ensures stable operation of the tool during the secondary tillage will be limited by the arc of the cutting blade of the helical spiral embedded in the soil, which is pulled together by the angle of \( 2\theta \), i.e. 90 degrees.

Considering the spiral-helical working body in the working position (Figure 4), we have:

\[
OB = OC - BC = D_{sh}/2 - a, \tag{12}
\]

where:
- \( a \) – the depth of soil tillage (rolling), m

On the other hand,

\[
OB = D_{sh}\cos\theta / 2, \tag{13}
\]

Equating the right sides of equation (12) and (13), we get:

\[
D_{sh}/2 - a = D_{sh}\cos\theta / 2,
\]

Now you can find the equation to determine the diameter of the working body, which has the form:
\[ D_{sh} = 2a / (1 - \cos \theta), \]  
\[ \text{Considering that } \cos \theta = \cos 45^\circ = 0.707, \text{ the connection (14) takes the following form:} \]  
\[ D_{sh} = 6.8a. \]  
\[ \text{If you take the depth of soil tillage } a = 0.06 \ldots 0.08 \text{ m, then in accordance with the equation (15) we have: } D_{sh} = 0.408 \ldots 0.544 \text{ m; When designing a rotary combined tool, we take } D_{sh} = 0.470 \text{ m as the basis.} \]  

We proceed to determination and justification of the optimal value relating to the inclination angle of the helical spiral. In the theory of cylindrical coil springs, this parameter is called the angle of helix elevation. The geometry of the cylindrical helix is such that the generatrices of the cylinder along the entire perimeter intersect it at the same angle \( \gamma \) (Figure 2). In this regard, the angle \( \epsilon \) of the inclination of the helical spiral is a constant value at all its points.

In the general case, that is, when the values of the structural parameters are known (given), the inclination angle of the helical spiral is found with the formula:

\[ \epsilon = \arctg \left[ \frac{S_{sh}}{\pi D_{sh}} \right], \]  

where \( S_{sh}, \ D_{sh} \) is the pitch and diameter of the helical spiral.

At the same time, the design parameters selected during the calculation and design of the proposed rotary combined tool should ensure that the helical spiral enters the soil with sliding. Otherwise, the traction resistance of the machinery unit increases.

As known, in the spiral-helical working bodies, the inclination angle of the spiral turns to the vertical (Figure 5a) is equal to the angle \( \epsilon \) of the inclination of the spiral (angle of helix elevation).

During the technological process, the cutting blade of the helical spiral cuts the soil (monolith), and its working surfaces produce compression and a slight shift of the soil. Each element of the spiral coil is a locally and continuously acting trihedral (spatial) wedge \( ABC \) [22].

Let an element of a spiral coil with the angle of inclination \( \epsilon \) at each moment of time under the influence of the vertical force \( P_v \) will be introduced into the soil at the angle \( \beta \) (Figure 5a). The frontal reaction of soil \( R_{fr} \) to the working surface of the spiral resists this action (Figure 5c).

A sliding entry of any rotary working body into the soil is ensured only when the frontal reaction of the soil to its surface goes beyond the so-called friction cone [23]. Therefore, in this case, the direction of the frontal soil reaction \( R_{fr} \) should go beyond the friction cone, and this is possible only if the following condition is met:

\[ P_v \cos (90^\circ - \beta) > F_{fr}. \]  

The friction force of the soil on the working surface of the helical spiral is found with the formula:

\[ F_{fr} = N t\tan \phi_{fr} = P_v \cos \beta t\tan \phi_{fr}. \]  

where \( N \) – normal soil reaction; \( \phi_{fr} \) – the angle of friction when soil is sliding on the working surface of the helical spiral.

**Figure 5.** Scheme to find the inclination angle of the spiral
After substituting the values of the friction force into equation (17) and, considering that \(\cos (90° - \beta) = \sin \beta\), we have:

\[
P_v \sin \beta > P_v \cos \beta \tan \phi_{fr} \tag{19}
\]

Dividing both sides of this inequation by \(\cos \beta\), we obtain:

\[
\tan \beta > \tan \phi_{fr} \text{ or } \beta > \phi_{fr} \tag{20}
\]

Equation (20) shows that the working body is introduced into the soil with sliding only when the angle of entry of the spiral into the soil is bigger than the angle of friction of the sliding of the soil against the working surface.

From the right triangle \(EFB\) we have:

\[
\beta = 90° - \epsilon. \tag{21}
\]

Substituting the value of the angle \(\beta\) in the inequation (20), we get the connection to reason the inclination angle of the spiral, which provides a sliding entry of the working body into the soil. It has the following form:

\[
\epsilon < 90° - \phi_{fr}. \tag{22}
\]

3. Results

The sliding friction angle depends on the type of working surface, the mechanical composition of the soil and its moisture. The sliding friction angle of cohesive sandy and loamy soils on the steel surface of the working bodies is \(25° \ldots 35°\), black soil \(-24° \ldots 39°\), medium loamy soil \(-19° \ldots 26°\) [18].

The analysis of equation (22), taking into account the above values of the sliding friction angle of various types of soil, as well as the practice of designing rotary rolling tools with spiral-helical working bodies, shows that the optimal value of the inclination angle of the spirals should lie within \(10° \ldots 25°\).

To ensure the operability of the proposed tool with minimal energy consumption, it is necessary to reason the angle \(\delta\) of the slope of the large side of the spiral strip to the generatrix of the cylindrical surface that describes the working body (Figure 1d). Based on the above methodology applied to determine the inclination angle of the spiral, we find an equation to reason this parameter. In order to shorten the paper text, we present a theoretical connection for substantiating the angle \(\delta\) only in its final form: \(\delta > \phi_{fr}\). Taking into account the values of the angle of friction-slip for various types of soil in project calculations, we take \(\delta = 25° \ldots 30°\).

After determining and justifying the optimal values of the diameter and inclination angle of the helical spiral, we can determine the pitch and total length of the helical spiral through the appropriate formulas:

\[
S_{sh} = \pi D_{sh} \tan \epsilon; L_{sh} = \pi D_{sh} n_{sh} \sqrt{1 + \tan^2 \epsilon}, \tag{23}
\]

where \(n_{sh}\) is the number of turns of the spiral.

In turn, the number of turns of the spiral is calculated by the formula:

\[
n_{sh} = B / S_{sh}, \tag{24}
\]

where \(B\) is the width of the capture of the tool (module), m.

For example, with \(D_{sh} = 0.470\) m, and also when \(B = 1.8\) m, \(\epsilon = 15°\), we get: \(S_{sh} = 0.395\) m; \(n_{sh} = 4.55\).

For the convenience of manufacturing, the number of turns of the spiral is rounded to an integer: \(n_{sh} = 5\). With this in mind, we adjust the pitch and inclination angle of the spiral: \(S_{sh} = 0.36\) m; \(\epsilon = 13.7°\). Thus, we finally have: \(L_{sh} = 7.593\) m.

4. Conclusion

The analytical connections and the results of calculating the parameters of the spiral-helical working body allow us to design the working body, which ensures high-quality performance of the technological process of surface tillage with minimal energy consumption.
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