Cultivator points of the rotary tillage loosening and separating machine of the stratifier

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Abstract. The object of the study is the process of functioning of the working bodies of a rotary tillage machine, with the help of which the lifting and feeding of the soil cut by them to the loosening and separating device is carried out. The technological process of the machine operation is described with the cultivator points from the chisel working body installed in the front part of the pointed paw, which are located at an angle of 26° to the horizon and properly ensure the penetration of the working bodies into the soil. Using the method of variational calcification, the form of the minimum traction resistance cultivator points for lifting and feeding the soil to the loosening and separating device is justified. It was experimentally determined that a cultivator points with a theoretically justified profile has a traction resistance 38.7% less than a cultivator points with a straight profile. The relevance of the study is to ensure the minimum traction resistance of the working bodies for cutting and lifting the soil of a rotary tillage machine, which will make it possible to reduce energy costs for pre-sowing tillage. The target group of consumers of information in the article is designers, specialists engaged in the development of tillage machines.

1. Introduction

Modern means of mechanization contribute to the re-compaction of the arable and sub-arable layers of the soil, an increase in the heterogeneity of the structure, the appearance of lumps with a density exceeding its density before processing, as well as to a decrease in the efficiency of fertilizer use.

The creation of new and modernization of existing tillage machines and tools requires justification of the main design and technological parameters.

The main indicators of the structural and technological parameters of agricultural tillage machines are the degree of soil crumbling, the stability of the working bodies in depth, the alignment of the field surface after processing, traction resistance, etc.
These and other indicators are used to analyze the technological process of machines, substantiate their design and technological parameters.

Well-known tillage working bodies do not allow providing optimal agrophysical conditions for their development to plants in one pass, they have a relatively high energy intensity and require a large number of mechanical treatments or the use of chemicals to destroy weeds.

Tillage in the cultivation of agricultural crops takes up 30-40% of the total costs. Part of the energy is spent on the execution of processes in the machines themselves. Therefore, the greatest savings in energy costs can be achieved by reducing the number of passes of units across the field. At the same time, the over-compaction of the soil is significantly reduced and its fertility is preserved [1-8].

2. Problem statement
The working bodies of the machine for pruning and lifting the soil [3] were developed on the basis of a plane-cutting pointed leg of a direct sowing planter. To ensure the necessary penetration of the working organs into dense soil, it is proposed to use a cultivator points in the front part of the pointed paw from the chisel working organ, which is located at an angle of 26° to the horizon.

![Figure 1. Working bodies for lifting and feeding the soil to the loosening and separating device.](image)

When conducting field tests of a tillage loosening and separating machine (figure 1), it was found that the cultivator points performs its functions to ensure the penetration of working bodies into the soil. However, with an increase in the depth of processing, lumps of soil of considerable size appear in the area of the cultivator points, which indicate an increase in the resistance of the cultivator points and an increase in the energy for the separation of lumps, therefore, it is necessary to justify its profile, which provides the least resistance when moving in the soil [9-16].

3. Purpose of the article
To justify the parameters of the working bodies that ensure the minimum energy costs for pruning and feeding the soil to the loosening and separating device of the tillage machine. To conduct a set of experimental studies to determine the reliability of the results of theoretical studies.

4. Results and discussion
We will look for the cultivator points profile in the form of a curve that passes through the specified limit points, and the angles of inclination of the tangents to the curve in them should be equal to the specified values in the mobile Cartesian coordinate system XOZ (figure 2).
The angle of inclination at the starting point of the cultivator points should provide the necessary deepening of it. The best penetration into dense soil, as practice shows, is the working bodies of chisel plows, the value of which is 26°. The angle of inclination of the rack at the \( X_k \) point is determined by the design features of the tillage machine to optimize the structural composition of the soil in terms of the depth of treatment. This angle was determined under the condition that the mounting posts of the working bodies pass behind the axis of rotation of the rotor of the loosening-separating device [17-20]. This arrangement of the racks contributes to the fact that the soil core, which is formed in front of the rack, falls into the operating zone of the rotor. This eliminates the possibility of clogging the machine with soil and provides the possibility of installing flat-cutting paws in a row order. The value of the end point \( X_kZ_k \) was determined experimentally in accordance with the height of the location of the soil rolls.

At the point \( O \), the curve passes at an angle \( \alpha_0 \), and at the point \( X_kZ_k \) - at an angle \( \alpha_k \). If we assume that the cultivator points moves in a homogeneous layer of soil at a constant speed, then the normal soil pressure force \( q \) and the friction force \( F \) act on an elementary segment of the working surface \( dl \).

To solve the problem, we use the method of calculus of variations. The main method for calculating various variational problems is reduced to solving a differential equation or a system of Euler differential equations [21-23]. To solve differential equations, numerical methods are used, which are solved using electronic computing technology. And when the problem becomes more complicated, it is necessary to carry out cumbersome transformations, which creates difficulties in composing Euler differential equations. Therefore, when solving problems of agricultural mechanics, obtaining and solving Euler equations is time-consuming [24, 25].

Due to the complexity of solving this kind of equations, it becomes necessary to use direct methods of calculus of variations. Direct methods make it possible to find the necessary curve when constructing successive approximations to it. This allows us to reduce the solutions of the problem of the extremum of the functional to the extremum of the function using the Ritz method.

To determine the function, and therefore the functional, it is enough to set an infinite sequence of coefficients \( C_1, C_2, \ldots, C_n \). If a sequence provides a minimum for the functional, it is called a minimizing sequence. The speed of convergence of the latter to a certain function will most often depend only on the successfully or unsuccessfully chosen rule for constructing the sequence. The Ritz method consists in the fact that the value of the functional is considered on possible linear combinations of selected functions with constant coefficients composed of the first terms of the sequence.

We select an elementary section \( dl \) on the working surface of the cultivator points, which is affected by the force of normal soil pressure \( q \) and the force of friction of the soil on the surface of the cultivator points \( F \). Then the elementary force of resistance to the movement of the cultivator points is determined by the formula

\[
\text{d} R_s = q \cdot \sin \alpha \cdot \text{d} l + F \cdot \cos \alpha \cdot \text{d} l,
\]

where \( q \) – is the elementary normal pressure of the soil on the working surface of the cultivator points; \( F \) – is the elementary friction force between the cultivator points and the soil; \( \text{d} l \) – the elementary length.
of the selected section on the cultivator points; $\alpha$ – is the angle of inclination of the tangent to the profile of the cultivator points on the elementary section and the coordinate axis.

If the equations of the desired profile are written in general form, we get the equation

$$Z = f(x).$$

It is well known that the tangent of the angle of inclination of the tangent to the desired profile of the cultivator points and the coordinate axis can be determined by the formula

$$Z' = \frac{dZ}{dx},$$

and the cosine and sine of the angle are expressed in terms of the tangent of the angle, respectively, we get

$$\sin \alpha = \frac{Z'}{\sqrt{1+(Z')^2}}; \quad \cos \alpha = \frac{1}{\sqrt{1+(Z')^2}},$$

then equation (1) will be written

$$dR_s = q \frac{Z'}{\sqrt{1+(Z')^2}} dl + F \frac{1}{\sqrt{1+(Z')^2}} dl, \quad (2)$$

Taking into account that

$$F = q \cdot f,$$

where $f$ is the coefficient of friction of the soil on the metal of the cultivator points,

$$dl = \sqrt{(dx)^2 + (dZ)^2} = dx \sqrt{1+(Z')^2},$$

and equation (2) is written

$$dR_s = q(Z' + f)dx. \quad (3)$$

Based on the fact that as a result of experimental studies [23], dependences for calculating the specific pressure of the soil on the cultivator points were determined

$$q = a_1 Z^{a_2}, \quad (4)$$

where $a_1, a_2$ are constant coefficients.

For chernozem soils, the indicators of the average mechanical composition, respectively, are $a_1 = 1.31$ N/m², $a_2 = 1.081$ N/m². The values of the coefficients were determined experimentally for chernozem soils.

After substituting equation (4) into equation (3) and integrating equation (3), we obtain the energy functional of the cultivator points operation

$$R_s = a_1 \int_0^{x_k} Z^{a_2} (Z' + f) dx, \quad (5)$$

where $x_k$ is the coordinate of the end point of the cultivator points.

We set the task: among the family of curves that pass through the limit points $Z(X_0)=0$ and $Z(Xk)=Zk$, exit from the starting point at an angle $\alpha_0$ and pass to the end point at an angle, find a curve
that describes the profile of the cultivator points of the minimum energy intensity, that is, provides the extremum of the functional.

To solve the problem, we use the method of direct calculus of variations, which allows us to translate the problem of determining the extremum of a functional into the problem of finding the extremum of a function. We define the equation of the cultivator points profile curve, which satisfies the boundary conditions

\[ Z = Z_0'X + \frac{3Z_k - X_k (Z_k' - 2Z_0')}{X_k^2}X^2 + \frac{(Z_k' + Z_0')X_k - 2Z_k}{X_k^3}X^3 + \]

\[ + (X_k - X)^2(C_1X + C_2X^2), \]  

(6)

where \( C_1 \) and \( C_2 \) are the desired coefficients; and \( Z_0' \) и \( Z_k' \) – tangents of the angles of inclination tangent to the profile line of the cultivator points; \( X_k; Z_k \) – coordinates of the end point of the curve describing the cultivator points profile.

The first derivative of equation (6) has the form

\[ Z' = Z_0' + 2X \frac{3Z_k - X_k (Z_k' - 2Z_0')}{X_k^2}X^2 + \frac{(Z_k' + Z_0')X_k - 2Z_k}{X_k^3}X^3 + \]

\[ + 2(X - X_k)(C_1X^2 + C_2X^3) + (X - X_k)^2(2C_1X + 3C_2X^2). \]  

(7)

Substituting equations (6) and (7) into the functional (5), we obtain a function for determining the traction resistance of the cultivator points

\[ R_x = a_1 \int_0^{X_k} \left[ Z_0'X \frac{3Z_k - X_k (Z_k' - 2Z_0')}{X_k^2}X^2 + \frac{(Z_k' + Z_0')X_k - 2Z_k}{X_k^3}X^3 + \right. \]

\[ + (X_k - X)(C_1X + C_2X^2) \left. \right]^{a_2} \cdot \left[ Z_0' + 2X \frac{3Z_k - X_k (Z_k' + 2Z_0)}{X_k^2}X^2 + \frac{Z_k' + Z_0'}{X_k^2}X^3 + 2(X - X_k)(C_1X^2 + C_2X^3) + \right. \]

\[ + (X - X_k)^2(2C_1X + 3C_2X^2) + f \right] dx. \]  

(8)

The task of the research is to determine, respectively, at the initial and final points, the values of the constant coefficients \( C_1 \) and \( C_2 \) in such a way that they provide a minimum of the function (8). Having determined the partial derivatives (8) with respect to \( C_1 \) and \( C_2 \) and equating them to zero, we obtain a system of equations, the solution of which will allow us to find the value of the desired coefficients.
The system of equations (9) was solved numerically with respect to the desired coefficients $C_1$ and $C_2$ using a personal computer. For the calculation, we used: $F = 0.5$, $X_o = 0$, $X_k = 0.18$ m, $Z_o = 0$, $Z_k = 0.085$ m, $Z'_o = \tan 15^0$, $Z'_k = \tan 25^0$. The found values of the desired coefficients $C_1$ and $C_2$, respectively, are equal to $C_1 = -104.0088$; $C_2 = -3346.742$.

After substituting the values of the obtained coefficients into equation (6), we obtain an expression that describes the profile of the counter of the stand of the tillage machine of minimal energy intensity

$$Z = 0.2679 X + 2.303 X^2 - 6.489 X^3 + 0.0144 (-104.0088 X^2 - 3316.742 X^3)$$  \hspace{1cm} (10)

The curved line constructed according to equation (10) shows the shape of the minimum traction resistance cultivator points (figure 3).

In order to determine the reliability of the results of theoretical studies, the energy indicators of the cultivator points for pruning and lifting the soil were determined. For this purpose, a cultivator points was made with a profile that was theoretically justified, and for comparison – with a straight profile.

\[
\frac{\partial R_x}{\partial C_1} = a_1 \left\{ a_2 Z^{a_2-1} \frac{\partial Z}{\partial C_1} (Z' + f) + Z'^2 \frac{\partial Z'}{\partial C_1} \right\} dx = 0,
\]

\[
\frac{\partial R_x}{\partial C_2} = a_1 \left\{ a_2 Z^{a_2-1} \frac{\partial Z}{\partial C_2} (Z' + f) + Z'^2 \frac{\partial Z'}{\partial C_2} \right\} dx = 0,
\]

Where

\[
\frac{\partial Z}{\partial C_1} = X^2 (X - X_k),
\]

\[
\frac{\partial Z'}{\partial C_1} = 2(X - X_k)X^2 + 2(X - X_k)^2 X,
\]

\[
\frac{\partial Z}{\partial C_2} = (X - X_k)^2 X^2,
\]

\[
\frac{\partial Z'}{\partial C_2} = 2(X - X_k)X^3 + 3(X - X_k)^2 X^2.
\]
The tangents to the cultivator points at the initial points were equal to 26°, and at the end points coincided with the direction of the racks passing behind the axis of the rotor of the loosening-separating device.

Figure 4 shows a general view of cultivator points with a direct and theoretically justified profile.

Experiments to determine the traction resistance of a head with a direct and theoretically justified profile were carried out in a soil channel at a processing depth of 0.11 m and a soil humidity of 17%. The speed of movement of the strain gauge trolley was 0.7 m/s. Data on the traction resistance of cultivator points with direct and theoretically justified profiles are given in table 1.

| Repeatability | Type of cultivator points | % to the cultivator points of a direct profile |
|---------------|---------------------------|-----------------------------------------------|
|               | direct profile            | experimental profile                          |
| 1             | 126.0                     | 89.45                                         | –                              |
| 2             | 142.5                     | 75.65                                         | –                              |
| 3             | 153.0                     | 89.15                                         | –                              |
| 4             | 135.0                     | 89.35                                         | –                              |
| Average       | 139.5                     | 85.3                                          | 38.7                           |

The analysis of the table data shows that the head with a theoretically justified profile has a traction resistance 38.7% less than the head of the direct profile, which confirms the reliability of the results of theoretical studies.

5. Conclusion
It is proved that theoretically the shape of the cultivator points of the minimum traction resistance for cutting and lifting the soil has the form (figure 3). It is proved that the cultivator points with a theoretically justified profile have a lower traction resistance compared to the cultivator points of a straight profile.

References
[1] Orekhovskaya A A and Klyosov D N 2021 Effect of application of organomineral fertilizers IOP Conference Series: Earth and Environmental Science 723(2) 022010
[2] Stupakov A G, Orekhovskaya A A, Kulikova M A, Manokhina L A, Panin S I and Geltukhina V I 2019 IOP Conference Series: Earth and Environmental Science 315(5) 052027
[3] Syromyatnikov Yu N 2021 Justification of the parameters of the soil cultivator of the stratifier machine Engineering technologies and systems 31(2) 257-73
[4] Babitsky L F, Sobolevsky I V and Kuklin V A 2019 Theoretical prerequisites for the bionic substantiation of the parameters of the working bodies of a spring leveler of the soil Agrarian science of the Euro-North-East 20(1) 48-56
[5] Lachuga Y et al. 2020 Energy-saving tillage with a combined unit with universal working bodies
IOP Conference Series: Materials Science and Engineering. - IOP Publishing 1001(1) 012121

[6] Mattetti M et al. 2017 Influence of the speed on soil-pressure over a plough Biosystems engineering 156 136-47

[7] Syromyatnikov Yu N 2018 Substantiation of the profile of the cultivator's loosening paw by the method of variational calculus Agrotechnika and energy supply 3 76-83

[8] Dewangan A and Rajput N S 2017 Stress Analysis of Cultivator: A Survey Approach International Research Journal of Engineering and Technology 4(01) 692-6

[9] Parkhomenko G G et al. 2021 Agrotechnical and energy indicators of tillage working bodies Engineering technologies and systems 30(1) 109-26

[10] Dula M W and Anawute D A 2021 Design of Sub-Soiler for Deep Tillage Operation of Compressed Soil Due to Heavy Duty Agricultural Machinery Traffic on the Field Middle East Journal of Applied Science & Technology 4(1) 30-50

[11] Liu S and Li M 2021 Determination of Passive Earth Pressure Coefficients for a Sloping Cohesive Backfill under Uniform Surcharge Loading International Journal of Geomechanics 21(6) 04021079

[12] Sheichenko V, Dudnikov I, Shevchuk V and Kuzmych A 2019 Research of Surface-Plane and Space-Deep Interaction of the Needle with Soil Mechanization in Agriculture & Conserving of the Resources 65(1) 13-6

[13] Babitsky L F, Sobolevsky I. V and Ismailov Ya N 2019 Substantiation of the design of a ring-cutting tillage roller according to a bionic prototype Izvestia of Agricultural Science of Tavrida 17 105-14

[14] Vetokhin V I 2010 On the dynamics of the shape of the surface of the working organs of soil pollinators Tractors and agricultural machines 6 30-5

[15] Vasilenko P M and Babiy P T 1961 Cultivators (Kiev) 240

[16] Kornienko S et al. 2016 Developing the method of constructing mathematical models of soil condition under the action of a wedge Eastern European Journal of Advanced Technologies 5(7) 34-43

[17] Syromyatnikov Yu N, Voinash S A and Nanka A V 2018 Naralnik of minimal traction resistance Science and innovations: vectors of development 70-3

[18] Turchin V Ya, Anikeev A I and Khramov N S 2017 Substantiation of the profile of a plane-cutting paw using methods of calculus of variations Vestnik of the Kharkiv National Technical University of the Silsk State Administration named after Peter Vasilenko 180 311-8

[19] Pashchenko V F et al. 2017 Substantiation of the parameters of a tillage machine for energy-saving soil treatment technology Vestnik of the Sumy National Agrarian University Series: Mechanization and automation of virobnichilkh processes 10 36-40

[20] Pashchenko V F, Kim V V and Batulin A A 2015 Theoretical studies of the technological process of a tillage machine Inzheneriya prirodokoristuvannya 1 79-83

[21] Loveikin V, Chovnyuk Yu and Dyachenko L 2013 Application of methods of variational calculus for analyzing the influence of The Shape of the working body of a vibroplug on its traction resistance during movement in the soil Technical and technological aspects of development and testing of new equipment and technologies for Agriculture of Ukraine 17(1) 117-27

[22] Pashchenko V F, Nanka O V and Siromyatnikov Yu N 2019 The design of the rotor knife of the rosrikhlyuyvalno-separuyuchogo attachment of the soil recycling machine Science zhurnal "Engineering of nature" 1(11) 56-67

[23] Syromyatnikov Yu N 2018 Justification of the profile of the pointed leg of the cultivator by the method of variational calculus Achievements of engineering and technologies in the agro-industrial complex: materials of the International scientific and practical Conference 222-30

[24] Pedregal P 2021 On non-locality in the calculus of variations SeMA Journal 1-22

[25] Syromyatnikov Yu N 2019 Design parameters of the rotor of a tillage loosening and separating machine Agriculture 2 7-27