The theoretical substantiation of the roller diameter of a versatile tillage implement

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Abstract. The paper is devoted to a soil compacting implement. To improve the quality of soil cultivation before sowing, a versatile tillage tool has been designed which consists of a frame, loosening and leveling rollers, and rods with springs. The versatility of the implement lies in the fact that it can be used in combination with disc harrows, cultivators, grain seeders and units for the main moldboard or non-moldboard tillage. Theoretical studies have demonstrated that when the hollow cylinder of the roller interacts with a clod of soil, two normal forces \( N_1 \) and \( N_2 \) arise. The resulting force \( N = N_1 + N_2 \) tends to push the soil clod out of the clearance area between the hollow cylinder and the surface of the field in the direction of the positive part of the \( Ox \) axis. The friction force \( F_2 \) arises between the surfaces of the soil clod and the soil and the force \( F_1 \) between the surface of the hollow cylinder and the soil. The resulting frictional force \( F = F_1 + F_2 \) is directed opposite the movement direction (rotation) of the leveling roller. Preliminary theoretical calculations showed that the minimum diameter of the hollow cylinder should be at least 0.35 m, and the height of the annular compacting components and pointed rippers should not exceed 6 cm. Then the total outer diameter of the leveling roller will be 0.47 m. It was proven in the course of theoretical studies that the minimum diameter of the hollow cylinder of the leveling roller depends on the quantity \( h_{cm} \) of the soil compaction, the maximum size of soil clods left after the pass of the loosening roller, and the physical and mechanical properties of the soil.

1. Introduction

The use of agricultural machines of a higher technical and technological level is one of the main conditions for the successful implementation of energy saving cultivation technologies.

The achievements of Russian and foreign science and industry have made it possible for enterprises of the agro-industrial complex to use chemical agents to combat weeds before sowing, simultaneously with sowing and after sowing seeds. The widespread use of herbicides and pesticides was the impetus to introduce energy-saving, minimal and no-till technologies for tillage and sowing into the farming system [1, 2, 3, 4, 5, 6, 7, 8, 9].

Any technology for the cultivation of agricultural crops, as a rule, comprises: the main and pre-sowing soil tillage, sowing and tending crops (mechanized, using row cultivators, or chemical - sprayers), harvesting and transportation of the yield. If to take into account that there are no alternatives to sprayers, harvesters and vehicles, the main reserve of energy conservation is the

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operations of preparing the field for sowing, sowing and tending crops which account for up to 50% of energy costs.

In addition, conservation technologies should be aimed not only at preserving the humus layer of the soil, but also at combating wind and water erosion of soils, accumulating and preserving soil moisture in the root layer during the growing season of plant development.

Having analyzed the well-known technologies of pre-sowing field preparation, one can conclude that the soil before sowing is tilled with cultivators, disc, tine and spike tooth harrows, as well as tillage rollers. Rolling before sowing ensures the destruction of soil clods, as well as partial field surface leveling [1, 2, 3, 6, 9].

However, the problem of high-quality preparation of the field for sowing with the use of soil-cultivating rollers is insufficiently solved at present. Therefore, it is necessary to substantiate the optimal basic design parameters of the implement for rolling the soil, containing new working bodies which include, in particular, annular compacting components and pointed rippers.

2. The study objects and research methods

A versatile tillage implement has been designed to improve the quality of soil cultivation before sowing. The novelty of the technical solution is confirmed by patents of the Russian Federation. The versatility of this tool lies in the fact that it can be used in combination with disc harrows, cultivators, seed drills and plows.

The versatile tillage implement (fig. 1) includes ripper (1) and leveling rollers (2), H-shaped frame (3), brackets (4) and rods (5).

Rods (5) are equipped with nuts (6) and springs (7). Ripper roller (1) also includes axle (8) and disc rippers (9). Disc rippers (9) are fixed on axle (8) at regular intervals, and grooves (10) are made around the circumference of each disc ripper (9). Tops (11) located between grooves (10) are made of a triangular shape and pointed in different directions from the geometric axis of rotation of disc rippers (9).

Figure 1. Versatile tillage implement: a - side view; b - top view; 1 - loosening roller; 2 - leveling roller; 3 - H-shaped frame; 4 - brackets; 5 - rods; 6 - nuts; 7 - springs; 8 - the axle of the loosening roller; 9 - disc rippers; 10 - grooves located on disc rippers; 11 - tops of disc rippers; 12 - axis of the leveling roller; 13 - side discs; 14 - hollow cylinder; 15 - annular compacting components; 16 - pointed rippers

Leveling roller (2) includes axle (12) and side discs (13). Hollow cylinder (14) is mounted on the periphery of side discs (13), on the outer surface of which, at equal intervals in the horizontal plane,
annular compacting components (15) are mounted that have the shape of an equilateral triangle in cross-section. Sharpened rippers (16) are diametrically installed between the annular compacting components.

Before the start of operation, by means of brackets (4), the implement is connected to a hitch (when used in a single-operation version) or connected to a disc harrow or cultivator (in a combined version). By screwing or unscrewing nuts (6) along the threaded part of each rod (5), the compression force of each spring (7) is changed and, thus, depending on the type and moisture of the soil, the required pressure of loosening rollers (1) and leveling ones (2) on the soil is achieved.

When moving the tool over the cultivated area, loosening roller (1) runs over the surface of the field, and disc rippers (9) cut the clods of soil from top to bottom to the required depth of the soil and loosen it.

Leveling roller (2), rolling, also runs over the surface of the field, and with the sharp edges of compacting components (15) and pointed rippers (16) additionally destroys clods of soil. Such an effect of the components of the implement structure on the soil will minimize the dispersal of the humus layer of the soil, and the maximum size of soil clods on the field will not exceed the minimum size of soil clods allowed by the agrotechnical requirements for sowing.

The presence of loosening roller (1) will make it possible not only to effectively loosen the soil to the required depth, but also to destroy the clods of soil with high quality that remain after the pass of tillage machines.

Mounting leveling roller (2) allows one to effectively break up soil clods and evenly compact the upper sowing layer of soil in compliance with the required agrotechnical parameters. The loose soil will exclude the evaporation of soil moisture and the formation of cracks on the surface of the field.

Rods (5), equipped with nuts (6) and springs (7), allows rollers (1) and (2), in the process of their rotation, to smoothly run over the field surface and, accordingly, to act on the field surface with equal force.

3. Research results

The maximum effect from the practical implementation of the leveling roller is ensured with the correct choice of its outer diameter. In this case, the roller will effectively crush soil clods and destroy them, and an incorrectly calculated roller will push the soil clods ahead of itself [3] (Figure 2).
\[ \theta \leq (\varphi_1 + \varphi_2). \] (1)

At \( \theta > (\varphi_1 + \varphi_2) \) soil clods will be squeezed out from a clearance between the surface of the hollow cylinder and the surface of the field.

In contact of the hollow cylinder of the soil rolling implement with the soil clod \( K \) two normal forces arise: \( N_1 = N \tan \psi \) that tend to push out the soil clod where \( \psi = 90^\circ - \theta \) – the angle between the normal forces and \( N_2 = N / \cos \psi \) – the force perpendicular to the surface of the hollow cylinder. The resulting force \( N = N_1 + N_2 \) tends to push the soil clod out of a clearance between the hollow cylinder and the surface of the field in the direction of the positive part of the \( O_x \)-axis.

Between the surfaces of the soil clod and the soil the friction force \( F_2 = f_2 N_2 \) arises and the force \( F_1 = f_1 N_1 \) arises between the hollow cylinder and the soil (\( f_1 \) and \( f_2 \) – coefficients of friction between the soil clod and the hollow cylinder and between the soil clod and the soil respectively). The resulting friction force \( F = F_1 + F_2 \) is directed opposite the movement direction of the leveling roller \([1, 3]\).

Having projected the forces \( N \) and \( F \) on the axis \( O_x \) and \( O_y \) we obtain:

\[ \Sigma x = N_1 \sin \theta - F_1 \cos \theta - F_2 = 0, \] (2)
\[ \Sigma y = N_2 - N_1 \cos \theta - F_1 \sin \theta = 0. \] (3)

In view of the value substitution:

\[ \Sigma x = N_1 \sin \theta - f_1 N_1 \cos \theta - f_2 N_2 = 0, \] (4)
\[ \Sigma y = N_2 - N_1 \cos \theta - f_1 N_1 \sin \theta = 0. \] (5)

Having expressed \( N_2 \) from equation (5) and by substituting in equation (4) we will obtain:

\[ N_1 \sin \theta - f_1 N_1 \cos \theta = f_2 N_1 \cos \theta + f_1 f_2 N_1 \sin \theta, \] (6)

or

\[ \sin \theta (1 - f_1 f_2) = \cos \theta (f_1 + f_2). \] (7)

Having divided both parts of equation (7) by \( \cos \theta \) and having made corresponding transformations we will obtain:

\[ \tan \theta = \frac{f_1 + f_2}{1 - f_1 f_2}. \] (8)

From Fig. 2 it follows that

\[ \cos \theta = \frac{OE}{OK} = \frac{OD - ED}{OK} = \frac{r - ED}{r}, \] (9)
\[ \sin \theta = \frac{EK}{OK} = \frac{EK}{r}. \] (10)

To calculate the distance \( ED \) we use Fig. 3.
Figure 3. Substantiation of the distance $ED$.

From Fig. 3 it follows that:

$$ED = KB = h_{cm} + r_{kn} + r_{sn} \cos(\phi_1 + \phi_2),$$

or

$$ED = KB = h_{cm} + r_{kn} \left[1 + \cos(\phi_1 + \phi_2)\right],$$

where $h_{cm}$ – the quantity of the soil compaction by a hollow cylinder, m; $r_{sc}$ – the soil clod radius, m; $\phi_1$ – the friction angle between the surfaces of a hollow cylinder and a soil clod, degrees; $\phi_2$ – the friction angle between the surfaces of a soil clod and the soil, degrees.

By substituting equation (12) in equation (9) we obtain:

$$\cos \theta = \frac{r - h_{cm} + r_{kn} \left[1 + \cos(\phi_1 + \phi_2)\right]}{r}.$$

From Fig. 2 it also follows that

$$(OK)^2 = (OE)^2 + (EK)^2,$$

or

$$EK = \sqrt{(OK)^2 - (OE)^2} = \sqrt{r^2 - \left[r - h_{cm} + r_{kn} \left[1 + \cos(\phi_1 + \phi_2)\right]\right]^2}.$$

By substituting expression (15) in (10) we obtain:

$$\sin \theta = \frac{\sqrt{r^2 - \left[r - h_{cm} + r_{kn} \left[1 + \cos(\phi_1 + \phi_2)\right]\right]^2}}{r}.$$

We divide (16) by (13):

$$\tan \theta = \frac{\sqrt{r^2 - \left[r - h_{cm} + r_{kn} \left[1 + \cos(\phi_1 + \phi_2)\right]\right]^2}}{r - h_{cm} + r_{kn} \left[1 + \cos(\phi_1 + \phi_2)\right]}.$$

Having equated equation (17) to (8) we get:

$$\frac{\sqrt{r^2 - \left[r - h_{cm} + r_{kn} \left[1 + \cos(\phi_1 + \phi_2)\right]\right]^2}}{r - h_{cm} + r_{kn} \left[1 + \cos(\phi_1 + \phi_2)\right]} = \frac{f_1 + f_2}{1 - f_1 f_2}.$$

Having made corresponding transformations of equation (18) we define the minimal diameter of a hollow cylinder of the leveling roller for the soil rolling implement:
\[
D_{\text{min}} = 2 \left( h_{\text{cm}} + r_{\text{K1max}} \left[ 1 + \cos(\phi_1 + \phi_2) \right] \right) + \frac{h_{\text{cm}} - r_{\text{K1max}} \left[ 1 + \cos(\phi_1 + \phi_2) \right] \left( 1 - f_1,f_2 \right)}{f_1,f_2},
\]

(19)

where \( D_{\text{min}} \) – the minimal diameter of the hollow cylinder of the leveling roller, m; \( r_{\text{scmax}} \) – the largest radius of a soil clod, m.

4. Analysis and discussion of results

Formula (19) expresses the relationship between the minimal diameter of the hollow cylinder of the leveling roller, the radius of the maximal soil clod, the quantity of the soil compaction, the angles \( \phi_1 \) and \( \phi_2 \) and friction coefficients \( f_1 \) and \( f_2 \). Preliminary theoretical calculations showed that the minimum diameter of the hollow cylinder should be at least 0.35 m.

Taking into account that the tillage depth before sowing, for most sown crops, is 5 ... 6 cm [10], therefore, the height of the compacting components and pointed rippers should not exceed 6 cm. Then the total outer diameter of the leveling roller should be no more than 0.47 m.

5. Conclusion

The use of the developed implement will improve the quality of soil cultivation before sowing, as well as the water regime and air conditions for the development of cultivated plants.

Theoretical studies have shown that the minimum diameter of the hollow cylinder of the leveling roller depends on the quantity \( h_{\text{cm}} \) of the soil compaction, the maximum size of soil clods left on the field after the pass of the loosening roller, and physical and mechanical properties of the soil.

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