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Improvement of the design of the plow-subsoiler-fertilizer to increase soil fertility

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ABSTRACT

The use of intensive technologies for the cultivation of agricultural crops provides for the application of fertilizers in the process of tillage. This reduces the compaction of the soil, increases its fertility and the quality of the crop. The purpose of these studies is to develop a universal working tool that allows you to combine several technological operations in one pass of the unit. The authors have developed an original design of a plow-subsoiler-fertilizer. This combined working body includes a reversible plow and a vibratory subsoiler with fertilizer ducts. This solution allows you to combine the application of fertilizers when plowing the field, loosening the subsoil layer and mixing the soil. As a result of the work, the dependences of the geometric dimensions of the structure on the traction resistance to movement in the soil were obtained. To implement the developed idea into a real design, the main parameters of the plow-subsoiler-fertilizer are determined. Particular attention is paid to the calculation of the spring mechanism that ensures the vibration of the subsoiler. The optimal number and location of belleville springs in the block and shock absorber were selected, at which the subsoiler will perform self-oscillations with a given amplitude.

1. Introduction

Crop production is impossible without mechanization and automation of crop cultivation operations (Kalimullin et al., 2019; Nukeshev et al., 2021). A set of measures to improve fertility and protect agricultural land from soil degradation has been developed in the Republic of Belarus for 2021–2025. It is aimed at: optimizing the acidity of arable soils; the use of microfertilizers in the cultivation of agricultural crops; increasing soil fertility; protection of land from degradation (Chervan et al., 2022).

Quality tillage is of paramount importance for a good harvest. Currently, agricultural producers widely use two types of basic tillage: moldboard plowing with seam turnover (Tarasenko et al., 2022) and non-moldboard plowing (Syromyatnikov et al., 2021). Each type of tillage has its own advantages and disadvantages (Latypov and Kalimullin, 2020; Syromyatnikov et al., 2022b).

Moldboard tillage provides for plowing with layer turnover. It creates good pre-sowing conditions for friendly seed germination, provides good drainage and distribution of minerals in the arable layer. The turnover of the earthen layer moves plant residues at a depth of 20–30 cm (Blednykh et al., 2017).

On soils subject to drying, water and wind erosion, non-moldboard tillage is used. With non-moldboard cultivation, plant residues from various crops remains on the soil surface. This reduces the risk of erosion. Non-moldboard tillage has been widely used on marginal soils with a small humus layer (Oskin and Tarasenko, 2017).

The combination of these types of tillage reduces time and improves the quality of tillage. In this case, the methods of applying fertilizers become more relevant (Fox and Piekielek, 1987). The combination of technological operations of tillage and fertilization is an urgent task.

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The purpose of this study is to develop a combined working body that allows for one pass of the unit to perform several technological operations: plowing; fertilization in the subsurface and arable layers; destruction of the plow pan at low traction resistance.

2. Materials and methods

The methodological design of the study is based on the hypothesis of the possibility of creating a complex tool for various soil cultivation and the introduction of organic and mineral fertilizers into the arable and subarable layers in one pass of the unit.

The use of complex tillage with deepening of the arable horizon and the simultaneous application of organic and mineral fertilizers to the soil will provide a significant increase in crop yields (Liu et al., 2021). Reducing traction resistance will increase the performance of the unit.

The design of the combined working body consists of a moldboard plow 1 and a chisel subsoiler 2 (Fig. 1).

Plow 1 for moldboard plowing is attached to the rack 3. Subsoiler 2 for non-moldboard tillage is mounted on the back of the bracket 4 (Nukeshev et al., 2022).

Soil cultivation. When plowing, the share-dump plow 1 makes a turnover of the undercut soil layer. It captures organic fertilizers from the soil surface and drops them to the bottom of the furrow formed by the previous plow pass. This ensures the incorporation of organic fertilizers into the topsoil.

Chisel subsoiler 2 destroys the soil horizon below the cutting plane of the plowshare. The front lower part of the subsoiler 2 is covered with a wear-resistant carbide alloy. For better soil cutting, the front hardened part of the subsoiler 2 is made along a parabolic curve and has a double-sided sharpening. The sharpening angle of the front part of the chisel subsoiler (from 15 to 25 degrees) contributes to a significant reduction in cutting resistance.

In the middle part of the chisel subsoiler 2, a spring mechanism 5 is installed. It consists of compression springs and a shock absorber. The rigidity of the spring block and shock absorber are selected according to the average value of soil hardness. As the resistance increases, the chisel subsoiler tilts back and compresses the spring block of mechanism 5. Soil hardness is a variable. When the resistance decreases, the potential energy of the spring mechanism 5 moves the subsoiler forward (Wang et al., 2019).

Application of fertilizers. Inside the subsoiler 2 there is a fertilizer line 6 connected to the fertilizer planter 8. In the lower part of the chisel subsoiler 2, fertilizer outlets 10 are provided for fertilizing the soil during its cultivation. (Fig. 2).

Inside the chisel subsoiler 2 there is a vertical channel 7, which has through holes 11 in the lower part. A high-pressure fan 9 delivers compressed air through the air duct through the vertical channel 7.

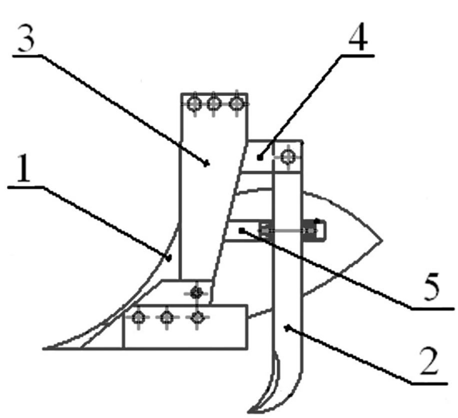

Fig. 1. Appearance of the combined working body.

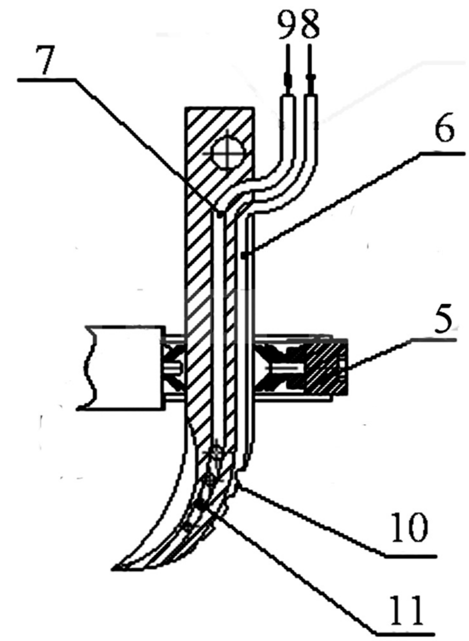

Fig. 2. The design of the subsoiler-fertilizer.

When mineral fertilizers are fed into the fertilizer line 6, a fertilizer-air mixture is formed under air pressure. The mixture passes through the fertilizer pipeline 6 to the fertilizer outlets 10. The fertilizers exit through the holes 10 under high pressure and penetrate into the cracks in the soil formed by the chisel subsoiler 2. This is how the subarable layer is saturated with fertilizers.

The air escaping through the through holes 10 creates a gas lubricant on its sides of the chisel subsoiler 2. It additionally reduces energy consumption for the execution of the technological process (Lu and Lu, 2017).

Design setup. The distance between the toe of the plowshare and the toe of the subsoiler must be at least 0.5 m. This will allow the loose layer of soil to pass freely between the subsoiler and the plow body during operation (Dubenok et al., 2017). According to recent studies (Nukeshev et al., 2022) it is recommended to install a chisel subsoiler in the transverse plane with an offset from the field cut by the value $b_\Delta = 0.07 + 0.5B$ (m), where B is is the width of the plow body share. The offset was $b_\Delta = 0.02$ m with a capture width$B$ = 0.4 m.

Calculation of the spring mechanism. When the deep-ripper chisel moves, the compression force of the spring block is proportional to the resistance force of the soil. In the event of a change in the force resistance, a spring mechanism comes into operation. To ensure the vibration mode, it is necessary that the resistance forces be close to the elastic forces of the spring mechanism (Yuan and Yu, 2020). Traction resistance P consists of two components: resistance of the working body along the bottom of the furrow P_1 and resistance to deformation of the soil layer P_2 (Chuyanov et al., 2021; Shepelev et al., 2023):

$$P = P_1 + P_2. \tag{1}$$

The force of resistance to movement P_1 of the deep-ripper chisel is applied in the plane of friction of the working body against the bottom of the furrow is equal to:

$$P_1 = fG, \tag{2}$$

where $G = G_p/n$ is weight of tillage tool per subsoiler, N; G_p is plow weight, N; n is number of plow support points; f is friction coefficient of soil on steel.

The force P_1 (2) creates a moment M_1 about the axis of rotation of the subsoiler (Fig. 3)

$$M_1 = fGL_1, \tag{3}$$

where L_1 is distance from the toe of the subsoiler to the axis of its rotation, m.

The second component of the traction resistance P_2 is the resistance to deformation of the soil layer

$$P_2 = mxhb, \tag{4}$$

where m is coefficient expressing the ratio of resistivity to soil hardness; x is hardness of topsoil, Pa; h is travel depth below the paired blade, m; b is working body width, m.

The moment from the force P_2 (4) is:

$$M_2 = mxhbL_2. \tag{5}$$

where L_2 is distance from the point of force application (the middle of the stroke depth h) to the axis of its rotation, m (Fig. 3).

External traction resistance is compensated by a spring mechanism. From the equation of moments about the axis of rotation

$$M_1 + M_2 = F_3L_3. \tag{6}$$

calculated the elastic force F_3 of the spring block

$$F_3 = (M_1 + M_2)/L_3, \tag{7}$$

where L_3 is distance from the axis of attachment of the deepener chisel to the attachment point of the spring mechanism, m.

The force of the spring mechanism from Eq. (7) taking into account the substitution of Eqs. (1)–(5), is equal to

$$F_3 = (fGL_1 + mxhbL_2)/L_3. \tag{8}$$

Eq. (8) allows you to calculate the force of the spring mechanism depending on the installation location.

3. Results

Initial data:

- weight of a five-furrow mounted plow $G_p = 8.5$ kN;
- the number plow support points $n = 11$ (5 blades, 5 subsoilers, 1 support wheel);
- depth of the subsoiler below the blade of the plowshare h from 0.1 to 0.2 m;
- subsoiler width b from 0.05 to 0.1 m;
- shoulders of the components of traction resistance $L_1 = 0.65$ m, $L_2 = L_1 - 0.5h$;

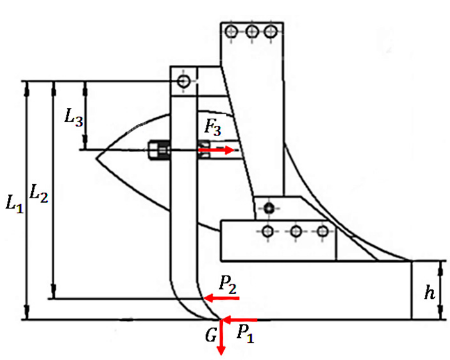

Fig. 3. Scheme of forces acting on the subsoiler.

- coefficient of friction of soil on steel$f$ = 0.45.

When working on old arable soils, the plow sole at a depth of 0.27 m has a hardness from 0.98 to 1.96 MPa. The plow pan formed during long-term plowing at the same depth has a hardness from 2.94 to 3.92 MPa (Svechnikov and Troyanovskaya, 2019; Wang et al., 2020). The dependence of the elastic force of the spring mechanism F_3 on the shoulder L_3 with the hardness of the plow pan $x = 3$ MPa and the depth of tillage $h = 0.15$ m is shown in Fig. 4.

The elastic force of the spring mechanism F_3 is directly dependent on the width b of the subsoiler. The minimum value of F_3 corresponds to the minimum subsoiler width $b = 0.05$ m.

The increase in the shoulder L_3 leads to a decrease in the compressive force F_3 of the spring mechanism. However, lowering the spring mechanism closer to the bottom of the furrow contributes to clogging the springs with soil and disabling them. Reducing the distance L_3 causes an increase in force F_3 and ensures the safety of the mechanism.

The nature of dependence $F_3(L_3)$ has a sharp break in the section L_3 from 0.12 to 0.17 m. In this section, the value of the force F_3 varies in the range from 4 to 6 kN. This confirms the instability of the external traction resistance and the possibility of the vibration mode of the subsoiler. Therefore, taking into account the operability of the mechanism, the optimal distance L_3 is located in the range from 0.12 to 0.17 m.

The dependence of the elastic force of the spring mechanism F_3 on the width of the subsoiler b with the hardness of the plow pan $x = 3$ MPa and the arm length $L_3 = 0.15$ m is shown in Fig. 5.

The value of the elastic force of the spring mechanism F_3 varies in a wide range from 4.4 to 9.2 kN. Most scientists recommend for the qualitative destruction of the plow pan the depth of the subsoiler stroke below the plowshare blade h from 0.15 to 0.17 m and the width of the subsoiler b from 0.05 to 0.07 m (Blednykh et al., 2015; Wang et al., 2017; Ednach et al., 2022; Syromyatnikov et al., 2022a). This corresponds to the compression force of the spring mechanism F_3 from 5 to 6.5 kN (Fig. 5).

The replacement of helical springs with belleville springs made it possible to make the spring mechanism more compact. Various ways of connecting the springs in the block allow you to adjust the spring mechanism in a wide range to work on soils of different hardness. Consistent installation of springs increases the total deformation while maintaining the load. Parallel assembly of the belleville springs (they are inserted one into the other) increases the load capacity with a constant amount of deformation.

Optimum amplitude of oscillations of soil-cultivating implements Δ from 4 to 6 mm. Self-oscillations at optimal frequencies

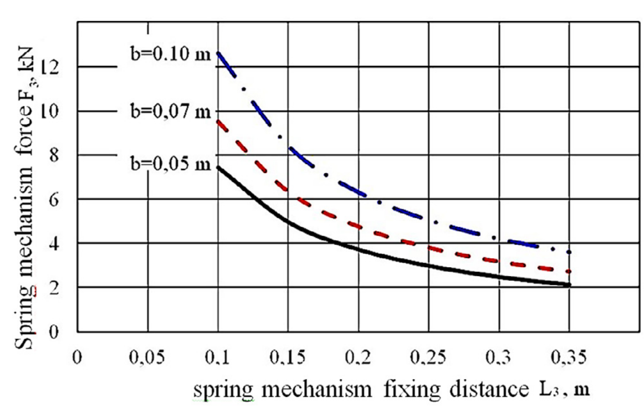

Fig. 4. Dependence of the spring mechanism force F_3 on the shoulder L_3 at different widths of the subsoiler b.

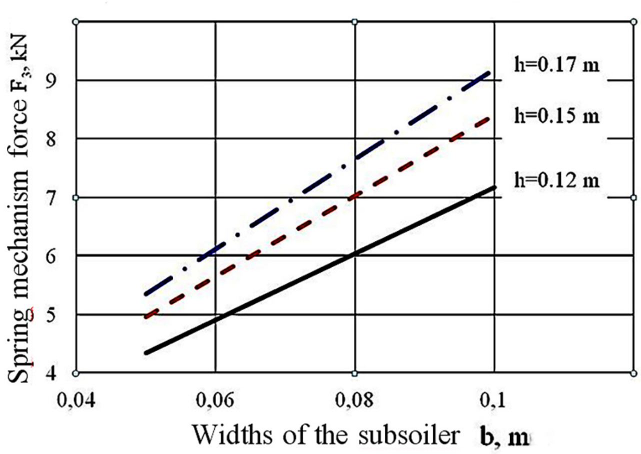

Fig. 5. Dependence of the spring mechanism force F_3 the width of the subsoiler b at different stroke depths h.

of 29–43 s^{-1} reduce the plow pan breaking force and traction resistance by up to 30% (Yuan and Yu, 2020). Based on these recommendations, the parameters of the spring mechanism for the subsoiler $L_1 = 650$ mm:

- mechanism fastening L_3 from 120 to 170 mm;
- number of springs in front (shock absorber) 2;
- number of springs at the back 4;
- spring diameter 50 mm;
- spring thickness 1.8 mm.

4. Conclusion

The authors have developed an original design of a plow-subsoiler-fertilizer, which makes it possible to saturate the subsurface horizon with mineral fertilizers in the process of tillage with simultaneous destruction of the plow pan. The dependences of the dimensions of the combined working body on the soil resistance forces obtained as a result of the studies made it possible to determine the optimal design parameters:

- subsoiler length $L_1 = 0.65$ m;
- longitudinal displacement of the subsoiler relative to the plow body 0.5 m;
- lateral displacement of the subsoiler from the field cut is 0.22 m;

Fig. 6. Prototype of a universal plow-deepsoiler-fertilizer.

- depth of the subsoiler below the plowshare blade h from 0.12 to 0.17 m;
- fastening of the spring mechanism L_3 from 0.12 to 0.17 m;
- oscillation amplitude Δ from 4 to 6 mm;
- spring mechanism forces F_3 from 4 to 6 kN;
- number of disc springs (diameter 50 mm) 6 pieces.

According to the obtained dimensions, a prototype of a universal plow-subsoiler-fertilizer was created (Fig. 6).

The combination of several technological operations in one pass of the unit made it possible to reduce energy costs and increase productivity. The combination of several technological operations in one pass of the unit allowed to reduce energy costs and increase productivity. The use of universal plow-subsoiler-fertilizer made it possible to increase work productivity, save time and money. We plan to launch the production of combined unit.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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