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Model optimization of structural layout parameters of a flexible subsoiler

Prolonged basic cultivation of agricultural soils leads to the formation of a compacted subsoil layer, commonly known as the plow sole. The presence of this over-compacted layer disrupts the soil's water-air regime, impairs nutrient uptake by crops, and ultimately reduces the potential fertility of the soil. The most effective method to counteract this phenomenon is mechanical loosening of the plow sole using subsoilers of various designs. Considering the specific features of crack formation in soil during mechanical destruction of the plow sole, a flexible chain subsoiler is among the most promising tools for loosening. Despite its significant technological and structural advantages, the anisotropy of the mechanical properties of cultivated soil layers causes stochastic oscillations in the subsoiler chain, which can destabilize the loosening process. Based on research into the simulator model of the working body of the subsoiler, a rational layout of a combined soil tillage unit has been developed, incorporating the PLN-5-35 plow and a flexible chain soil subsoiler. The contour of this subsoiler is designed to include a mechanical absorber of stochastic vibrations in the form of an elastic damper, which stabilizes the loosening process. Field tests of the proposed combined soil tillage unit demonstrated that the hardness of the plow sole layer loosened by the flexible chain subsoiler was reduced by a factor of 2,5 compared to cultivation performed with the standard PLN-5-35 plow.

Keywords: soil; plow sole; subsoiler; simulator model; chain; flexible contour; structural layout.

Introduction. One of the most significant technological problems associated with long-term cultivation of agricultural soils is the formation of the so-called plow sole, typically at a depth characteristic of primary soil tillage [1–3, 6, 11]. Notably, the formation of the plow sole occurs not only with traditional moldboard tillage but also with any soil-working implement, including discs of various configurations, chisel plows, and cultivators [5–8, 12]. Overall, the formation of the plow sole is primarily a technogenic problem, linked not only to the action of tillage equipment but also to the impact of mobile agricultural machinery on the soil [4, 7, 10].

Analysis of the current state of the issue and formulation of the working hypothesis. The most effective method for preventing the formation and, in most cases, the destruction of the plow sole remains its mechanical treatment, which is carried out by deep loosening of the subsoil layers. This is practically implemented by various designs of «subsoilers» such as chisels, deep rippers, mole plows, etc. [13, 15, 17]. These tools can be used as combined soil tillage implements in conjunction with smooth rollers, slatted and toothed structure-forming rollers, cultivators, etc. (Fig. 1).



Fig. 1. Combined chisel-type deep cultivators: a – with smooth rollers; b – with cultivator tines; c – with a slatted roller-structure-forming; d – with a toothed roller-structure-forming

Given the characteristic features of crack initiation and propagation processes [15, 16, 18] in the transversely isotropic environment of soils during mechanical treatment, the most suitable implement for loosening the plow sole is a flexible subsoiler [19], which is used as part of primary soil tillage equipment (Fig. 2). Despite certain significant advantages of the flexible chain subsoiler in terms of agrotechnical quality indicators for loosening

overcompacted soil layers [12, 14, 18], a major drawback is the stochastic oscillatory disturbances that disrupt the stability of the working process when loosening the overcompacted soil layer. These disturbances are caused by the considerable variability in the mechanical properties of the transversely isotropic soil environment. Such destabilization of the loosening process by the flexible chain subsoiler is observed both in the direction of movement of the soil-tillage machine-tractor unit and in the horizontal plane of the subsoiler's movement.

To prevent this drawback, a working hypothesis was proposed: installing a mechanical absorber of stochastic oscillations in the form of an elastic damper on one branch of the flexible subsoiler's chain contour (Fig. 3).

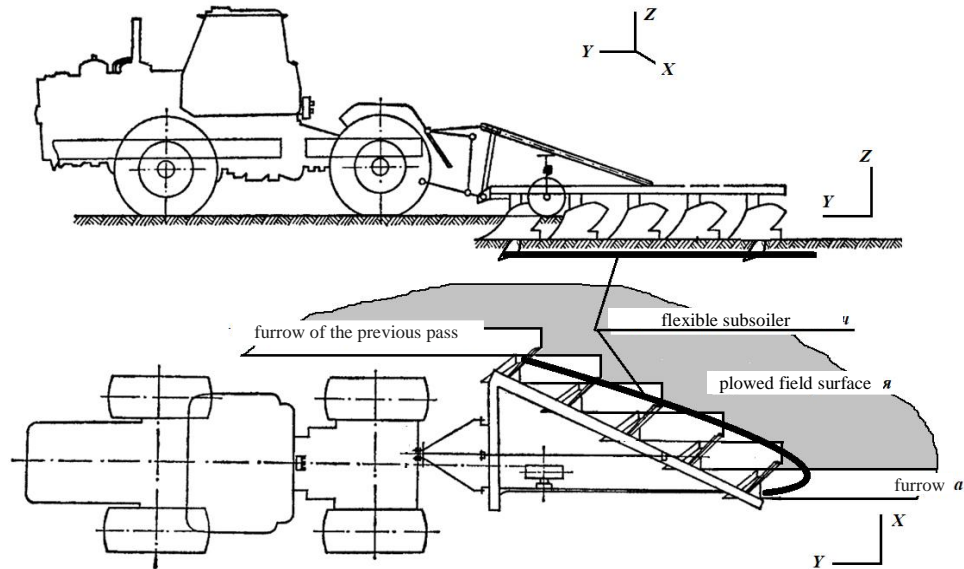


Fig. 2. PLN-5-35 plow equipped with a flexible subsoiler

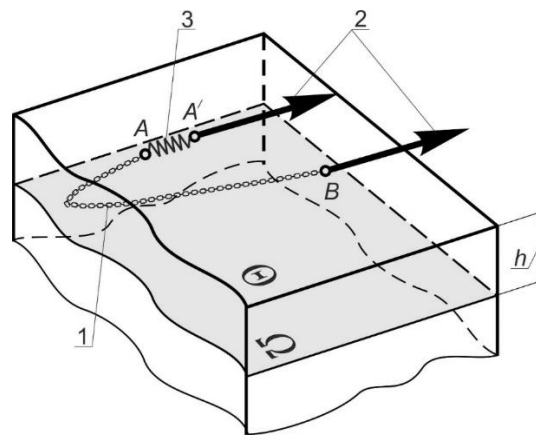


Fig. 3. Contour of a flexible subsoiler, outlined by a chain line: 1 – chain of a flexible subsoiler; 2 – direction of movement of the tillage machine-tractor unit; 3 – elastic damper AA'; Θ – surface of the soil; Ω – plane of movement of the subsoiler

Objective of the work. Stabilization of the working process of loosening the plow sole with a flexible chain subsoiler by optimizing the parameters of the subsoiler's structural layout.

Tasks of the work. To achieve the stated objective, the following tasks must be accomplished:

- substantiate the structural features of the flexible chain subsoiler that ensure the development of separation cracks in the overcompacted plow sole layer towards the surface of the open furrow formed between the passes of adjacent plow bodies;
- determine the main structural parameters of the mechanical absorber of stochastic oscillations in the chain contour of the subsoiler to stabilize the process of continuous loosening of the plow sole;
- propose an optimized layout for a combined soil tillage implement consisting of the PLN-5-35 plow and the flexible chain subsoiler, and manufacture a corresponding experimental sample of the combined implement;
- conduct experimental testing of the experimental sample of the combined soil tillage implement based on quality indicators for plow sole loosening.

Modeling the contour of the flexible subsoiler, main equipment, and experimental research methodology. To implement a physically materialized simulator of the contour of a flexible chain subsoiler (Fig. 4, *a*) in the form of the generatrix of a chain line (Fig. 4, *b*), a short-link cargo chain DIN5685A 5/10 was used, freely suspended at two points as shown in Figure 4, *c*.

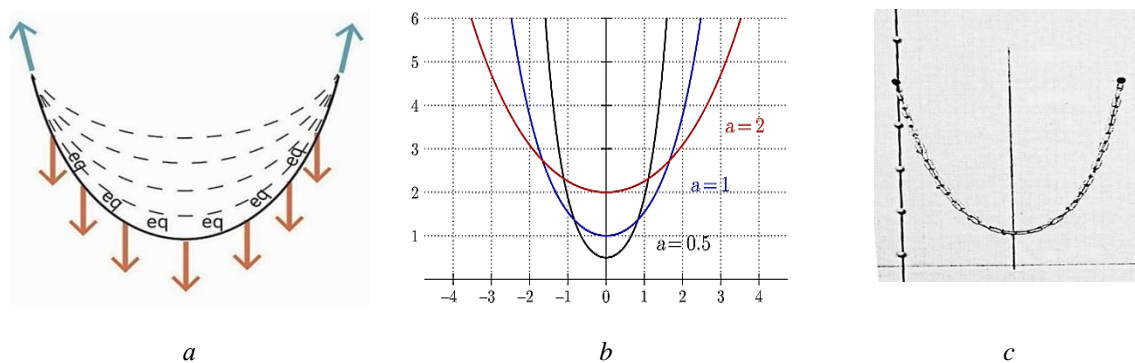


Fig. 4. Step-by-step verbal explanation of the model-simulator of the contour of the flexible chain subsoiler:
a – contour of the flexible subsoiler moving in the soil,
b – generatrix of the chain line, c – model-simulator of the flexible chain subsoiler

The laboratory setup for conducting experimental studies on the dynamics of the contour of the model-simulator of the flexible subsoiler was implemented using a universal laboratory optical-mechanical bench, on which a stand for securing the model-simulator and a digital camera on an adjustable tripod were installed (Fig. 5). To model the optimal parameters of the mechanical absorber of stochastic oscillations in the chain contour of the subsoiler, double-acting (tension-compression) and single-acting (tension) coil springs with various geometric characteristics, deformation magnitudes, and equivalent stiffness coefficients were tested (Fig. 6, *a*). An example of the configuration of the model-simulator of the flexible subsoiler with the model of the elastic damper is shown in Figure 6, *b*.

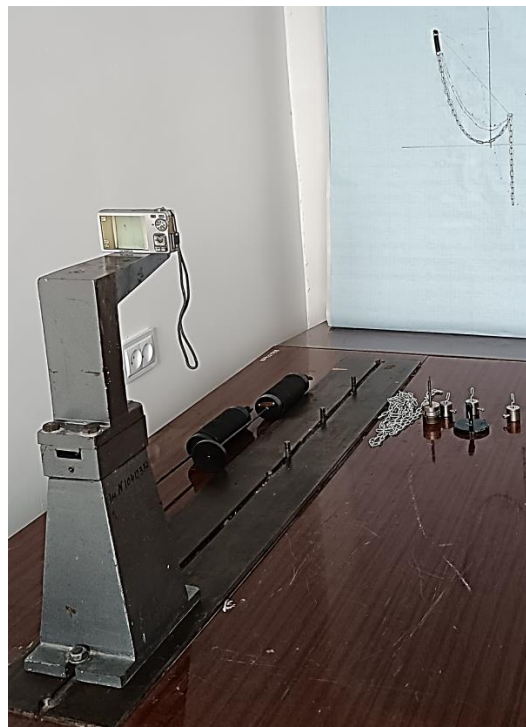


Fig. 5. Laboratory setup for studying the contour of the model-simulator of the flexible subsoiler

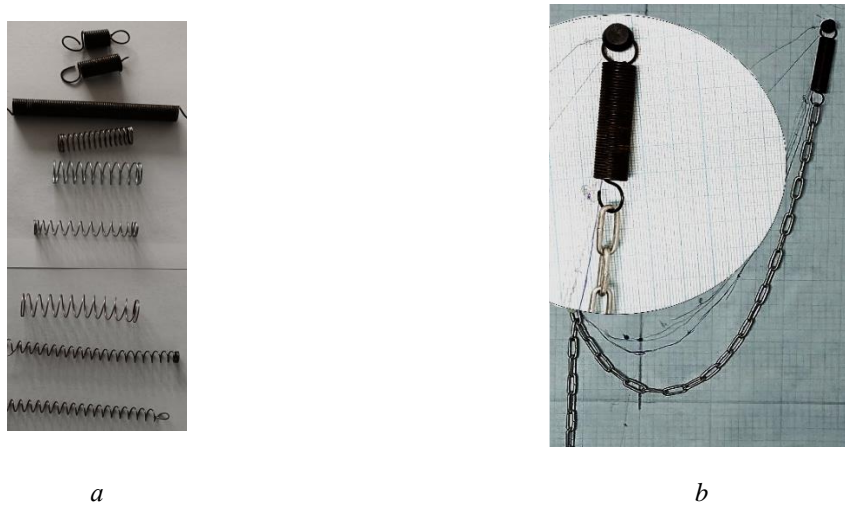


Fig. 6. Models of the mechanical absorber of stochastic oscillations in the chain contour of the subsoiler: a – variants of the elastic dampers studied; b – example of the configuration of the model-simulator of the flexible subsoiler with the elastic damper model

The first stage of optimizing the structural layout parameters of the flexible chain subsoiler involves determining the chain loop length that would ensure the destruction of the overcompacted soil layer within the length of the open furrow between the aligned plow bodies. To achieve this optimization of the chain length, the following conditions for studying the dynamics of the chain line contour were established using experimental design methods. Analytically, these conditions can be represented as (Fig. 7):

- coordinates of the right hinge at the chain attachment point, $C_1(x_1, y_1)$;
 - coordinates of the left hinge at the chain attachment point $C_2(x_2, y_2 = -a \cosh \frac{x}{a})$;
 - length of the considered part of the generatrix $l = l_0 - \frac{l_0}{n} \cdot t$, where l_0 – initial length of the generatrix;
- n – conditional number of links on the initial length of the generatrix; t – step of movement of the movable hinge.

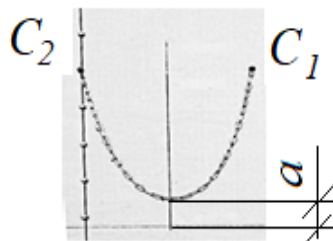


Fig. 7. Parameters for optimizing the contour of the subsoiler chain

The analytical model of the length L of the subsoiler chain, represented as the «catenary of a flexible thread loop», describes a specific curve in the horizontal X - Y plane: $y = f(x)$ (Fig. 8).

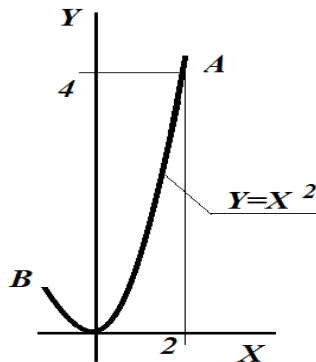


Fig. 8. Analytical model of the «flexible thread» loop of the subsoiler

Hence the structural length L of the subsoiler chain, represented as the «catenary of the flexible thread loop» (where the integration limits $a \div b$ are determined by the length the curve segment from $(\cdot)A$ to $(\cdot)B$), is given by:

$$L = \int_a^b \sqrt{1 + (\dot{f}(x))^2} dx, \quad (1)$$

or, if $x = x(y)$, and y in the interval $a \div b$ varies within the limits $c \leq y \leq d$, then:

$$L = \int_c^d \sqrt{1 + (\dot{x}(y))^2} dy. \quad (2)$$

For the considered model $y = f(x) = x^2$ according to (1), we restrict the length of the «chain line of the flexible thread loop» of the subsoiler to the right branch of the parabola, and after transforming the integrand, we obtain:

$$L = \int_0^2 \sqrt{1 + (\dot{x}^2)} dx = \int_0^2 \sqrt{1 + (2x)^2} dx = \int_0^2 \sqrt{1 + 4x^2} dx. \quad (3)$$

To calculate the integral (3), we multiply the integrand and divide it by $\sqrt{1 + 4x^2}$. We obtain:

$$\begin{aligned} \int_0^2 \sqrt{1 + 4x^2} dx &= \int_0^2 \frac{1 + 4x^2}{\sqrt{1 + 4x^2}} dx = \\ &= \int_0^2 \left(\frac{1}{\sqrt{1 + 4x^2}} + \frac{4x^2}{\sqrt{1 + 4x^2}} \right) dx = \int_0^2 \frac{dx}{\sqrt{1 + 4x^2}} + 4 \int_0^2 \frac{x^2 dx}{\sqrt{1 + 4x^2}} \end{aligned} \quad (4)$$

For further calculations of the right-hand side of (4), we reduce the first integral to a standard (tabular) integral, and apply the integration by parts formula to the second integral:

$$\begin{aligned} \int_0^2 \frac{dx}{\sqrt{1 + 4x^2}} + 4 \int_0^2 \frac{x^2 dx}{\sqrt{1 + 4x^2}} &= \frac{1}{2} \int_0^2 \frac{2 dx}{\sqrt{1 + (2x)^2}} + \\ &\left| \begin{array}{l} u = x \Rightarrow du = dx \\ dv = \frac{x dx}{\sqrt{1 + 4x^2}} \Rightarrow v = \frac{1}{8} \cdot 2\sqrt{1 + 4x^2} = \frac{1}{4} \cdot \sqrt{1 + 4x^2} \end{array} \right| + \\ &+ 4 \cdot \left(\frac{x}{4} \cdot \sqrt{1 + 4x^2} \right) \Big|_0^2 - \frac{1}{4} \int_0^2 \sqrt{1 + 4x^2} dx = \\ &= \frac{1}{2} \ln |2x + \sqrt{1 + 4x^2}| \Big|_0^2 + x \sqrt{1 + 4x^2} \Big|_0^2 - \int_0^2 \sqrt{1 + 4x^2} dx = \\ &= \frac{1}{2} \ln |2 \cdot 2 + \sqrt{1 + 4 \cdot 2^2}| - \frac{1}{2} \ln |2 \cdot 0 + \sqrt{1 + 4 \cdot 0}| + \\ &+ 2\sqrt{1 + 4 \cdot 2^2} - 0 - \int_0^2 \sqrt{1 + 4x^2} dx = \\ &= \frac{1}{2} \ln(4 + \sqrt{17}) - \frac{1}{2} \ln 1 + 2\sqrt{17} - \int_0^2 \sqrt{1 + 4x^2} dx = \\ &= \frac{1}{2} \ln(4 + \sqrt{17}) + 2\sqrt{17} - \int_0^2 \sqrt{1 + 4x^2} dx. \end{aligned} \quad (5)$$

So:

$$\int_0^2 \sqrt{1 + 4x^2} dx = \frac{1}{2} \ln(4 + \sqrt{17}) + 2\sqrt{17} - \int_0^2 \sqrt{1 + 4x^2} dx. \quad (6)$$

We solve equation (1) by considering the desired integral, $\int_0^2 \sqrt{1 + 4x^2} dx$, as the unknown. We obtain:

$$2 \cdot \int_0^2 \sqrt{1 + 4x^2} dx = \frac{1}{2} \ln(4 + \sqrt{17}) + 2\sqrt{17}, \quad (7)$$

or:

$$L = \int_0^2 \sqrt{1 + 4x^2} dx = \left(\frac{1}{4} \ln(4 + \sqrt{17}) + 2\sqrt{17} \right) \text{ (linear units)}, \quad (8)$$

where:

$$L = 4,62 \text{ (linear units)}. \quad (9)$$

According to Figure 4, conventional linear units are determined by the structural and operational parameters of the tillage implement. Thus, for the PLN-X-35 plow (Fig. 3), two linear units will be:

$$2\|(\text{linear units})\| = a \cdot (n - 1). \quad (10)$$

where $a = 0.35$ (m) – the width of the plow body; n – the number of plow bodies in the tillage implement. Therefore, the calculated structural minimum total length of the flexible subsoiler for the PLN-5-35 plow will be:

$$L = 4,62 \cdot \frac{1}{2} \cdot [a \cdot (n - 1) + a] = 4,62 \cdot \frac{1}{2} \cdot [0,35 \cdot (5 - 1) + 0,35] = 4,0425 \text{ (m)}. \quad (11)$$

Model studies of the magnitude of the absolute deformation Δl of the absorber (damper) involved simulating the loading of the subsoiler chain model with a uniformly distributed load, as shown in Figure 4, *a*, and with a certain concentrated force N , which simulated the case of the subsoiler working body coming into contact with an obstacle (for example, a stone).

The quality of plow sole loosening was checked based on the determination of the ultimate shear stresses τ , measured using a digital analog of the Revyakin hardness tester equipped with a conical punch. The apex angle of the punch cone was $\alpha = 30^\circ$ (Fig. 9).

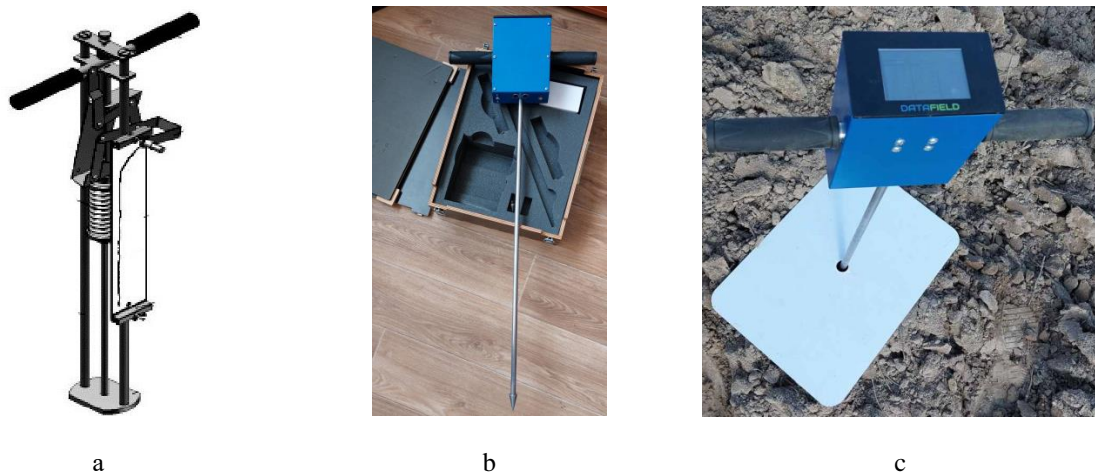


Fig. 9. Revyakin soil hardness tester: *a* – traditional design of Revyakin hardness tester; *b* – digital analog of Revyakin hardness tester; *c* – measurement of soil hardness

According to the results of measuring the ultimate shear stresses τ according to Revyakin, the following were determined:

- the hardness of the plow sole soil layer at a depth of 35 cm from the soil surface under three comparison scenarios: *a* – without mechanical cultivation (control), *b* – treatment with the basic soil tillage implement (PLN-5-35 plow), *c* – treatment with the combined soil tillage unit (modernized PLN-5-35 and flexible chain subsoiler);

- indicators of the quality of continuous plow sole treatment according to the «range of variation» of the ultimate shear stresses in the plow sole soil layer along the axis perpendicular to the direction of movement of the experimental combined soil tillage unit, both in absolute and relative terms, calculated by the formula [20]:

$$\mathcal{R} = \tau_{\max} - \tau_{\min}, \quad (12)$$

and by the value of the unweighted root mean square deviation:

$$\Delta_{sq} = \sqrt{\frac{\sum_{i=1}^n \tau^2}{n}}, \quad (13)$$

where \mathcal{R} is the value of the «variation range»;

τ – shear stresses determined by the Revyakin hardness tester;

Δ_{sq} – is the mean square deviation.

Research results and discussion. The results of computer visualization of the model study of the dynamics of the length l of the generator of a flexible chain subsoiler changes in the left coordinate at a specified step, are shown in Figure 10.

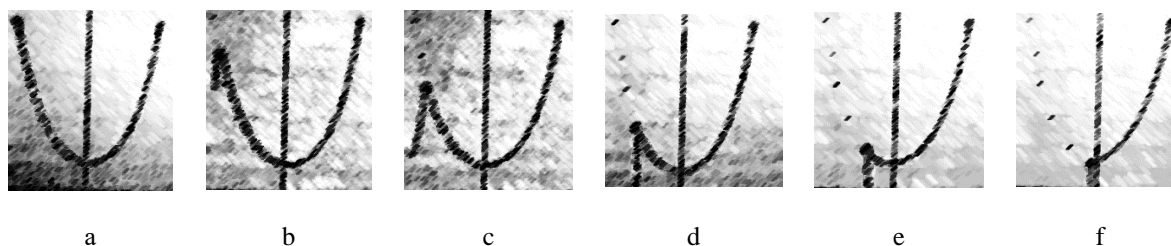


Fig. 10. Computer visualization of a model study of the dynamics of the length of the generator of a flexible chain subsoiler

It was established that under the condition of a normalized chain length $\|L\|$, which is defined, according to formula (1), the loop of the flexible subsoiler with the coordinates of the contour point $C_2 \left(x_2, y_2 = -a \cosh \frac{x}{a} \cdot \frac{1}{5} \right)$ ensures the destruction of the overcompacted soil layer within the length of the open furrow between the combined plow bodies. Figure 11 shows a diagram of the implementation of the working process of loosening the plow sole by a flexible chain subsoiler, which is aggregated to the modernized PLN-5-35 plow. In particular, the modernization of PLN-5-35 provides for the installation of one pillar of the subsoiler in place of the front plow body, and another pillar behind the last fifth plow body. The front and rear pillars of the subsoiler are connected by a G80: 10 30 load chain with a working load of $N = 31,5$ (kN) [19], the simulation model of which is shown in the left zone of Figure 9 and corresponds to the model contour of the generating chain line presented in Figure 10, *e*. The specified contour of the flexible subsoiler chain provides the possibility of unhindered development of separation cracks of the overcompacted layer of the plow sole towards the bottom surface of the open furrow, which is formed between the passes of adjacent plow bodies. In the scheme of implementation of the plow sole loosening work process (Fig. 11): zone A defines the zone of the loosened plow sole, which is formed by the previous pass of the plowing unit, three consecutive zones B – zones of loosening the plow sole between bodies 2, 3, 4, 5 of the plow, zone C – zone of loosening the plow sole, which is prepared for the next adjacent pass of the plowing unit. The implementation of this working process scheme ensures continuous treatment of the overcompacted soil layer, which results from long-term cultivation.

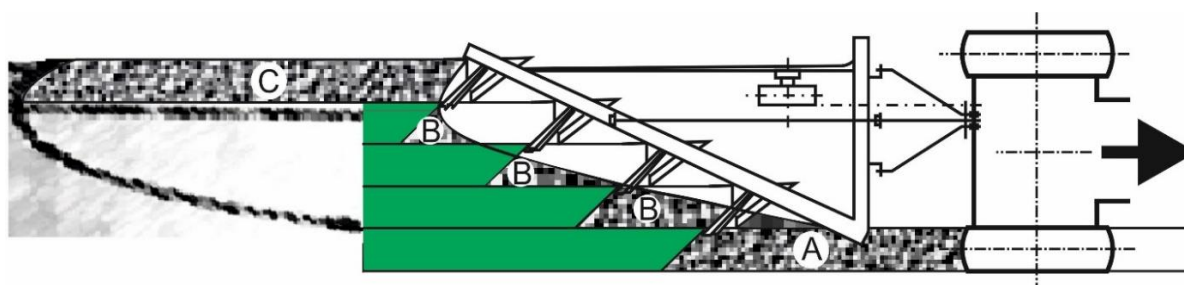


Fig. 11. Scheme of the working process of plow sole loosening with a flexible chain subsoiler aggregated with a modernized PLN-5-35 plow

To stabilize the working process of loosening the plow sole with a flexible chain subsoiler, it is proposed to install a mechanical absorber of stochastic oscillations in the chain contour of the subsoiler in the form of an elastic damper. Based on the results of modeling (Fig. 12) of the dynamics of the subsoiler's operation, the following requirements for the mechanical absorber of stochastic oscillations in the chain were formulated:

- an elastic damper (mechanical vibration absorber) should be designed to operate only in one direction (to absorb only the deformation Δl of elongation, Figure 12, *a*), in contrast to a double-acting damper (tension-compression, Figure 12, *b*), which, due to the doubled deformation value $2 \cdot |\Delta l|$, leads to an increase in the normalized chain length $\|L\|$;
- minimal changes in the contour of the flexible chain subsoiler, under the action of a distributed load along the length of the chain (Fig. 12, *c, d*), as determined by the change in parameter a (Fig. 7), are observed when the length of the elastic compensator, measured along its axis, is less than $5 \cdot \|L\| \cdot 10^{-2}$ (Fig. 12, *c*);
- a similar result as described in the previous paragraph, is observed in the case of the combined action of the distributed load and the concentrated force N , which simulates the contact of the subsoiler working body with an obstacle, for example, with an «absolutely rigid body», (Fig. 12, *e, d*).

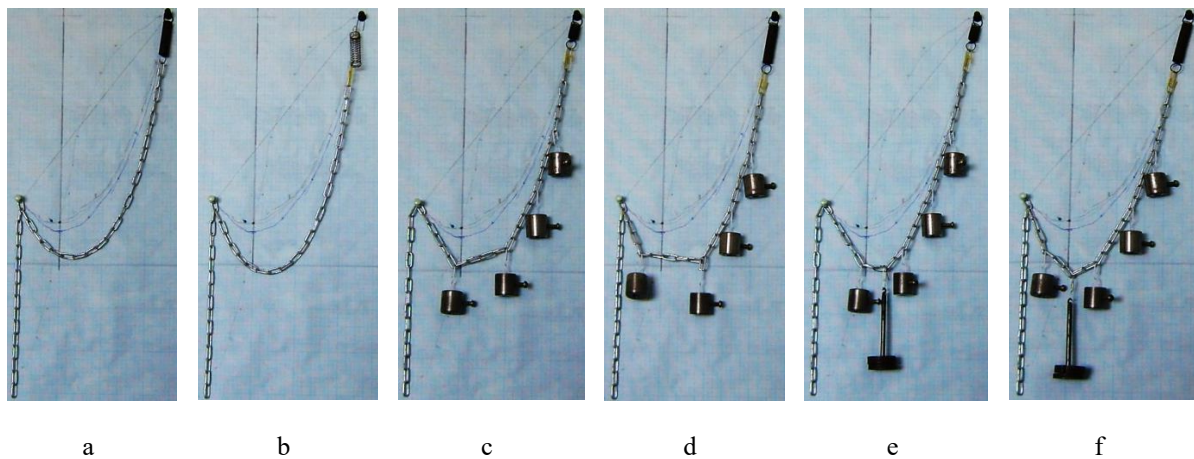


Fig. 12. Key variants of the study on the dynamics of the model-simulator of the elastic vibration absorber installed on a model of a flexible subsoiler chain: a – a single-acting (tension) damper, b – double-acting (tension-compression) damper, c, d – change in the chain contour with the vibration absorber under distributed load, d, e – change in the chain contour with the vibration absorber under the load and a concentrated force

Based on the results presented above from the study of the dynamics of the model-simulator of the flexible chain subsoiler equipped with an elastic mechanical absorber of stochastic oscillations, an optimized layout of the combined soil tillage tool consisting of a PLN-5-35 plow and a flexible chain subsoiler is proposed (Fig. 13).

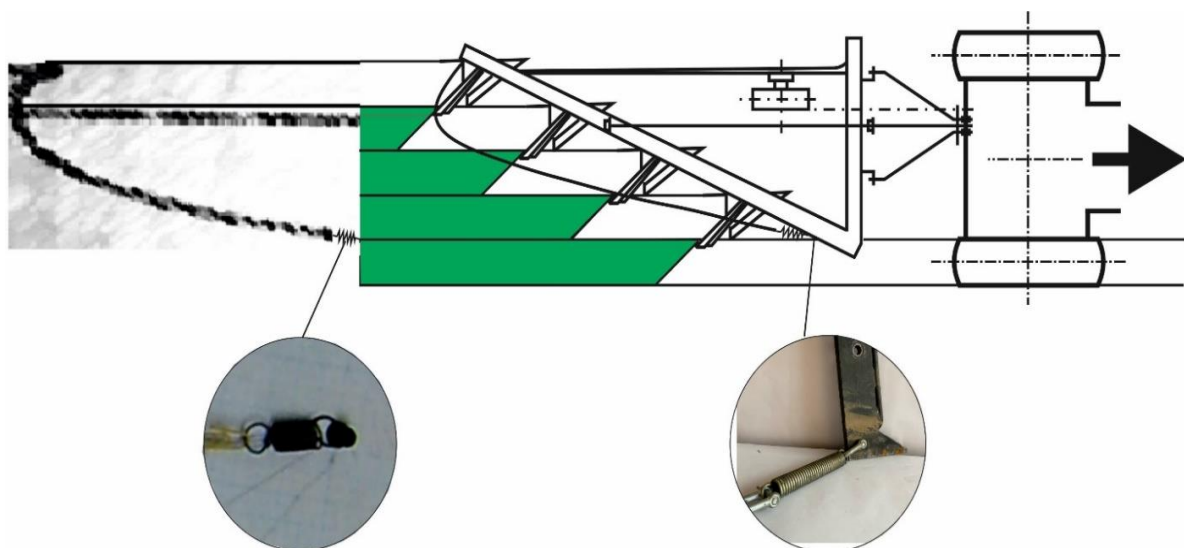


Fig. 13. Diagram of the layout of the combined soil tillage unit consisting of a PLN-5-35 plow with four plow bodies and a flexible chain subsoiler

The proposed structure of the combined soil tillage unit layout was practically implemented based on the PLN-5-35 plow (Fig. 14, 15).



Fig. 14. Combined soil tillage unit consisting of: PLN-5-35 plow (modernized) and flexible chain subsoiler



a



b

Fig. 15. Elastic absorber of stochastic vibrations of the subsoiler: a – general view of the layout of the damper installation unit, b – elastic absorber of stochastic vibrations installed on the shank of the front plow body

The modernization of the PLN-5-35 plow for the installation of a flexible chain subsoiler, in accordance with Figure 11, involves reducing the number of plow bodies from five to four. This is necessary to ensure continuous loosening of the plow sole across the horizontal plane of the subsoil layer. Such modernization of the plow leads to a decrease in the width of the plowing unit and, consequently, to a certain decrease in its productivity. To prevent a reduction in the productivity of the combined soil tillage unit consisting of the PLN-5-35 plow and a flexible chain subsoiler, a structural improvement has been proposed. This improvement (Fig. 16) involves modifying the plow frame to install an additional plow body and appropriately adjusting the position of the support wheel by relocating it to the outer side of the longitudinal beam of the plow frame. The elements of the improved design of the combined soil tillage unit are shown in Figure 16 in red.

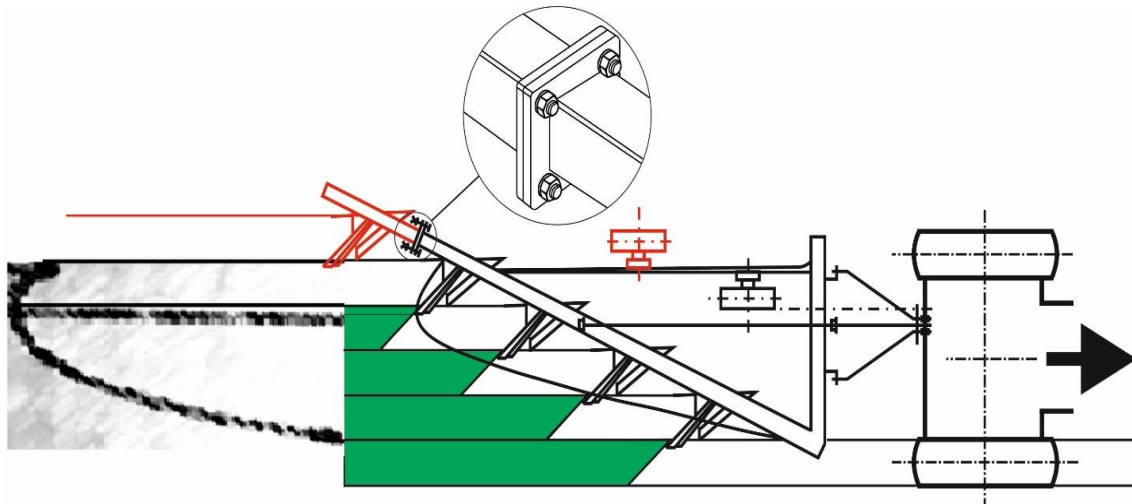


Fig. 16. Structural improvement of the combined soil tillage unit

Based on the results of field testing of the combined soil tillage unit consisting of the modernized PLN-5-35 plow and the flexible chain subsoiler (Fig. 17), it was established that:

- the hardness of the plow sole soil layer at a depth of 35 cm from the soil surface, loosened by a flexible chain subsoiler is reduced by 2,54...2,58 times according to the ultimate shear stress τ measured by the digital analog of the Revyakin hardness tester, compared to the control and the main cultivation performed with the basic model of the PLN-5-35 plow (Fig. 18);
- the variation range of the plow sole soil layer indicator (35 cm from the soil surface) along the axis perpendicular to the direction of movement of the combined soil tillage unit (PLN-5-35 and flexible chain subsoiler) in terms of the shear stress limit indicator is $\pm 0,02$ MPa, or $\pm 3,23$ % with a root mean square deviation $\Delta\sigma = 0,895$ 10–2 MPa, which indicates a high level of continuity of destruction of the plow sole soil layer (Fig. 19).



Fig. 17. Field testing of the combined soil tillage unit consisting of: PLN-5-35 plow (modernized) and flexible chain subsoiler

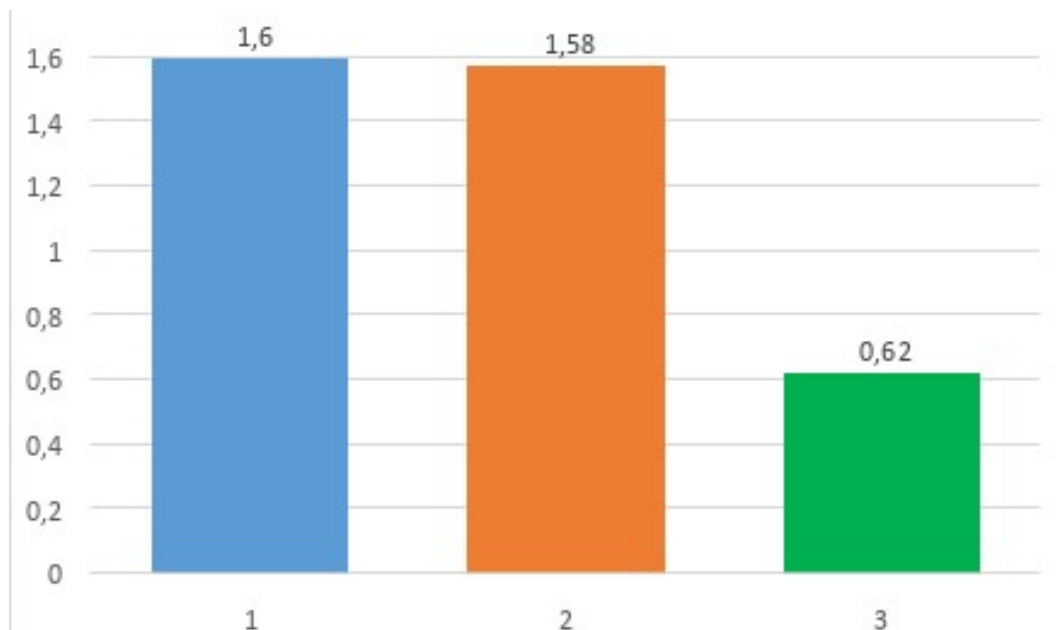


Fig. 18. Hardness of the plow sole soil layer:

1 – control; 2 – cultivation with the basic tool PLN-5-35; 3 – cultivation with a combined soil tillage unit (experimental version)

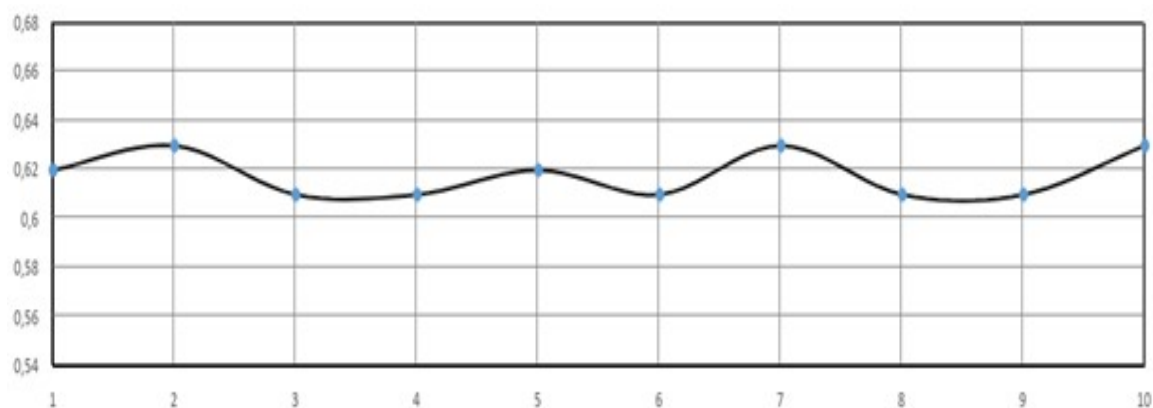


Fig. 19. Indicator of ultimate shear stresses of the plow sole soil layer along the axis perpendicular to the direction of movement of the experimental combined soil tillage unit

Conclusions. The structural features of the contour of the flexible working body of the chain subsoiler have been substantiated, ensuring the development of separation cracks in the overcompacted plow sole layer towards the surface of the open furrow formed between the passes of adjacent plow bodies.

The implementation of the proposed subsoiler design as part of a combined soil tillage unit integrated with plows of the PLN line ensures continuous processing of the overcompacted soil layers, which results from long-term primary cultivation.

The installation of a mechanical absorber of stochastic oscillations in the flexible contour of the chain subsoiler, in the form of an elastic damper, stabilizes the process of loosening the plow sole not only under distributed loads acting on the subsoiler chain, but also in cases where the chain comes into contact with a concentrated force, such as an obstacle in the form of a rocky «absolutely rigid body».

The results of the field testing and pilot implementation of a combined tillage unit consisting of a modernized PLN-5-35 plow and a flexible chain subsoiler showed that the hardness of the plow sole soil layer at a depth of 35 cm from the soil surface, loosened by the flexible chain subsoiler, was reduced by 2,54 times compared to the cultivation with the basic PLN-5-35 plow model and by 2,58 times compared to the hardness of the untreated plow sole.

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Моделювання оптимізації параметрів конструкційної компоновки гнучкого ґрунтопоглиблювача

Наслідком багаторічного основного обробітку ґрунтів сільськогосподарського призначення є утворення переущільненого підорного шару, так званої плужної підшви. Наявність такого переущільненого шару призводить до порушення водно-повітряного режиму ґрунту, що погіршує умови живлення сільськогосподарських рослин та зрештою знижує повноту використання потенційної родючості ґрунту. Найефективнішим способом запобігання цьому негативному явищу є механічне розпушування ґрунту плужної підшви глибокорозпушувачами різної конструкції. Враховуючи характерні особливості утворення тріщин у ґрунті при механічному руйнуванні плужної підшви, одним з найперспективніших знарядь для її розпушування є конструкція гнучкого ланцюгового ґрунтопоглиблювача. Зважаючи на суттєві технологічні та конструкційні переваги такого ґрунтопоглиблювача, необхідно зазначити, що анізотропність механічних ознак середовища оброблюваних шарів ґрунту призводить до виникнення стохастичних коливань ланцюга ґрунтопоглиблювача і, як наслідок, до порушення стабільності робочого процесу розпушування плужної підшви. За результатами досліджень моделі-симулятора робочого органу ґрунтопоглиблювача, розроблено раціональну компоновку комбінованого ґрунтообробного агрегата в складі плуга ПЛН-5-35 та гнучкого ланцюгового ґрунтопоглиблювача. в контурі якого передбачено установку механічного поглинача стохастичних коливань у вигляді пружного демпфера, який стабілізує процес розпушування плужної підшви. Виробнича перевірка запропонованого комбінованого ґрунтообробного агрегата засвідчила, що твердість шару ґрунту плужної підшви, розпушеного гнучким ланцюговим ґрунтопоглиблювачем, зменшено в 2,5 рази порівняно з обробітком, виконаним базовою моделлю плуга ПЛН-5-35.

Ключові слова: ґрунт; плужна підшва; ґрунтопоглиблювач; модель-симулятор; ланцюг; гнучкий контур; конструкційна компоновка.

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