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GRAPHO-ANALYTICAL ANALYSIS OF THE CHARACTERISTICS OF OBLIQUE CUTTING OF STOCHASTIC SOIL STRUCTURE BY THE FLEXIBLE WIRE OF A SOIL-DEEPENING TOOL

Bohdan SHELUDCHENKO, Candidate of Technical Sciences, Professor
Yevheniy SYROID, Assistant
Polissia National University

ШЕЛУДЧЕНКО Богдан Анатолійович, к.т.н., професор
СИРОЇД Євгеній Сергійович, асистент
Поліський національний університет

The design features of most modern tillage implements determine a characteristic aspect of their operating processes associated with the oblique-angle cutting regime applied to the heterogeneous and stochastic structure of the soil. Therefore, a detailed study of soil deformation and failure under oblique cutting conditions is important for substantiating and optimizing the structural and operational parameters of innovative tillage machinery at the stages of development, design and further practical application. The paper presents the results of a graphical-analytical investigation of the oblique cutting characteristics of a "flexible wire" subsoiler intended for loosening over-compacted sub-arable soil layers and eliminating the negative effects of a plow pan.

Based on the obtained research results, the structural layout of the proposed subsoiler was substantiated. Its design incorporates a double-acting mechanical damper installed within the "flexible string" circuit. The application of this element makes it possible to significantly reduce the draft resistance of the subsoiler by promoting soil failure mainly through a system of longitudinal and transverse shear cracks propagating toward the open surface of the soil half-space. This operating principle reduces unnecessary compaction and improves the energy efficiency of deep soil loosening.

The installation of the mechanical damper induces controlled self-excited oscillations of the flexible working element, thereby ensuring stable oblique cutting along the entire contour of the "flexible string", regardless of local changes in its curvature during interaction with the soil. It was established that the use of an 8 mm gauge G80 grade short-link load chain manufactured in accordance with ASTM A391 as the flexible subsoiler string provides an average transverse dimension of approximately 20 mm. Furthermore, a tillage unit consisting of a PLN-5-35 plow combined with the developed flexible subsoiler, designed for loosening a sub-plow layer with a plow-pan thickness of 100 mm, ensures an operating depth of h = 0.35–0.40 m. The obtained results can be used to improve the design of deep-loosening implements, reduce draft force and energy consumption, and increase the efficiency of till

***Keywords**: oblique cutting, stochastic structure, subsoiler, mechanical damper, guillotine effect, crack formation.*

Eq. 7. Fig. 11. Ref. 18.

1. Problem formulation

The vast majority of tillage tools interact with the treated layers of the soil in the oblique cutting mode, which is characterized by the location of the cutting edge of the tillage tool at an angle other than 90° to the direction of the cutting speed vector - the direction of the main movement of the working body of the tillage tool [1]. The working process, characterized by oblique cutting of the medium, is often defined as the "guillotine effect". The processing of subsoil layers with a flexible soil deepener [2], equipped with a working body in the form of a "flexible string", the structural scheme of which is shown in Fig. 1, is no exception.

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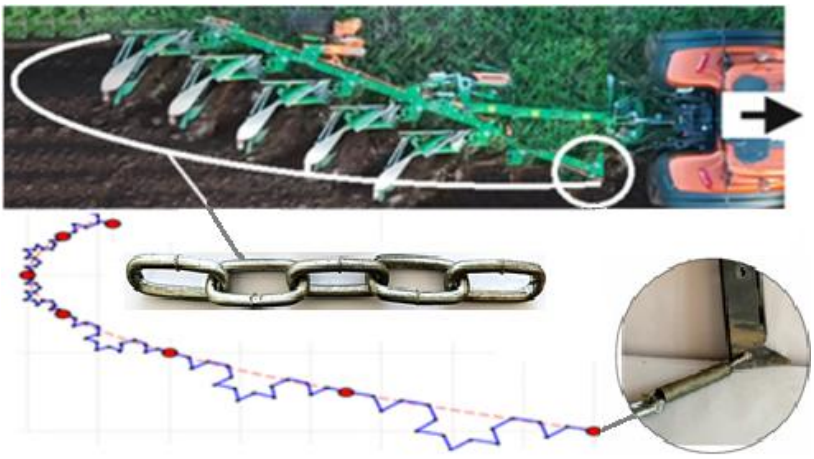


Fig. 1. Structural diagram of a flexible soil deepener as part of a PLN-5-35 plow

The most characteristic features of oblique cutting are that the soil deformation occurs according to three defining schemes of crack development: detachment (Mod I), longitudinal (Mod II) and transverse (Mod III) shears [3], which necessitates the analysis of the spatial stress-strain state. In this case, the actual cutting angles of the working body of the soil dredger change along the cutting edge of the tool, which is determined by the contour of the "flexible string" of the soil dredger.

The study of the parameters of the working process of oblique cutting of stochastic soil structure allows, at the stage of developing the design of the soil dredger, to optimize the main features of the working process and its operational parameters for loosening the subsoil layer.

2. Analysis of recent research and publications

Oblique cutting is classified, as a rule, according to the kinematics of the cutting tool or tool, the shape of the blade and the method of interaction of the tool with the processed medium. The main methods of applying oblique cutting, in addition to the above-mentioned tillage, are:

- cutting with an inclined blade [4], which is determined by the inclination of the cutting edge of the blade at a certain angle to the direction of the cutting speed vector;
- rotating or rotary cutting [5], caused by the forced rotation of the rotor-shaped cutting edge or disk knife around an axis perpendicular to the cutting plane;
- cutting with a combined or combined feed of the cutting edge of complex geometry [6], which involves a combination of longitudinal movement of the tool in the direction of the cutting speed vector with its simultaneous transverse displacement;
- cutting with a curved blade [7], which involves the use of a cutting edge, the contour of which is outlined by some algebraic curve, cycloid, spiral or tractric.

It is the last of the listed methods of using oblique cutting that is an analogue of the cultivation of subsoil layers with a soil deepener equipped with a working body in the form of a "flexible string" [2].

The main advantages of oblique cutting include: stability of the cutting work process [8] and the ability to control the characteristics of the quality of processing [9], reducing the total energy consumption for the implementation of the work process [10] and increasing the service life of the cutting tool, tools and equipment [11].

The most common use of oblique cutting is in the performance of technological operations in metalworking: oblique turning [12], spiral and step milling [13], screw drilling and broaching, as well as in woodworking during planing and peeling of veneer [14]. It is for these technological operations that thorough analytical and experimental studies have been carried out, the results of which have optimized the characteristics of the working processes of oblique cutting and the parameters of the equipment used. The basic characteristic of the processed media in the study of the working processes of such technological operations is their continuity [15]. In contrast to the above-mentioned working processes of oblique cutting, the processing of subsoil layers with a flexible soil deepener involves the implementation of a working process for the conditions of oblique cutting of a stochastic structure of transversely anisotropic organization, which is characteristic of soils for agricultural use.

3. The purpose of the article

The aim of the work is the design optimization of the operating parameters of a flexible soil deepener and stabilization of the working process of oblique cutting of the stochastic structure of the subsoil layer.

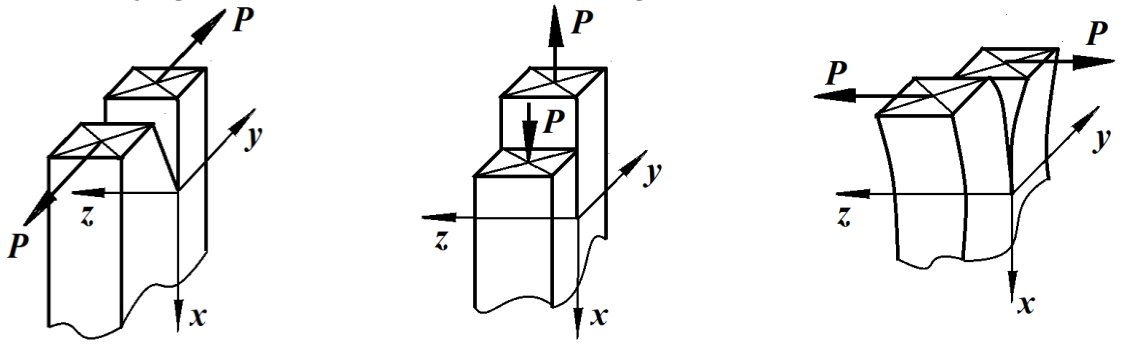
To achieve the declared goal, the following tasks must be solved:

- to establish the main patterns of destruction-loosening of the stochastic structure of the soil under conditions of oblique cutting in the presence of a damping element in the contour of the curved cutting edge;
- to substantiate the structural layout of a flexible soil deepener in the presence of a mechanical damper of double-sided action;
- to optimize the main operating parameters of the tillage unit consisting of a PLN-5-35 plow and a flexible soil deepener.

The object of the work is the process of oblique horizontal cutting of the stochastic structure by a "flexible string" of variable curvature under conditions of destruction-loosening of the subsoil layer.

The subject of the study is the main physical and mechanical characteristics of the stochastic soil structure and the geometric parameters of the "flexible string" of variable curvature.

Three classical schemes of crack development dynamics [3], shown in Fig. 2, were chosen as the basic criterion for studying the nature of the destruction-loosening of the stochastic soil structure.



Mod I **Mod II** **Mod III**

Fig. 2. Three schemes of deformation and crack formation during the destruction-loosening of the processed media

As a complex integral characteristic of the physical and mechanical state of the short-order structure, the internal friction angle φ of the structure was used, the averaged indicator of which for most agricultural soils is φ=21°…23° [16].

The flexible string of the soil dredger is structurally a short-link cargo chain of class G80 according to the ASTM A391 standard, caliber 8 mm, made of 20MnNiCrMo5-2 steel.

To study and visualize graphic models of the characteristics of the working process of cutting stochastic structures, the software packages "Wavelet Toolbox" and "FracLab" in the "MATLAB" environment were used.

4. Results and discussion

Analysis of the nature of the oblique cutting of the stochastic structure determines two clearly defined distinct zones of crack formation: a critical zone near the apex of the parabolic loop of the "flexible string", where the "guillotine effect" from oblique cutting is minimal and a zone defined by the branches of the parabolic loop of the subsoiler where the string acts as an oblique blade and the "guillotine effect" rapidly increases. In this cutting zone, the direction of the speed vector of the subsoiler movement almost coincides with the tangents to the branches of the parabolic loop of the "flexible string". Based on the basic graphic model of the parabolic loop of the subsoiler "flexible string" (Fig. 3), the nature of the deformation of the stochastic structure in the zone adjacent to the apex of the parabolic loop (Fig. 4) was modeled.

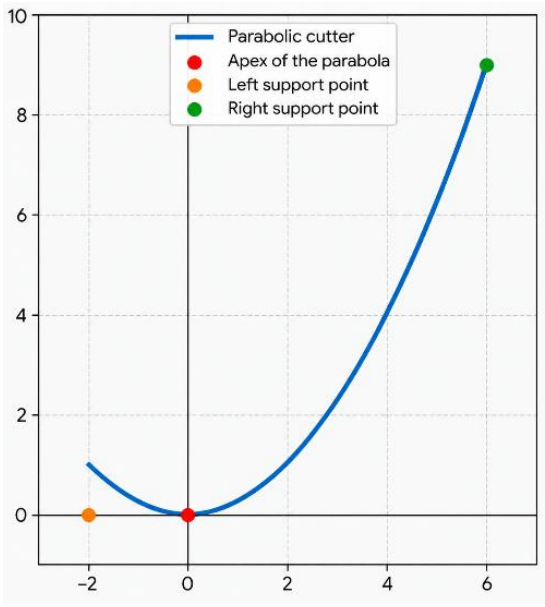


Fig. 3. Basic graphical model of a parabolic loop of a "flexible string"

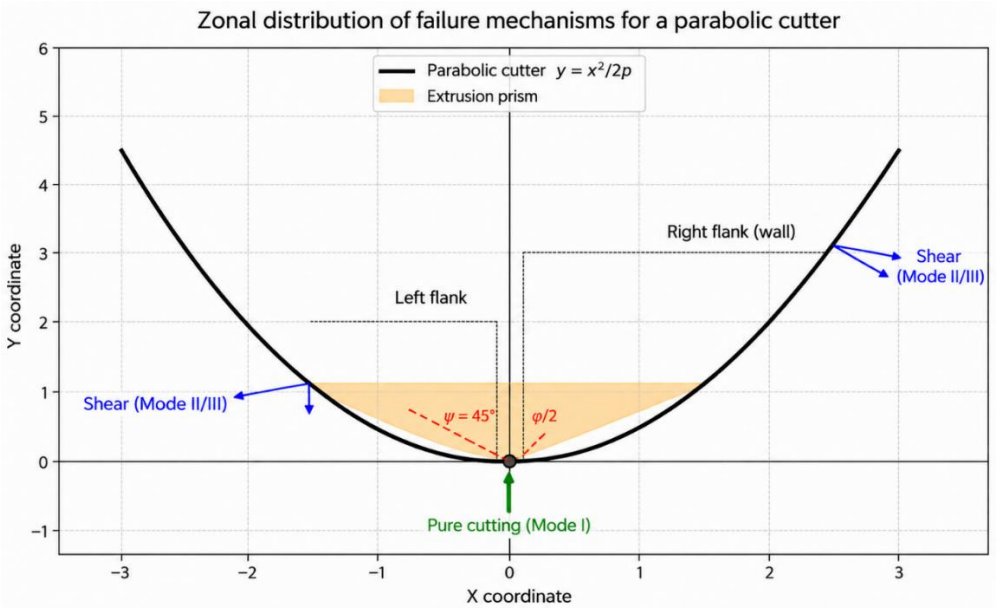


Fig. 4. Model of deformation of the stochastic structure in the zone adjacent to the vertex of the parabola loop

Based on the results of modeling the cutting of the stochastic soil structure by a "flexible string" of a soil auger, an analysis of the transformation of the mechanism of structural failure along the string contour was performed. The analysis clearly delimits two zones, different in the nature of crack formation:

the zone of dominance of longitudinal and transverse shear cracks (see Mod II and Mod III in Fig. 2), which is characteristic of cutting by both branches of the parabolic "flexible string" contour. In this zone, the string movement causes oblique sliding, which activates the mechanism of longitudinal (pure) shear (Mod II) along the string and transverse shear (Mod III) due to the inclination of the branch of the parabolic string contour. The "guillotine effect" here is maximum, since the string cuts the soil layer by layer, and the separation cracks develop mainly sideways and upwards, forming oblique "bulging" prisms.

The zone of dominance of pure detachment (Mod I) is characteristic of the zone near the apex of the parabolic contour of the "flexible string". There is no slip in this zone. The frontal compression of the structure leads to the emergence of critical tensile stresses at a certain distance in front of the string, which is determined by the size of the compacted core of the soil structure in the form of a wedge with an angle at the apex ψ, which is determined by the angle of internal friction of the structure φ (Fig. 4). The structure is destroyed by pure detachment (Mod I) towards the open (exposed) surface. The crack develops in the direction of least

resistance - upwards at an angle that depends on the depth of cultivation and the angle of internal friction of the structure. The zone where the "guillotine effect" tends to a minimum is limited by the transition point from shear failure (Mod II and Mod III) to detachment (Mod I). Mathematically, this limit is determined through the critical angle α_{crit} defined as the angle ψ at the vertex of the compacted wedge-shaped core at the vertex of the parabolic contour of the string:

$$|\pm x_{crit}| \le p \cdot \tan \alpha_{crit} = p \cdot \psi = p \cdot \left(\frac{\pi}{4} - \frac{\varphi}{2}\right) \quad (1)$$

where $\pm x$ – coordinates of the extreme points of the compacted core of the structure; p – parameter of the parabola of the "flexible string" contour; α_{crit} – critical angle of the boundary between zones; ψ – angle at the apex of the wedge of the core of the compacted structure; φ – angle of internal friction of the structure.

Expression $\left(\frac{\pi}{4} - \frac{\varphi}{2}\right)$ determines the angle of inclination of the slip plane when forming a classical bulging prism according to the Coulomb-Rankin strength theory [17].

Since the considered medium is a stochastic structure, the separation crack (Mod I) near the top of the parabolic contour of the "flexible string" does not grow smoothly, but jumpily (discrete formation of cleavage blocks occurs). When the crack tip reaches the free surface of the medium, the resistance at the crack tip drops almost to zero and the "guillotine effect" zone sharply expands. At the moment of the genesis of a new crack, a sharp growth of the compacted core of the structure occurs, and therefore the "guillotine effect" zone decreases. Such autopulsation of the working process leads to constant transverse autooscillations of the top of the parabolic contour of the "flexible string" loop of the soil dredger.

To enhance the effect of transverse self-oscillations of the "flexible string" of the soil dredger, a spring damper is installed on the longer branch of the parabolic contour of the "flexible string" (Fig. 5).

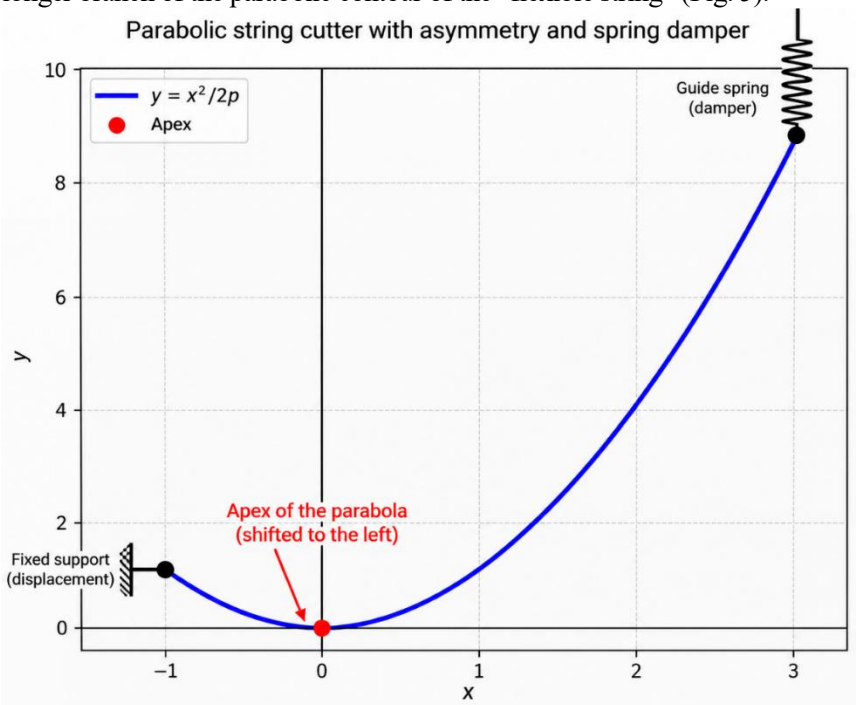


Fig. 5. Graphical model of a "flexible string" of a soil dredger with a spring damper

Installing a double-sided mechanical damper at the top of the longer branch of the parabolic loop of the "flexible string" radically changes the statics of the bevel cutting workflow. If previously the zone of minimum "guillotine effect" was symmetrically equal to $\pm x_{crit}$, then it now decreases by the value Δx(t), which depends on the stiffness of the damper k and the difference in the resistance forces ΔF on the branches of the "flexible string" contour :

$$\begin{cases} -x_{crit_{left}} = x_{crit} + \Delta x(t) \\ +x_{crit_{right}} = x_{crit} - \Delta x(t) \end{cases} \quad (2)$$

Due to the horizontal oscillation of the top of the "flexible string" contour, the effect of an artificial dynamic guillotine arises. The string begins to "saw" the wedge of the compacted core due to the work of the damper. Considering that the angle of internal friction is compared with the angle of the tangent to the longer

branch of the parabolic contour, and the parameter p is fixed, the boundary of the zone where the "guillotine effect" is minimal (but now not zero, but is measured by the amplitude of the self-oscillations of the top of the parabola) is defined as:

$$|x - \Delta x_{stat}| \leq \tan\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) \pm A_{\omega} \quad (3)$$

where Δx_{stat} – constant shift of the zone of minimal "guillotine effect" towards the shorter branch of the "flexible string" contour; A_{ω} – the amplitude of oscillations of the zone of minimum "guillotine effect", which are generated by the damper when cutting stochastic clusters of the structure.

The amplitude of oscillations of the zone of minimum "guillotine effect", which are generated by the damper when cutting stochastic clusters of the structure.

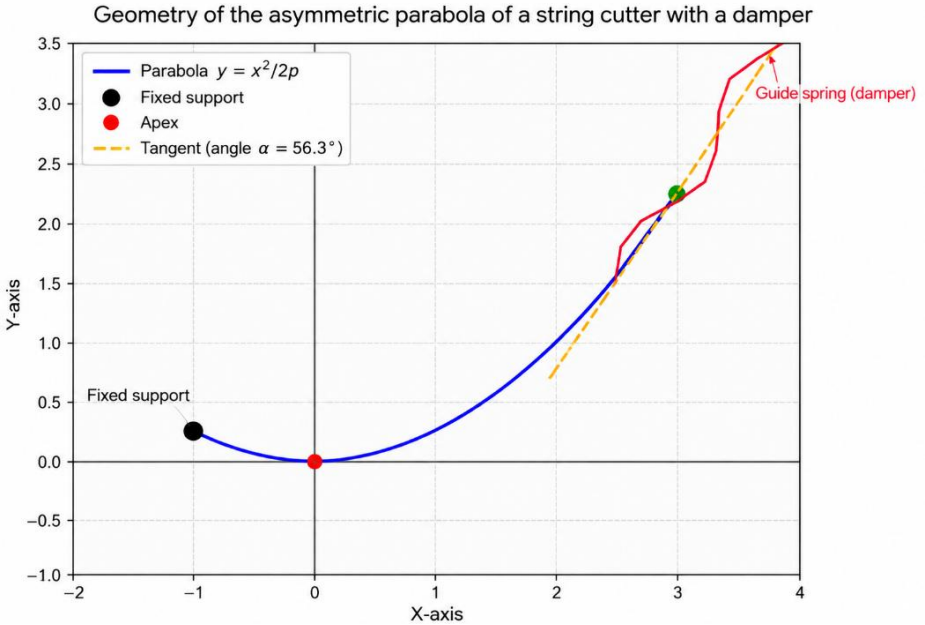


Fig. 6. Model of the "flexible string" contour with a damper

A graphical and numerical study of the model of the "flexible string" contour with a damper allows us to identify the working process of "sawing" the stochastic structure by a wedge of a compacted core as a "stick-slip" mode [18]. A visualization of the dynamic "micro-sawing" mode in phase space (velocity ẋ relative to the transverse coordinate x), which demonstrates a closed limit cycle of the "stick-slip" mode, destroying the static core of the compacted stochastic structure, is shown in Fig. 7.

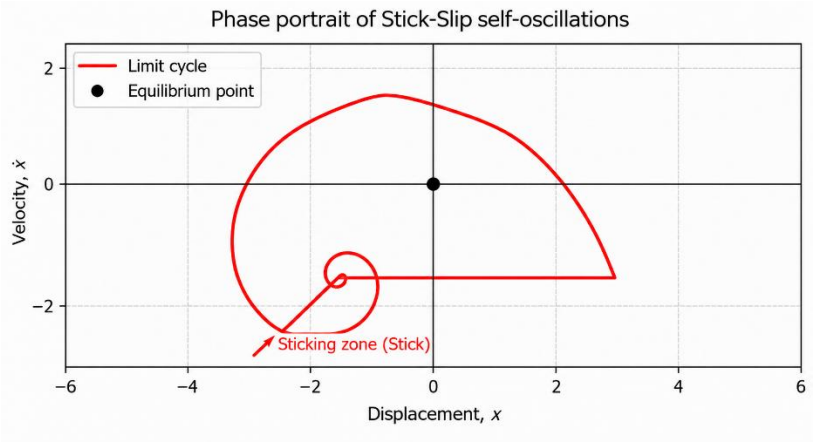


Fig. 7. Limit cycle of the "stick-slip" regime destruction of the static core of a compacted stochastic structure

The initial catalyst for the damper operation to ensure the "stick-slip" mode is the structural asymmetry of the branches of the "flexible string" loop. It is the asymmetry of the branches of the "flexible string" loop that causes the shear zone (Mod II and Mod III) on the longer branch to be significantly longer

in terms of the area of interaction with the stochastic soil structure. At the vertex of the parabolic "flexible string" loop with the damper (Fig. 6), a clean separation (Mod I) occurs through the bulge prism that forms in front of the core of the compacted stochastic structure at an angle $\psi = 45° - \frac{\varphi}{2}$ (fig.8).

The tangential force of the deformed (stretched) damper is transmitted along "flexible string" and is decomposed at each point of the contour into normal (destruction by detachment –Mod I) and tangential (shear – Mod II and Mod III) components. At the apex of the parabolic contour of the "flexible string" this force is transformed into a purely horizontal one, maximally intensifying the dynamic detachment of the bulging prism at an angle ψ (Fig. 9).

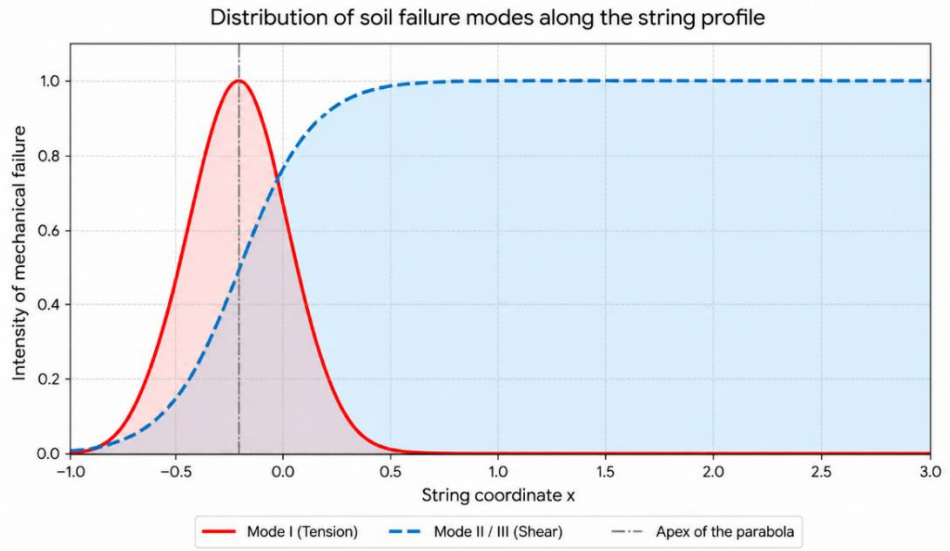


Fig. 8. Distribution of types of crack formation along the contour of the "flexible string"

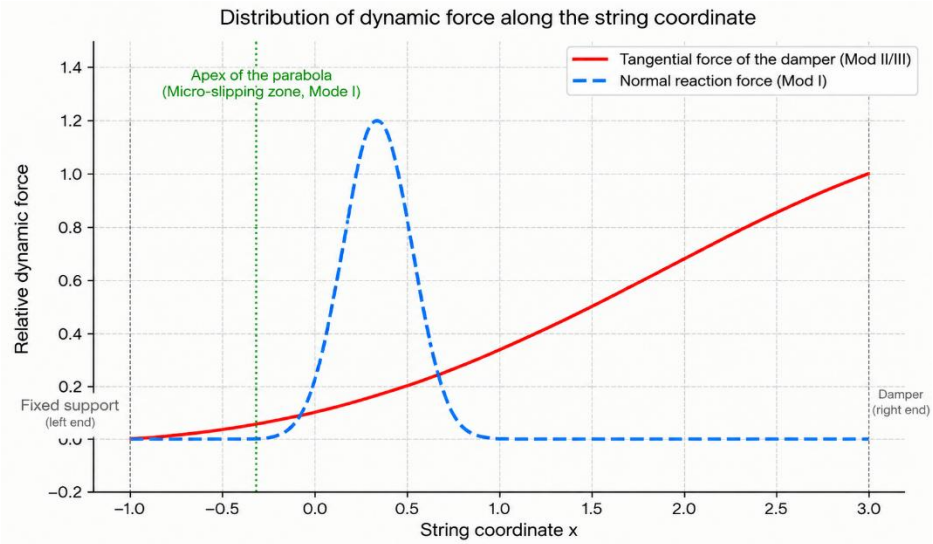


Fig. 9. Dynamics of normal and tangential forces of oblique cutting along the coordinate of the longer branch of the parabolic contour of the "flexible string"

Since the damper acts along the tangent to the right (long) branch of the parabolic contour of the "flexible string", and the left support is essentially a rigid anchor fixing the end of the left (short) branch of the loop of the parabolic contour, the top of the "flexible string" loop performs the working process of cutting the stochastic structure in the "stick-slip" mode. The phase portrait of the self-oscillating displacements of the top of the loop of the parabolic contour of the "flexible string" is shown in Fig. 10.

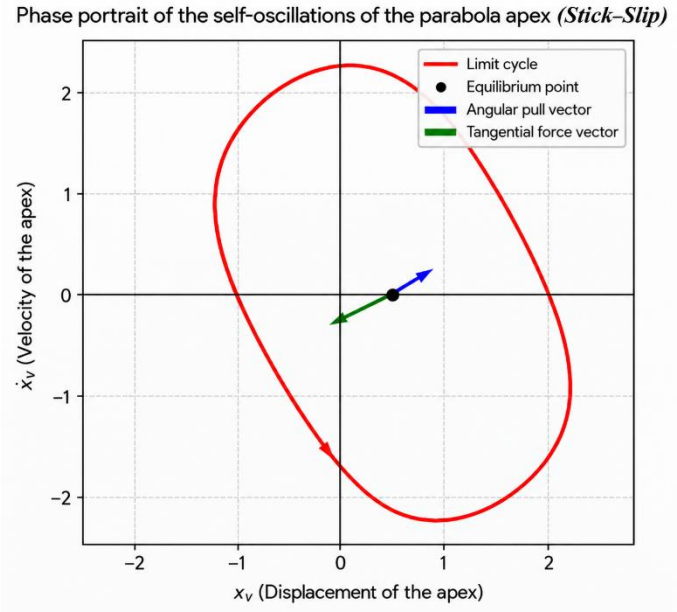


Fig. 10. Phase portrait of self-oscillations of the vertex of the loop of the parabolic contour of a "flexible string"

This arrangement of the dredger design with a "flexible string" eliminates the presence of bending moments along the entire parabolic curve of the string. The damper operates exclusively on pure tension-compression along the contour of the "flexible string". This ensures the maximum efficiency of the dredger thanks to the "stick-slip" mode, which provides pulsed self-oscillating "micro-sawing" of the stochastic soil structure with the effect of an "artificial dynamic guillotine".

The use of a G80 class short-link chain according to ASTM A391 standard with a caliber of 8 mm as a "flexible string" of the dredger determines the average transverse size of the string $d = 20\ mm$. The power of the plow sole in most cases is h=100 mm. And with the ratio of these parameters $h \div d = 100 \div 20 = 1 \div 5$ the process of ultra-shallow oblique cutting is implemented. For a stochastic structure, this is a "classic" case of the formation of a "bulging prism" with the emergence of detachment cracks (Mod I) to the free surface. In such an oblique cutting geometry, the "guillotine effect" disappears in a clearly defined zone at the apex of the parabolic contour of the "flexible string", where the stress field of pure tension and vertically oriented shear prevails.

At a cutting depth of h=100 mm, the transverse dimension of the string d=20 mm acts as a "blunt edge" (impactor). In the area at the apex of the "flexible string" parabolic contour |x|≤x_crit, the tangential component of the string tension force is unable to overcome the frontal resistance of the soil to implement the sliding process. The string pushes the compacted soil core purely forward with the expulsion of the soil "bulging prisms" upwards to the free surface.

Within this zone, a compacted soil core in the form of a wedge with an angle at the apex of 2·ψ is formed in front of the string. This wedge moves together with the string, actually changing the cross-section of the string d=20 mm into a sharp virtual blade that initiates separation cracks (Mod I). The "guillotine effect" in this case is minimal, since the cutting is performed by the moving soil itself. If φ=21°…23° (see above), then the tangent of the critical angle ψ will be:

$$\tan\psi\left(45° - \frac{22°}{2}\right) = \tan\psi\,(34°) = 0{,}67 \tag{4}$$

Then the zone of minimum "guillotine effect":

$$|x| \le x_{crit} = 0{,}67 \cdot p \approx 230\ (mm) \tag{5}$$

Therefore, the width of the clean separation zone with minimal "guillotine effect" is about 230 mm (±115 mm from the axis of symmetry of the parabolic contour of the "flexible string". Within this zone, energy is spent exclusively on overcoming frontal resistance and lifting the soil prism upwards. Outside this zone ($|x| \le x_{crit}$) lateral sliding ("guillotine effect") with shear failure dominating (Mod II and Mod III) immediately begins to operate.

If a mechanical damper is installed at the point of attachment of the right branch of the "flexible string" loop, the axis of which is oriented along the tangent to the parabolic loop contour, the system obtains maximum

kinematic freedom along the entire "flexible string" contour. Since the stochastic soil structure causes uneven resistance to each elementary section of the string, the right branch of the parabolic contour constantly "twitches" the damper. This leads not only to longitudinal oscillatory microdisplacements along the string itself, but also to self-oscillating displacements of the zone of minimal "guillotine effect" at the top of the parabolic contour. Due to the tangential orientation of the damper, an artificially generated slip occurs at the top of the parabolic contour of the "flexible string" with a speed of:

$$v_{slip}(t) = \frac{dl(t)}{dt} \tag{6}$$

where $l(t)$ – damper deformation.

This means that the zone of minimal "guillotine effect" is completely eliminated dynamically. The "flexible string" starts working like a band saw with an oscillating motion, destroying the core of the compacted structure with microcracks at the angles of internal soil friction $\psi = 45° - \frac{\varphi}{2}$. The zone of minimal "guillotine effect" is now determined not by the static angle of the natural slope of the structure, but by the amplitude of transverse slip of the apex of the parabolic contour of the "flexible string":

$$|x(t) - x_{stat}| \leq p \cdot \tan\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) \pm \Delta s(t) \cdot \cos\alpha_{apex} \tag{7}$$

Since the damper is installed at the end of the longer branch of the parabolic contour of the "flexible string", its elastic response smoothes the pulsations of soil pressure on the soil deepener, converting the stochastic discrete "noise" of the structure into smooth wave-like harmonics of the string stresses. This significantly reduces the tractive effort of the soil deepener, since the longer branch of the parabolic contour of the "flexible string" no longer wedges the soil, but smoothly drains it through a system of shear cracks (Mod II and Mod III).

According to the results of the conducted graph-analytical studies, a soil tillage unit consisting of a PLN-5-35 plow and a flexible soil deepener for the destruction of the loosening of the subsoil layer with the depth of the soil deepener $h = 0{,}35 \div 0{,}40$ м (fig.11).



Fig. 11. Combined tillage unit consisting of: PLN-5-35 plow (modernized) and flexible chain soil deepener

5. Conclusion

The installation of a tangentially oriented mechanical damper on the longer branch of the loop of the parabolic contour of the "flexible string" of the soil dredger causes artificially generated self-oscillations of the zone adjacent to the top of the parabolic contour loop, which ensures the implementation of the oblique cutting mode along the entire contour of the "flexible string" regardless of the variation of its curvature.

It is substantiated that the structural layout of the soil dredger, which provides for the presence of a mechanical damper of double-sided action installed on the longer branch of the parabolic contour of the "flexible string" significantly reduces the traction force of the soil dredger due to the implementation of the

process of destruction-loosening of the stochastic soil structure exclusively through the system of longitudinal and transverse shear cracks in the direction of the open surface of the soil half-space.

It was determined that using a G80 class short-link chain according to ASTM A391 standard with a caliber of 8 mm as a "flexible string" of a soil dredger, the average transverse size of the string is d=20 mm. The soil tillage unit consisting of a PLN-5-35 plow and a flexible soil dredger for loosening the subsoil layer with a plow sole thickness of 100 mm should provide a depth of the soil dredger stroke h=0.35÷0.40 m.

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ГРАФОАНАЛІТИЧНИЙ АНАЛІЗ ОЗНАК КОСОКУТНОГО РІЗАННЯ СТОХАСТИЧНОЇ СТРУКТУРИ ҐРУНТУ ГНУЧКОЮ СТРУНОЮ ҐРУНТОПОГЛИБЛЮВАЧА

Конструкційні особливості більшості сучасних ґрунтообробних знарядь зумовлюють характерні ознаки їх робочих процесів, пов'язані з реалізацією режиму косокутного різання стохастичної та неоднорідної структури ґрунтового середовища. У зв'язку з цим дослідження закономірностей деформування і руйнування ґрунту в умовах косокутного різання є важливим для обґрунтування та оптимізації конструкційних і експлуатаційних параметрів інноваційних зразків ґрунтообробної техніки ще на стадіях їх розроблення та проєктування. У роботі наведено результати графоаналітичного аналізу особливостей косокутного різання «гнучкою струною» ґрунтопоглиблювача, призначеного для розущільнення переущільнених підорних шарів ґрунту та руйнування плужної підошви.

За результатами проведених досліджень обґрунтовано структуру конструкційної компоновки ґрунтопоглиблювача, яка передбачає встановлення механічного демпфера двобічної дії в контурі «гнучкої струни». Застосування такого елемента дає змогу суттєво знизити тягове зусилля ґрунтопоглиблювача завдяки реалізації процесу руйнування ґрунту переважно через формування системи тріщин поздовжнього та поперечного зсуву, орієнтованих у напрямку відкритої поверхні ґрунтового напівпростору. Установлення демпфера зумовлює штучну генерацію автоколивань робочого елемента, що забезпечує стабільне косокутне різання вздовж усього контуру «гнучкої струни» незалежно від зміни її кривизни під час взаємодії з ґрунтом.

Встановлено, що використання як «гнучкої струни» вантажного коротколанкового ланцюга класу G80 за стандартом ASTM A391 калібру 8 мм є конструктивно доцільним для роботи в умовах підвищених навантажень. Ґрунтообробний агрегат у складі плуга ПЛН-5-35 та гнучкого ґрунтопоглиблювача може бути ефективно використаний для розпушування підорного шару за наявності плужної підошви потужністю 100 мм. Отримані результати можуть бути використані для подальшого вдосконалення конструкції ґрунтопоглиблювача, зниження його тягового опору, енергоємності процесу та підвищення ефективності глибокого обробітку ущільнених ґрунтів.

Ключові слова: *косокутне різання, стохастична структура, ґрунтопоглиблювач, механічний демпфер, ефект гільйотини, утворення тріщин.*

Ф. 7. Рис. 11. Літ. 18.

INFORMATION ABOUT THE AUTHORS

Bohdan SHELUDCHENKO – Candidate of Technical Sciences, Professor, Professor at the Department of Mechanical Engineering and Machine Building Technology, Polissia National University (7 Staryi Boulevard, Zhytomyr, Ukraine, 10008; e-mail: sheludchenkobogdan@ukr.net; https://orcid.org/0000-0002-8137-0905)
Yevhenii SYROID – Assistant at the Department of Mechanical Engineering and Machine Building Technology, Polissia National University (7 Staryi Boulevard, Zhytomyr, Ukraine, 10008; e-mail: syroides@ukr.net; https://orcid.org/0009-0000-6993-7430)

ШЕЛУДЧЕНКО Богдан Анатолійович – кандидат технічних наук, професор, професор кафедри машинобудування та технологій машинобудування Поліського національного університету (бульвар Старий, 7, м. Житомир, Україна, 10008; e-mail: sheludchenkobogdan@ukr.net; https://orcid.org/0000-0002-8137-0905)
СИРОЇД Євгеній Сергійович – асистент кафедри машинобудування та технологій машинобудування Поліського національного університету (бульвар Старий, 7, м. Житомир, Україна, 10008; e-mail: syroides@ukr.net; https://orcid.org/0009-0000-6993-7430)