Розглянуто питання роботи циліндричної щітки з гнучкими прутками ворсу при розкритті кореневої системи маточних рослин. Встановлено, що основними складовими сили опору при роботі даної щітки є сума опорів, що спричинені силою в'язкості ґрунту, силою статичного опору сипучих частинок ґрунту та силою опору відкидання частинок ґрунту. Виходячи з мінімізації затрат енергії, визначено оптимальні кінематичні параметри щітки з вертикальною віссю обертання. Великий влив на значення загальної сили опору має кутова швидкість щітки. Крім сили опору на прутки ворсу щітки діє нормальна реакція ґрунтової основи. Знайшовши результуючу цих двох сил за допомогою методу еліптичних інтегралів Лежандра, встановлено оптимальні розмірні параметри прутків ворсу, що виготовлені з поліпропілену. Даний метод дозволив врахувати значні, у порівнянні з довжиною прутків, їх деформації в результаті їх згину. Довжина прутків визначена як максимально можлива для забезпечення умови видалення ґрунту з валка, що вкриває кореневу систему маточних рослин клонових підщеп. Також досліджено вплив сили тертя під час роботи щітки. Це тертя частинок ґрунту між собою та по поверхні прутків ворсу. Визначено, що сили тертя, як і нормальна реакція ґрунту, мало впливають на роботу циліндричної щітки при розкритті кореневої системи маточних рослин. Це пояснюється відсутністю твердої основи при роботі прутка ворсу, що в свою чергу дозволяє розміщувати прутки ворсу по одному на поверхні щітки. Відсутність потреби у значній відносній жорсткості дозволяє пруткам ворсу видаляти ґрунт з валка мінімізуючи при цьому пошкодження рослин. За допомогою еліптичних інтегралів Лежандра другого роду досліджено прогин прутків ворсу циліндричної щітки при розкритті кореневої системи маточних рослин. Величина прогину прутка в процесі роботи впливає на повноту видалення ним частинок ґрунту. При збільшення прогину змінюється кут між робочою гранню прутка ворсу і поверхнею ґрунту. Це призводить до зменшення видалення частинок і збільшення їх ущільнення у валку. Тому розрахована довжина прутків ворсу, які здатні забезпечити необхідні робочі параметри при заданому навантаженні

Ключові слова: коренева система, маточні рослини, клонові підщепи, різання ґрунту, деформація згину

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DEFINING THE PARAMETERS FOR A BRUSH WITH POLYPROPYLENE BRISTLE WHEN UNCOVERING THE ROOT SYSTEM OF MATERNAL PLANTS

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1. Introduction

An important stage in the production of fruit saplings is to cultivate rootstocks. The most common are the clonal rootstocks, due to their capability to provide high orchard performance. One of the issues in the cultivation of clonal rootstocks has been the insufficient mechanization level of technological processes. These include the disclosure of the root system of maternal plants in order to separate saplings.

The technological process of disclosing the root system must be mechanized taking into consideration the minimal impact from the machinery working bodies on maternal plants. The designed devices with a mechanical action caused significant damage to plants, which often led to their destruction. Pneumatic and pneumatic- mechanic machinery did not make it possible to fully uncover the root system and required the use of additional manual labor. Another disadvantage of such machines was a wind soil erosion. All these shortcomings of the mechanized techniques for uncovering the root system of maternal of plants have led to the fact that at present a given operation is performed manually.

Working bodies in the form of active cylindrical brushes with elastic bristle rods have a series of advantages. These include the absence of wind erosion, almost no damage to maternal plants, and the possibility to remove up to 95 % of soil in the growth area of the root system. It is possible to improve operational efficiency of such working bodies and, consequently, the effectiveness of a clonal rootstock production technology in general, by defining the optimal structural and kinematic parameters for brush devices.

Thus, it is a relevant task to undertake a study aimed at improving technical equipment in order to mechanize the process of uncovering the root system of maternal plants. Such research is important for the development of production of fruit planting material.

2. Literature review and problem statement

The dynamics of a body penetrating the medium at high speed that corresponds to the linear values for brush operation were studied in [1]. However, when uncovering the root system, one should consider a combined environment that has the properties of flowability and plasticity. Plastic deformations that occur during soil treatment cause additional resistance forces, thereby increasing the load on the working bodies.

The operation of elastic elements during soil cultivation was considered in paper [2]. However, the authors examined the work of metallic elastic supports with a large cross-sectional area, which have different physical-mechanical properties compared to polypropylene.

Study [3] proposed a model to select the design of a brush rotating working body. In this case, although the authors considered bristle as the working elements of a brush, the model holds for metallic rods of bristles rather than propylene. In addition, they addressed the issue on removing particles of rust from metal, so the model needs clarification for the conditions of removal of soil particles.

The influence of technological parameters and the type of a brush fiber was investigated in [4]. It was found that these parameters largely affect the intensity of interaction between a brush and the treated metallic surface. However, similar to the previous paper, more research is needed in order to establish applicable dependences for soil surfaces.

The dynamic models of brush devices' operation considering a large 3D deflection were investigated in [5]. The authors accounted for interaction both between the bristle and the surface and bristles against each other. All the calculations were conducted for brushes with a vertical rotation axis. The unresolved issue has been related to interaction between bristle and the particles that are removed with a brush.

The above research was advanced in paper [6]. The authors determined the impact of bristle oscillations in the operational process on quality in removing small particles. However, the study focused mainly on particles of gravel of different sizes, which acts similar to a loose environment. The issue of influence of the medium's plasticity requires further consideration.

Dynamic loads on the brush with elastic working elements were simulated in paper [7]. A regressive mathematical model makes it possible to define the characteristics for operation of conical brushes with a vertical rotation axis.

The above work was continued in study [8]. The authors analyzed the deformative and force characteristics of bristle and established their relationship. As was the case in [4, 7], the unresolved issue has been the operation of cylindrical brushes with a vertical supporting surface.

The influence of structural parameters for brush devices on root crop cleaning quality was investigated in [9]. It was found that the rotating brush increases the degree of cleaning while reducing energy cost for the execution of the process. However, the unresolved issue has been the influence of properties of soil or soil mixture.

Analysis of the scientific literature reveals the absence of studies into the operation of brushes with polypropylene bristles when uncovering the root system of maternal plants. Application of metallic bristle whose operation has been studied enough is impossible in terms of minimizing the damage to plants. In addition, papers [1–9] emphasize the operation of brushes within a metal or loose environment with large particles rather than soil particles.

3. The aim and objectives of the study

The aim of this study is to build a model of force interaction between the polypropylene bristle rods at a cylindrical brush and particles of soil or a substrate when uncovering the root system of maternal plants.

To accomplish the aim, the following tasks have been set:

– to determine the resistance force that is responsible for the deflection of bristle rods during operation of a cylindrical brush;

– to establish the effect of kinematic parameters for the operation of a brush with elastic rods of bristles on the resultant resistance force;

– to define the optimal technique to arrange bristle rods at the surface of the brush;

– to determine the deflection of bristle rods when uncovering the root system of maternal plants with a brush.

4. Determining the components of resistance force in the operation of a cylindrical brush, as well as the kinematic parameters, on its operation

Removal of soil from a swath with a brush implies cutting the monolith with bristle rods or bundles of them, shredding the soil, its partial compaction and removal. In this case, cutting involves the separation of ground chips. In other words, while a brush rotates, the bristle rod bends and, under the action of elasticity force, penetrates the depth of soil. After leaving a contact zone, the rod straightens, thereby removing. along with it, the separated particles of soil. Complete removal of soil is achieved by increasing the active action of bristles in the process of brush rotation.

Fig. 1 shows the process diagram of soil removal by two elastic elements rotating in the same plane of sweeping.

During operation of the rotating brush the power is mostly used to enable two processes – cutting the soil (or substrate) and discarding the particles. Force F of the soil resistance in the brush operation depends both on the properties of soil and on the structural and kinematic parameters of the brush [10–13]:

$$F = f\left(\sigma, \tau, \rho, p, W, a, b, s, \vartheta_a, \omega, \vartheta\right), \quad (1)$$

where σ and τ are the boundary stresses of compression and shear, N/m^2; ρ is the soil density, kg/m^3; p is the soil hardness, Pa; W is the soil moisture content, %; a, b are the depth and width of cutting, m; s is the feed per a single bristle rod, m; υ_a is the motion speed of an assembly, m/s; ω is the angular speed of a brush, rad/s; υ is the absolute speed of the end of a bristle rod, m/s.

Among these parameters, we can significantly alter the structural and kinematic parameters for a working body. The soil parameters could vary to a certain degree, though they will be defined by natural-climatic conditions.

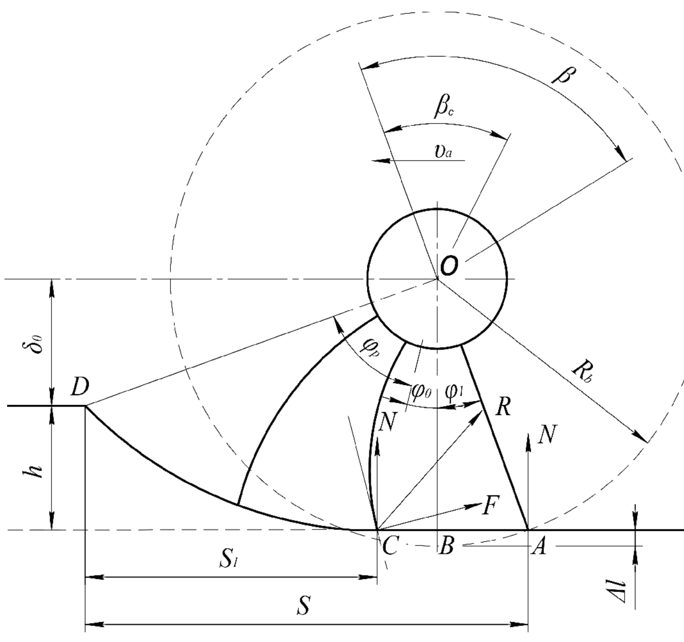

Fig. 1. Diagram of brush operation

In a general form, force F_p of the soil resistance to cutting can be recorded:

$$F_p = \int_0^{S_c} \eta \frac{d\upsilon}{dx} dx + \frac{(\tau+\sigma) 2\pi a \upsilon_a}{\operatorname{tg}\varphi_t \omega z} \sin\alpha_i, \quad (2)$$

where η is the soil viscosity coefficient at displacement, N·s/m^2; S_c is the length of a displacement section, m; φ_t is the internal friction angle of soil particles, rad.; z is the number of bristle rods along a single horizontal row of the brush, pcs.; α_i is the rotation angle of the brush, pcs.

Force F_B for removing the particles of soil can be determined from the theorem about a change in the amount of movement of a material point; we obtain:

$$F_B = \frac{\pi a \upsilon_a \upsilon h k_c^2 \mu}{z \arccos\left(1 - \dfrac{h}{R_b}\right)}, \quad (3)$$

where k_c is the relative coefficient that takes into consideration the movement of soil particles before and after a contact with a bristle rod; μ is the soil density, kg/m^3; h is the thickness of the soil layer that a brush must remove, m; R_b is the radius of the brush, m.

By combining equations (2) and (3), we derive a value for the total resistance force during brush operation to remove the particles of soil from a swath that covers the root system of maternal plants.

$$F = \frac{\pi\upsilon_a}{z}\left(\frac{2\sin\alpha}{\omega}\left(\eta\upsilon + \left([\tau]+\sigma\right)a\right) + \frac{a\upsilon h k_c^2 \mu}{\arccos\left(1-\dfrac{h}{R_b}\right)}\right). \quad (4)$$

Quite often, calculations of rotary working bodies neglect the force of friction. The earlier studies [14, 15] have proven that friction takes up to 3–7 % of the total cost of energy related to the drive of a working body. The friction force itself includes two components. A first one is the friction of soil particles against the surface of a working body – a bristle rod. A second component is the friction due to the displacement of a dragged prism, formed between the rod and soil base. In general, the force of friction F_T in brush operation can be determined from equation:

$$F_T = g\mu f\left(ab\delta C_p + V_p\right), \quad (5)$$

where δ is the thickness of soil chips, m; C_p is a coefficient, which takes into consideration the amount of removed soil; V_p is the volume of a dragged prism, m^3; f is the coefficient of soil friction against polypropylene.

A given friction force must also be taken into consideration when determining the overall force of soil resistance during brush operation.

At the same time, along section AD (Fig. 1), the bristle rods are exposed to the action of the normal reaction from soil base N. A given force leads to the additional deformation of the bristle, but it strongly affects the penetration depth of bristles into the soil. A deeper penetration would lead to better soil loosening and more effective removal of particles from a swath.

Force N grows along section AC. Up until this time, there is an increase in the bristle deformation. Hereinafter, the main load on a bristle is due to force F, while the normal reaction only supports the steady deepening of the rod. Along section CD, the two forces complement each other; their resultant R is responsible for the execution of the technological process. Transportation of separated particles of soil with a rod occurs to point D, followed, as a result of sharp straightening of the rod, by that the particles are thrown in the radial direction.

Force of the normal reaction from a soil base can be determined from the following formula:

$$N = 0.01 D k_E \left(\frac{E \cdot I}{l^2}\right) \Delta l^{-1} i_s \cos^{-1}\left(1 - 2\frac{l}{R_b}\right), \quad (6)$$

where D is the diameter of the brush, m; i_s is the number of bristles per a single sweeping element; E is the modulus of elasticity, Pa; I is the moment of inertia of the cross-section of a bristle rod, m^4; l is the initial length of a brush bristle rod, m; Δl is the magnitude of deflection of a bristle rod, m; k_E is the coefficient that takes into consideration a decrease in the module of elasticity of a bristle material under operational conditions, which should be taken: k_E=0.6...1.0.

The modulus of elasticity for polypropylene depends both on its fabrication technique and the nature of action of the bending force. Following recommendations from [16], we can accept the values of 2.9–3.2·10^3 MPa.

At the same time, the normal reaction of soil base is responsible for an increase in the force of friction. The larger the deflection of a bristle rod, the larger the effort and the area of its contact with soil. Given the fact that during brush operation the deformations of bristle are significant compared to its length, we shall determine this component of the friction force as well [17].

$$F'_T = \frac{2EI\tan\theta}{l^2} f, \tag{7}$$

where F'_T is the component of the force of friction, caused by the normal reaction from a soil base, N; θ is the angle between the tangent to the working edge of a bristle rod and the axis of the non-deformed rod, rad.

Considering equations (4) to (7), the resultant R of resistance force in the operation of a bristle rod at a cylindrical brush can be written in the form:

$$R = \sqrt{F_\Sigma^2 + \left(\frac{EI}{l^2} A\right)^2}, \tag{8}$$

where F_Σ is the total soil resistance force, N:

$$F_\Sigma = \frac{\pi \upsilon_a}{z}\left(\frac{2\sin\alpha}{\omega}\left(\eta\upsilon + \left([\tau]+\sigma\right)a\right) + \frac{a\upsilon h k_c^2 \mu}{\arccos\left(1-\dfrac{h}{R_b}\right)}\right) + $$
$$+ g\mu f\left(ab\delta C_p + V_p\right), \tag{9}$$

A is the replacement, introduced to reduce the equation:

$$A = 0.01 D k_E \Delta l^{-1} i_s k_c \tan\theta f, \tag{10}$$

where k_B is the coefficient that takes into consideration the ratio of length of the bristle rods to the overall radius of the brush.

$$k_B = \cos^{-1}\left(1 - 2\frac{l}{R_b}\right). \tag{11}$$

A given coefficient must be determined for each individual case depending on the dimensional parameters of a brush. It could be approximate in character, when one needs to solve equation (8) relative to the length of bristle rods. In this case, the ratio of length of the bristle rods to the overall radius of the brush can be taken equal to 0.3...0.5. When determining other parameters, for example kinematic, a given coefficient would accept the exact value; equation (8) would have a solution.

Equation (8) takes into consideration the kinematical and structural parameters of a brush, as well as the properties of soil during operation. However, while the dimensional and mechanical-technological properties of bristle rods are partially taken into consideration, it is necessary to better account for rods deformation during operation.

5. Determining the deflection of bristle rods at a cylindrical brush and the optimal technique to arrange them

General approaches from theoretical mechanics, which consider the bending of a cantilever-fixed rod, do not accurately describe the process in a given case. In this case, we observe a considerable bending of the thin bristle rods compared to their length. It is possible to solve a given problem by using the Legendre elliptic integrals of the first kind, which describe the condition of a deformed elastic rod. This method takes into consideration significant displacements of the loaded end of a rod relative to the fixed one.

By using the Legendre elliptic integrals, we derive values for the resulting resistance force during a bristle rod operation in the following form:

$$R = \left(\int_{\psi_0}^{\pi/2} \frac{d\psi}{\sqrt{1-k^2\sin^2\psi}}\right)^2 H / l^2, \tag{12}$$

where $H=EI$ is the rigidity of bristle rod at bending, N·m^2; k, ψ are the module and amplitude of elliptic integral, respectively.

The module and amplitude of the elliptic integral actually depend on a single metric. This is the angle Θ that determines the extent of deformation of the axis of an elastic rod. However, in their determining, one must consider the nature of the force that bends a given rod. The force can be directed in parallel to the axis of the non-deformed rod, it acts on compression. In this case, it is part of the normal reaction from a soil base N. The force can act perpendicularly to the axis, similar to the case, during brush operation, to the soil resistance force F_Σ. Consequently, to correctly determine parameters k and ψ, one must take into consideration the angle at which the vector of action of resulting force R is arranged.

Considering the above, we equate equations (8) and (12) and obtain the following equality:

$$\sqrt{F_\Sigma^2 + \left(\frac{H}{l^2} A\right)^2} = \left(\int_{\psi_0}^{\pi/2} \frac{d\psi}{\sqrt{1-k^2\sin^2\psi}}\right)^2 H / l^2. \tag{13}$$

A given equality makes it possible to define the kinematic and structural parameters for a cylindrical brush with a vertical rotation axis when uncovering the root system of maternal plants. It takes into consideration both the properties of the soil that covers the root system and the impact of significant deflection of elastic rods of bristles.

As an example, it is possible to determine the length of bristle rods from equation (13) using the following formula:

$$l = \sqrt[4]{\frac{H^2}{F_\Sigma^2}\left(\left(\int_{\psi_0}^{\pi/2} \frac{d\psi}{\sqrt{1-k^2\sin^2\psi}}\right)^4 - A^2\right)}. \tag{14}$$

It was established that angle θ has a significant impact on the process of brush operation [18]. When it exceeds 25°, there is an increase in the unevenness of bristle rods operation as a result of sudden bending stresses. Such stresses cause significant deformations of rods, cause their vibration that negatively affects the execution of the technological process. The angle θ is largely dependent on the rigidity of bristle rods and their length. In turn, rigidity depends on the material and dimensions of the cross-section of rods. If one manufactures brushes using a standard bristle, it is possible to influence the value for angle θ only by changing the bristle rods length.

Increasing angle θ corresponds to an increase in the deflection of a bristle rod. It is possible to derive a given magnitude by using the Legendre elliptic integrals of the second kind.

$$\Delta l = l\left(1-\left(\left(\frac{2}{\beta}\int_{\psi_0}^{\frac{\pi}{2}}\sqrt{1-k^2\sin^2\psi}\cdot d\psi-1\right)\sin\theta + \frac{2}{\beta}k\cos\psi_0\cos\theta\right)\right), \quad (15)$$

where β is the force coefficient at bending, which takes into consideration both the relative rigidity of bristle rods and the force that causes them to bend:

$$\beta=\sqrt{Rl^2/H}. \quad (16)$$

The initial value for the amplitude of elliptic integral ψ_0 also depends on angle θ.

$$\psi_0=\sin^{-1}\left(\frac{1}{k}\sin\left(\frac{\pi}{4}-\frac{\theta}{2}\right)\right). \quad (17)$$

To find a solution to equations (13) and (15), it is necessary to assign the value for angle θ between 0 and 25°.

6. Results of research into the influence of parameters for a cylindrical brush on the process of uncovering the root system

When analyzing equation (12), one can draw the following conclusions (Fig. 2). A significant impact on the resultant force R is exerted by the assembly's translational velocity. Its increase within 3...12 km/h increases the resistance force from 0.3 to 1.5 N per each bristle rod. In this case, there is a non-linear dependence, and one can predict an even larger growth in the resistance force with an increase in the assembly's velocity. Such a growth is explained by the increase in feeding the soil to a bristle rod over its single working cycle. This should increase the productivity of the brush in general, but a large load would cause a greater deflection of bristle rods and would aggravate, and even prevent, its operation. A greater deflection of rods would increase the value for angle θ, which, when exceeding the limit of 25°, would make the process of removing soil from a swath unstable. At the same time, there may be an increase in the compaction of soil base by bristle rods, which would adversely affect the completeness of soil removal from a swath.

Increasing the angular velocity of brush ω does not resolve the issue on loading the bristle rod. Although the soil feed decreases in this case, but there occurs an increase in the absolute speed of the end of the rod. This in turn leads to an increase in the total resistance force. Increasing angular velocity from 15 to 35 s^{-1} leads to an increase in the resultant R within 0.35...0.45 N. By analyzing the chart in Fig. 2, one sees that the optimal value for the brush angular velocity is 20 s^{-1}.

By applying a graphical analysis of equation (14), we determined the effect of translational velocity υ_a and the number of bristle rods i in the bundles of a brush on the maximally permissible length of rods (Fig. 3). The main condition was to maintain the value for angle θ within up to 25° to ensure the most effective operation mode of bristle rods.

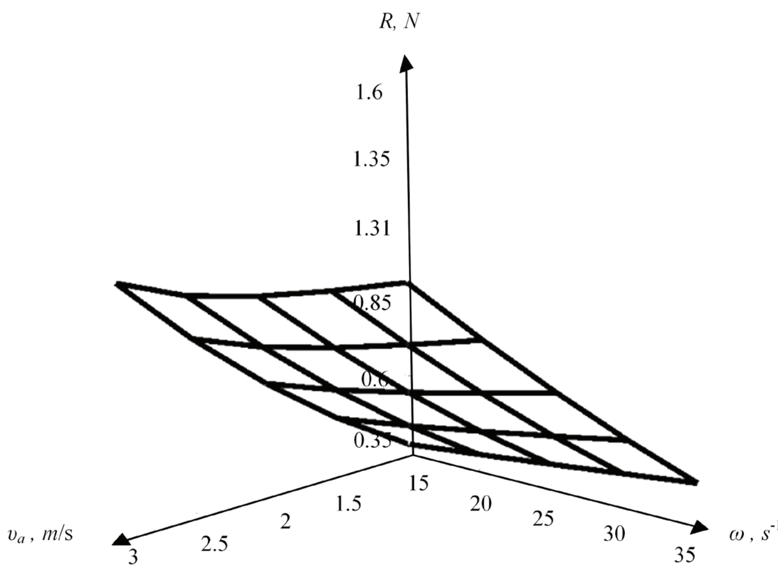

Fig. 2. Dependence of the resultant resistance force to the displacement of a bristle rod on the assembly's translational speed υ_a and the brush angular velocity ω

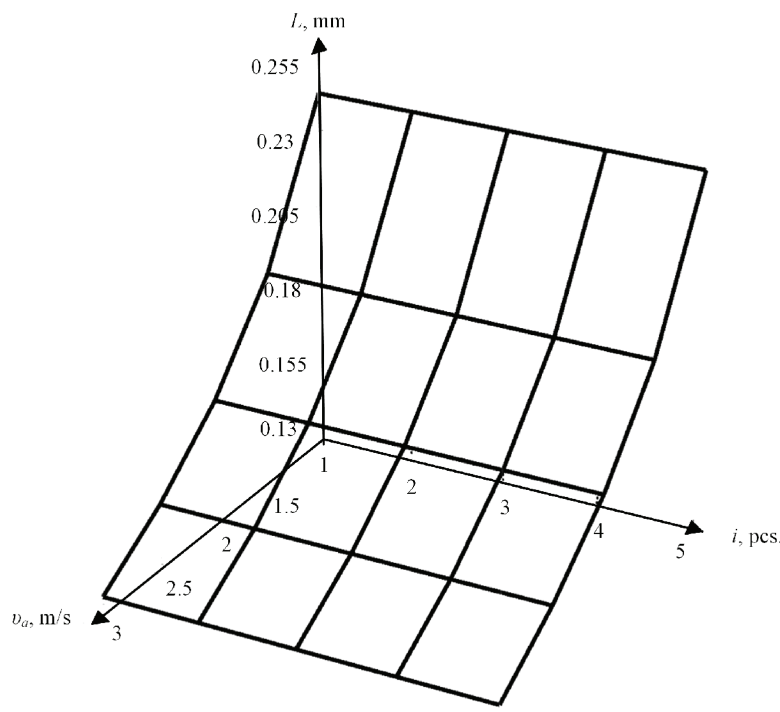

Fig. 3. Dependence of length of the bristle rod on the assembly's translational velocity υ_a and the number of bristles in a bundle i

It was established that at the assembly's speed of 3 m/s or about 12 km/h the maximally possible length of bristle rods is 120 mm. At the speed of 7 km/h, one can use longer rods – up to 160 mm. And decreasing the velocity to 3.5 km/h leads to that the range of possible length of bristle rods increases dramatically. In this case, the maximally permissible rods are those with a length of up to 240 mm.

Arranging the bristle rods in bundles has no influence on the possible length of the rods. This is due to the insignificant influence of the normal reaction from a soil base *N* on the overall resistance force *R*. In general, force *N* is 1–2 % of *R*. A brush attempts to completely remove all the soil and almost never interacts with the swath base. Thus, for the better uniformity of brush operation, the rods must be evenly, one by one, fixed over its entire surface in a checkerboard pattern.

According to equation (15), Fig. 4 shows the graphical dependence of deflection Δl of bristle rods depending on their length l and the assembly's working velocity υ_a.

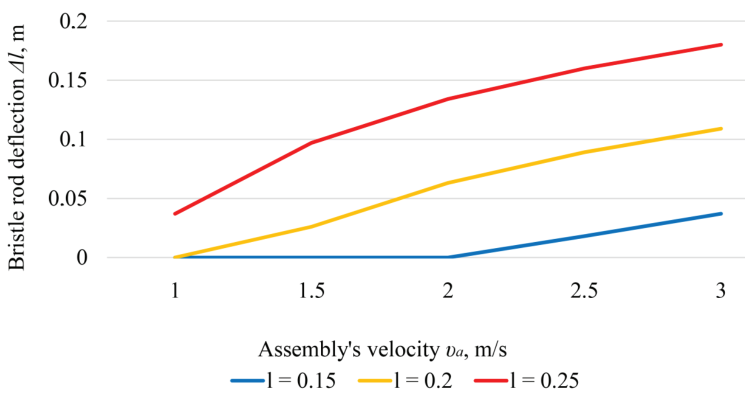

Fig. 4. Dependence of deflection Δl of bristle rods on their length l and the assembly's working velocity υ_a

Graphical analysis of equation (15) has revealed that increasing the length of bristle rods leads to a growth in their deflection at the same value for the force that causes it. Because the resistance force depends largely on the speed of the machine, the deflection also depends on this parameter. Rods with a length of 150 mm start to deflect at a value for motion speed of 2 m/s, which corresponds to the resulting resistance force of 0.85 N per each bristle. At the same time, rods with a length of 250 mm, under these values for motion speed and, therefore, the resultant resistance force, demonstrate deflection for 140 mm. This magnitude is comparable to the length of the rod itself. At such values for deflection, the brush operation is complicated and it is rational to decrease bending force by reducing the assembly's velocity. For bristle rods with a length of 200 mm the velocity should not exceed 1.5 m/s, and for rods with a length of 250 mm – 1 m/s.

7. Discussion of results of studying the parameters for polypropylene bristle rods of the cylindrical brush

When uncovering the root system of maternal plants, a defining impact on the operation of the brush with elastic bristles is exerted by soil resistance. These include the resistance forces to deformation, displacement, and the removal of soil particles from a swath, as well as the friction against each other. All these components of the resistance force depend to a large extent on the absolute motion speed of the working face of a bristle rod. Given the significant differences in the values for translational velocity of the machine and angular velocity of the brush, it is the latter that mainly determines the absolute movement velocity and affects the value for resistance force.

The normal reaction from soil has little impact on the resultant resistance force due to the lack of a solid base along which the bristle rods could move. This phenomenon takes place in the operation of brushes with a metal, a hard road surface, and other solid surfaces. In this case, it is advisable to arrange bristle rods in bundles composed of several pieces in order to enhance the overall rigidity. While being more rigid, a bundle of bristles deflects less and performs its operation better.

When removing soil from a bulk swath that has no a solid base, rods, it is not appropriate to arrange the bristle rods in bundles. It is better to arrange them evenly, one by one, at the surface of the brush. While having a lower rigidity, the bristle rods exert a smaller mechanical impact on plants, which positively affects quality of the technological operation execution.

Existing studies did not take into consideration the properties of the treated surface related to a swath of soil or a substrate (a mixture of soil, sand, and wood sawdust).

In addition, in order to accurately determine the length of a separately fixed polypropylene bristle rod, we have used the method of elliptic integrals.

A given method outperforms classic methods from theoretical mechanics in terms of accurate determination of deflection of the cantilever-fixed rods.

During operation, a bristle rod may deflect at magnitudes commensurate with its length. The method of elliptic integrals makes it possible to take into consideration such magnitudes of deflection. By considering the force load on a rod, we can determine its maximally permissible length at which soil particles would be removed.

This mathematical model makes it possible to solve the set tasks. It takes into consideration the properties of soil as an object of treatment, the possibility of a significant bristle deflection, which is its advantage over existing ones.

A given model has limitations. The radius of the brush, which is required for calculations, depends on the length of bristle rods. It should be assigned and adjusted by using the radius of a brush hub.

In addition, to solve the model, one needs to assign a value for the angle between the working surface of a rod and the soil surface. In terms of quality of the process execution, the optimal value is 90°. However, during operation, the bending of a rod varies, so a given indicator may change as well. That, in turn, would affect the angle of application of the resultant resistance force. Both parameters affect the value for the amplitude and module of elliptic integral.

The shortcomings of the model are in that it does not take into consideration the vibration of bristle rods during operation, the resistance of air, and the moisture content of soil. All these criteria must be considered in the further research.

In addition, the current work could be advanced by determining the performance and energy efficiency during operation of the cylindrical brush with ground swaths.

8. Conclusions

1. We have established the dependence of resistance force R to the displacement of a rod in soil on basic parameters of the brush. This is the sum of resistances caused by the force of soil viscosity, the force of static resistance of soil particles, the force of resistance to removing the particles of soil, the friction force, and the normal reaction from soil. Our theoretical study has shown that the normal reaction from soil when uncovering the root system of maternal plants with a brush does not exceed a value of 2 % of the total resistance force.

2. The angular speed of the brush does not have much impact on the value for total resistance force. This is due to the simultaneous decrease in the feed of soil per a single rod and an increase in its absolute movement velocity. A rational value for the angular velocity is 25 s^{-1}. In this range, the smallest resistance force is observed.

In contrast to the brush angular speed, the assembly's translational velocity exerts a significant impact on the overall resistance force. To ensure minimum energy costs, as well as the steady and smooth operation of bristle rods, one must not exceed the speed of 2 m/s.

3. Arranging the bristle rods in bundles does not produce a positive effect in terms of reducing the force of resistance when uncovering the root system of maternal plants. This is due to the absence of a solid base that could cause the bristle rods' ends to slide. In this case, for a uniform brush operation, the rods should be arranged one by one in a checkerboard pattern.

4. It was established that the assembly's translational velocity significantly affects the deflection of bristle rods at the cylindrical brush with a vertical rotation axis. Shorter bristle rods can operate at a minor deflection at higher speeds. This is explained by their greater relative rigidity. Therefore, when selecting the speed for a machine while uncovering the root system, one must mandatorily take into consideration the length of bristle at brushes.

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