THEORETICAL STUDY OF TRACTION RESISTANCE OF HARROWS WITH HELICAL WORKING BODIES
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ТЕОРЕТИЧНЕ ДОСЛІДЖЕННЯ ТЯГОВОГО ОПОРУ БОРОНИ З ГВИНТОВИМИ РОБОЧИМИ ОРГАНАМИ

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DOI: https://doi.org/10.35633/inmateh-74-33

Keywords: *tillage machines, traction resistance, angle of attack, model*

ABSTRACT
The paper presents a general view of the new working surface of the harrow with helical working bodies. With the help of SOLIDWORKS software package, a computer model of this soil tillage equipment with helical working bodies for surface tillage has been created. The obtained new analytical dependence made it possible to determine the traction resistance of the harrow, equipped with a spiral working element which, in turn, served as the basis for constructing graphs, showing a change in the traction resistance depending on various values angle of attack of the harrow and the soil resistance. On the basis of a computer model of a helical tillage body created in the SOLIDWORKS program, it was found that when the angle of attack of the body increases, the traction resistance P increases, as well, and its greatest increase is observed for the maximum diameter D. It was found that the thickness of the screw λ has a much smaller effect on the traction resistance P compared to the diameter D.

АНОТАЦІЯ
У статті представлено загальний вигляд нової робочої поверхні борони з спіральними робочими органами. За допомогою програмного забезпечення SOLIDWORKS створено комп'ютерну модель цього ґрунтообробного знаряддя з гвинтовими робочими органами для поверхневого обробітку ґрунту. Отримана нова аналітична залежність дала можливість визначити тяговий опір борони, оснащеної спіральним робочим органом, що у свою чергу послужило основою для побудови графіків, що показують зміну тягового опору в залежності від різних величин кута атаки борони та опору ґрунту. На основі комп'ютерної моделі гвинтового ґрунтообробного знаряддя, створеного в програмі SOLIDWORKS, встановлено, що при збільшенні кута атаки спіральної борони зростає також тяговий опір P, причому найбільше його збільшення спостерігається для максимального діаметру D. Встановлено, що товщина спіралі λ значно менше впливає на тяговий опір P порівняно з діаметром D.

INTRODUCTION
To perform technological operations of tillage it is necessary to choose a rational set of units that will have high productivity, low cost and operating costs, to ensure optimal conditions for plant growth. Technologies, units and complexes for tillage are being improved to ensure tillage quality and reduce energy costs.

The issues under consideration are the subject of works, published by many authors. In addition, considerable attention is paid to the study of the energy parameters of machine and tractor units, in particular soil-cultivating ones, the working bodies of which will not only perform these technological processes efficiently, but will also have minimal energy costs. If the energy costs of the tillage machines are assessed only by the main indicator – traction resistance, then it is necessary to take into account many factors, the consideration of which is mandatory. First of all, the traction resistance of such aggregates directly depends on the design parameters of the tillage machines, and this is the type, size, shape of the working parts and their number in the unit.

Besides this, the material used in their manufacture and its physical and mechanical properties, the manufacturing technology and quality, the properties of the working surfaces, etc. are important. When studying the traction resistance, the physical and mechanical properties of the soil and the climatic conditions in which the soil is cultivated are essential. And finally, technical and operational conditions are also important, such as precise adjustment of the working parts to a preset processing depth, the state of sharpness and wear of the cutting edges of the tillage machines, etc. There are works (*Lech, 2001; Bulgakov et.al., 2022a; Olt et.al., 2022*) devoted to taking these factors into account when studying the soil-cultivating machine-tractor aggregates to reduce the traction resistance. In addition, it should be remarked that there are well-known works in this area, which most deeply present the analytical and experimental results on reducing the traction resistance of the tillage machines (*Pylypaka et.al., 2019; Bulgakov et.al., 2017, 2022b; Pylypaka et.al., 2018*). The use of spiral working bodies as a working element in soil cultivation, as well as the study of the quality of their work and the selection of optimal design, kinematic and energy parameters are the subject of the works (*Bulgakov et.al., 2019; Pylypaka et.al., 2021; Pastushenko et.al., 2020; Hevko et.al., 2020; Klendiy and Dragan, 2021; Hristov et.al., 2016; Lyashuk et.al., 2016*).

Several previous studies have focused on the physical and mechanical properties of the treated soil to determine the parameters that have the greatest impact upon the crop germination and emergence (*Tagar, et.al., 2020*).

In the work by *Serrano et.al., (2007)*, a study of the dynamics of the system: “Tractor-tiller attachment” is presented, for soil cultivation. The configuration of the combination tractor-harrow, based on the measurement of the traction required under the operating conditions, provides important information on the recommended power, required for each harrow model produced. Due to this type, it is possible to make decisions on the selection of an appropriate combination of the specified system. This is what will make it possible to increase the productivity of the tractor harrow and improve the efficiency of the field surface processing.

Conventional free-rotating disc implements require multiple harrow passes after moldboard ploughing to achieve the desired soil treatment (*Kumari and Raheman, 2024*), resulting in harmful soil compaction, excessive consumption of fuel and delay in sowing.

In addition, poor penetration of passively driven discs (*Nalavade et al., 2010*) creates the need to add extra weight to the disc harrows, resulting in increased traction, excessive slippage, increased fuel consumption and excessive soil compaction.

Therefore, at the present time, the main task in the creation and substantiation of the parameters of new constructions of transport-technological agricultural machines and their working bodies, providing the expansion of technological possibilities, is the development of such constructions that would ensure a reduction of energy and material resources with improved conditions for their operation, wide multi-functionality, mechanization and automation of production processes. The aim of this study is to reduce the traction resistance of a harrow, equipped with spiral working bodies, based on the theoretical determination of its optimal design parameters.

MATERIALS AND METHODS

Traction resistance of disk and screw working bodies are determined by soil resistance forces acting on the blade and working surface of disks or spirals. Application of this or that type of construction of these working bodies leads to the prevalence of a certain type of deformation of the soil layer. Therefore, the traction resistance of one working body in the direction of movement of the machine-tractor unit will be determined using such an analytical expression:

$$P = k \cdot A_n + \mu \cdot Q + \varepsilon \cdot A_S \cdot V^2 \tag{1}$$

where: k – specific traction resistance of the working body, (k = 20000...70000 N·m^{-2}); A_n - the total area of the screw surface immersed in the soil, [m^2];

A_S – cross-sectional area of the soil layer subject to tillage, [m^2];

μ – the coefficient of rolling resistance;

Q – weight of harrow with helical working bodies, [N];

ε – coefficient depending on the shape of the working body and soil properties, [N·s^2·m^{-4}];

V – unit movement speed, [m·s^{-1}].

In the relation 1, $k \cdot A_n$ - resistance, which takes into account the resistance of working bodies; $\mu \cdot Q$ - harrow weight; $\varepsilon \cdot A_S \cdot V^2$ - placement and form of working bodies.

Value A_S can be expressed by the product of the angle of attack *α* by the area *A* [m^2] the contact of one coil with the soil. Taking this into account, the dependence (1) will have the form (2):

$$P = n\,A\,\sin\alpha \cdot [1 + \tan(\gamma + \varphi)] \cdot (k + \varepsilon \cdot V^2) + \mu \cdot Q \quad (2)$$

where:

n – the number of coils of the helical surface, simultaneously buried in the soil;

φ – angle of elevation of the helical surface of the tillage body, $\varphi = \arctan(h \cdot R^{-1})$ [deg];

β – the angle of the harrow section to the direction of travel of the machine [deg];

γ – angle between the front working surface of the soil tillage body coil and the harrow surface [deg];

h – screw pitch [m];

R – screw implement radius [m].

Using the SOLIDWORKS software package, a computer model of an implement with helical working bodies for surface tillage was created (Fig. 1).

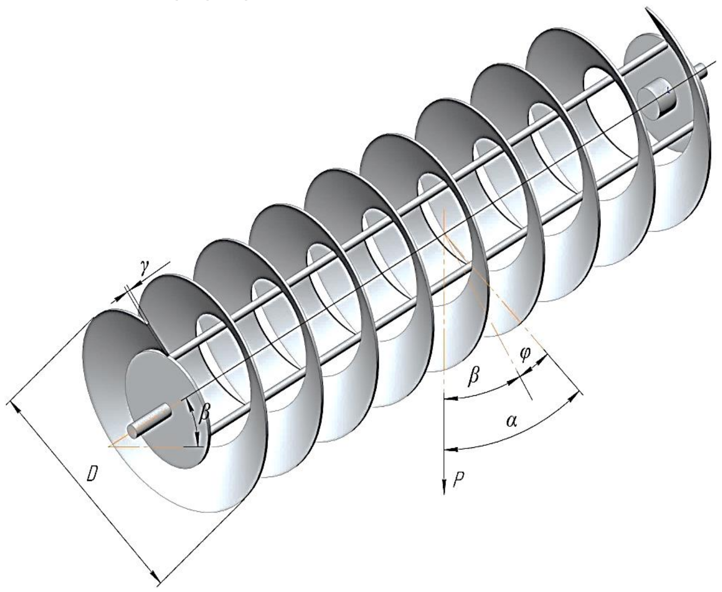

Fig. 1 – Calculation scheme of the screw working body

A general view of the working surface of the screw harrow is shown in Fig. 2.

Fig. 2 – General view of the working surface of the screw harrow

The area *A* of contact of one coil of the helical surface of the implement with the soil can be determined by the relationship (3).

$$A = \int_0^{\arccos(1-a/R)} \left(R \cdot \sqrt{R^2 + b^2} - \frac{R-a}{\cos\theta} \cdot \sqrt{\frac{(R-a)^2}{\cos^2\theta} + b^2} \right) d\theta \quad (3)$$

where: θ – angle of spiral segment [deg];

R – outside radius of the helical surface, [m];

a– tillage depth, [m]; b – screw pitch, [m].

After integrating the expression (3) and the corresponding transformations, relation (4) is obtained:

$$P = n\left[R^2 \cdot \arccos\left(1-\frac{a}{R}\right) - (R-a)\cdot\sqrt{2Ra-a^2}\right]\sin\alpha\cdot\left[1+\tan(\gamma+\varphi)\right](k+\varepsilon V^2)+\mu Q \qquad (4)$$

Thus after carrying out the next transformation, the analytical expression that allows determining the traction resistance P of a harrow equipped with a spiral working body can be presented in the following final form (5):

$$P = kn\left[R^2 \cdot \arccos\left(1-\frac{a}{R}\right) - (R-a)\cdot\sqrt{2Ra-a^2}\right]\sin\alpha\cdot\left[1+\tan(\gamma+\varphi)\right]+\mu Q \qquad (5)$$

Using the obtained analytical expression (5) in its final form makes it possible to perform calculations of the traction resistance P of a harrow, equipped with a spiral working element, using a personal computer. However, at first it is necessary to specify the numerical values of the constants included in expression (5).

In this case it is assumed that: the harrow weight Q = 1720 N – (this mass value will provide the required depth of the soil cultivation, equal to a = 0.08 m; for a tillage depth equal to a = 0.10 m the harrow is loaded up to the weight of Q = 1950 N; outside radius of the helical surface R = 0.28 m; number of coils of the helical surface, simultaneously buried in the soil n = 10 (2 working bodies of 5 turns each); attack angle α = 20°…40°; the reduced conditional coefficient of rolling friction can be set in such limits μ = 0.07…0.012. It depends on the properties of the soil and the material of the screw surface.

RESULTS

The analysis of the calculated data shows that with increasing the angle α from 20 to 40° the traction resistance of the harrow with helical bodies increases linearly (Fig. 3).

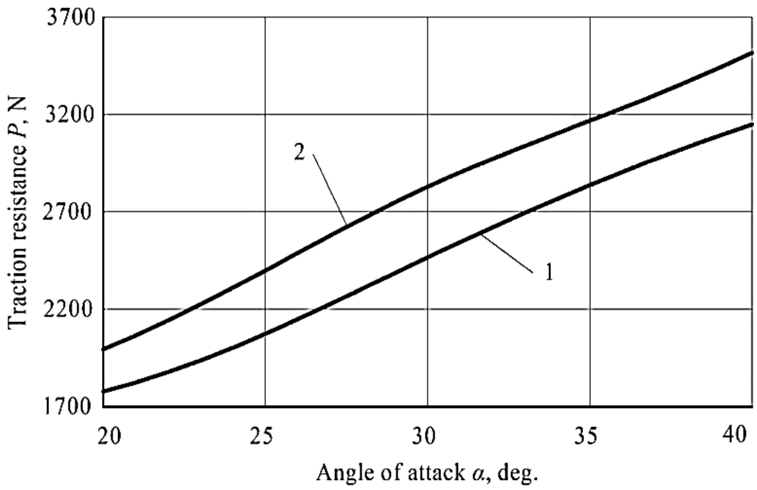

Fig. 3 – Dependencies of the traction resistance of the harrow with helical working bodies on changes in the angle of attack α with k = 20000 N·m^{-2}

1 – for a tillage depth of 0.08 m, 2 – for a tillage depth of 0.10 m

Within one value of tillage depth (lines 1, 2 and 3) this gain is 42…44%. At the same time, within the limits of one value of parameter α, the value of P when changing the depth of tillage from 0.08 to 0.10 m increases by 11...13%.

Consequently, within the accepted limits of variation, the angle of attack parameter α has a greater influence on the increase in traction resistance P for a harrow with a working element in the form of a spiral body than the depth of tillage.

Hence, it is quite obvious that to reduce it, preference should be given to smaller values of the parameter α. The depth of tillage in this case will be determined by the agricultural requirements for the technological operation performed by the harrow.

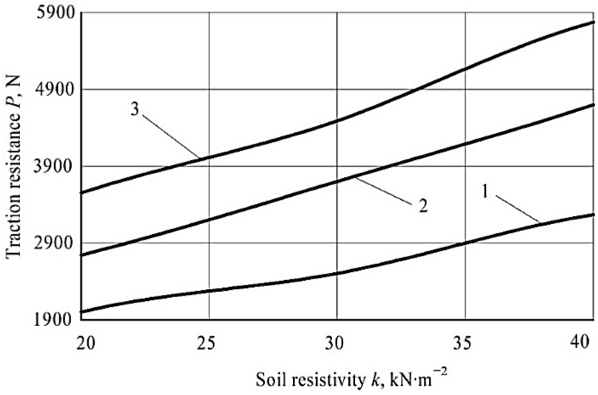

Fig. 4 – Dependencies of the traction resistance of the harrow with helical working bodies on changes in the value of the resistivity of the soil *k*, width = 0.1 m

1 – for angle of attack *α* = 20°; 2 – for angle of attack *α* = 30°; 3 – for angle of attack *α* = 40°

The analysis of the obtained dependencies (Fig. 4) shows that the traction resistance of a harrow equipped with a spiral working body at a = 0.1 m within the limits of the change in soil resistivity k = 20…40 kN·m^{-2} increases linearly. In this case, the resistance for the angle of attack α = 20° changes within the range of P = 1980…3210 N, which is 1.62 times, for tillage depth, α = 30° varies within the range of P = 2820…4630 N, which is 1.64 times and for tillage depth, α = 40° changes in the range of P = 3555…5871 N, which is 1.65 times.

In order to study the angle of attack of the helical working body and obtain the corresponding graphical relationships to the traction resistance, simulation of the corresponding conditions of the experience was carried out. The working body was clamped on both sides and a force perpendicular to the plane rotated by an angle β. During the modelling of the helical working body, the variables were the following parameters: the value of the angle β; the thickness of the helical spiral of the working body λ; the diameter of the helical working body D. Further on the PC a graphic image of the displacement (Fig. 5), the components of the working body under the action of traction resistance and torque were obtained.

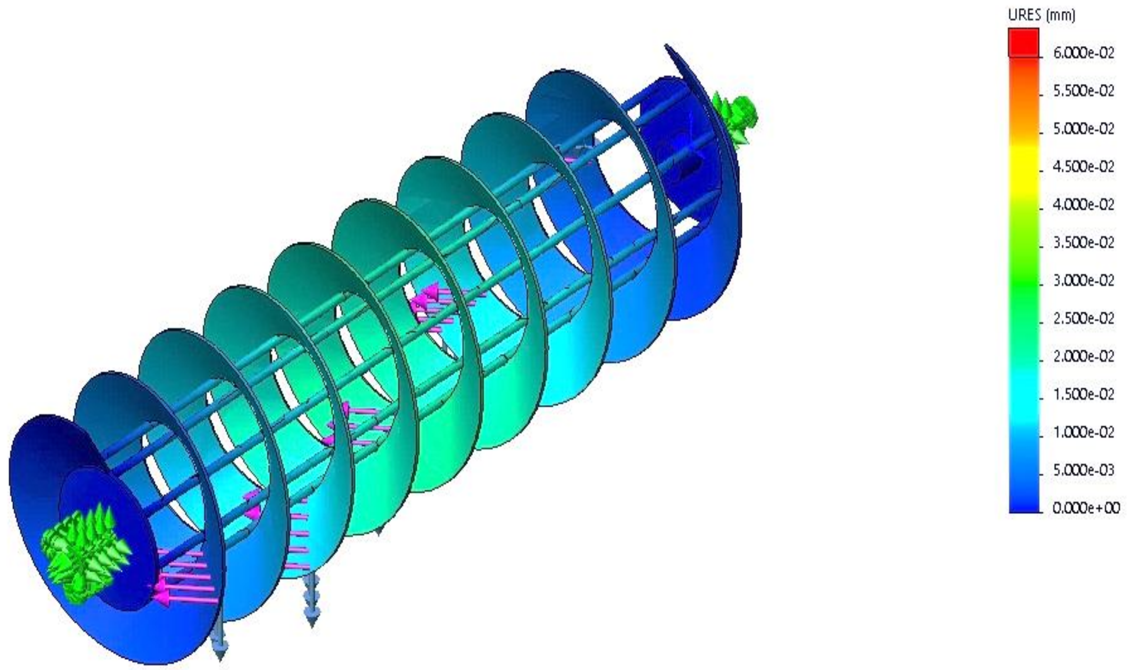

Fig. 5 – Movement of the helical body's components under the influence of traction resistance and torque

According to the results of the simulation, the angle of attack of the helical working body was obtained, while changing the value of the angle β, the thickness of the helical spiral of the working body λ, the diameter of the helical working body D and traction P.

The corresponding graphical relationships are shown in Figs.6-8.

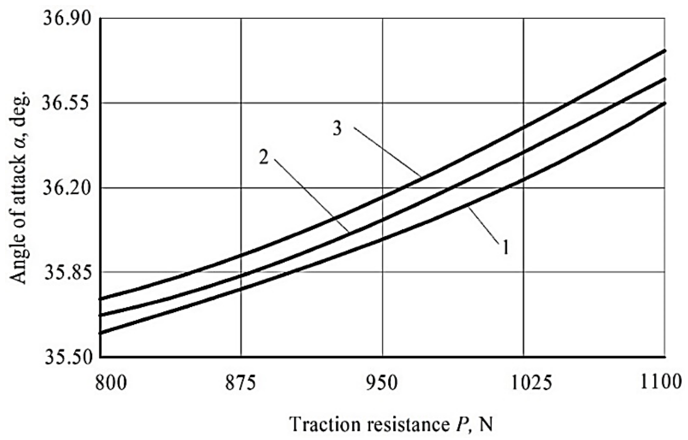

Fig. 6 – Dependencies of changes in the value of traction resistance on the angle of attack of the helical working body at different thicknesses of the helical body

1 – λ = 0.006 m; 2 – λ = 0.008 m; 3 – λ = 0.01 m

As can be seen from the graphical relationships, the tractive force P increases as the angle of attack of the body increases. The greatest increase is observed for the diameter of the body D = 0.6 m, and the smallest – for D = 0.4 m (Fig. 8).

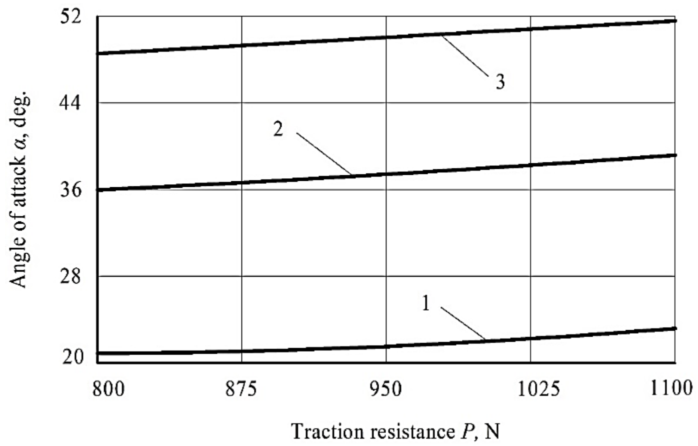

Fig. 7 – Dependencies of the change in the value of traction resistance on the angle of attack of the screw working body at different angles of the working body

1 – β = 10°; 2 – β = 25°; 3 – β = 40°

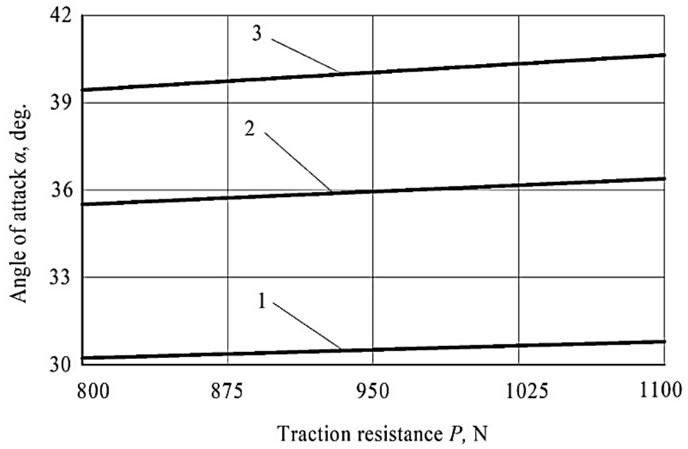

Fig. 8 – Dependencies of changes in the value of traction resistance on the angle of attack of the helical working body at different diameters of the helical body

1 – D = 0.4 m; 2 – D = 0.5 m; 3 – D = 0.6 m

As can be seen from the graphical relationship shown in Fig. 6, the thickness of the helical spiral λ has much less influence on the angle of attack α, compared to diameter D. The graphical dependencies themselves are close to linear.

The comparison of the obtained results allows us to conclude about the similarity of the values obtained and the corresponding graphical dependencies constructed on their basis.

CONCLUSIONS

Based on the analysis of literature sources and patent search, the design of the harrow with helical working body was developed and manufactured. With the help of SOLIDWORKS software package, a computer model of the equipment with helical working body for surface tillage was created. On the basis of the derived relations for determining the traction resistance of the harrow with helical working body, graphical dependence of its value on the angle of attack α and the soil resistivity k has been plotted. It was found that within one value of tillage depth (lines 1, 2 and Fig. 3) this increase is 42…44%. At the same time, within the limits of one value of parameter α the value P at a change of tillage depth from 0.08 to 0.10 m grows by 11...13%. Consequently, the parameter of the angle of attack α, within the accepted limits of its variation, has a practically greater influence on the growth of the traction resistance P of a harrow with a helical working body than the depth of tillage. At the same time, within one value of parameter α the value of P at a change of tillage depth from 0.08 to 0.10 m grows by 11…13%. Consequently, the angle of attack parameter α, within the accepted limits of its variation, has a practically greater influence on the growth of the traction resistance P of helical harrows than the working depth.

It was also found that within the limits of the change in soil resistivity k = 20…40 kN·m^{-2}, it increases linearly. In this case, the resistance for the angle of attack α = 20º changes within the range of P= 1980…3210N, which is 1.62 times, for tillage depth, α = 30º changes within the range of P = 2820…4630 N, which is 1.64 times for tillage depth, α = 40º changes within the range of P = 3555…5871 N, which is 1.65 times.

It was found that with increasing the angle of attack of the working body traction force P increases, and its greatest increase is observed for the maximum diameter of the working body D, while the thickness of the screw has a much smaller influence on the angle of attack α, compared with the diameter D.

Comparison of the obtained results allows us to conclude about the similarity of the values obtained and the corresponding graphical dependencies constructed on their basis.

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