INVESTIGATION OF THE ENERGY INDICATORS FOR THE SURFACE TREATMENT OF SOIL BY A HARROW WITH A SCREW-TYPE WORKING BODY
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ДОСЛІДЖЕННЯ ЕНЕРГЕТИЧНИХ ПОКАЗНИКІВ ПОВЕРХНЕВОГО ОБРОБІТКУ ҐРУНТУ БОРОНОЮ З ГВИНТОВИМ РОБОЧИМ ОРГАНОМ

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ABSTRACT
Restoration of the soil fertility is an important task for scientists and practitioners. Based on the constructed mathematical model of the surface of a screw-type working body, rotating around a fixed horizontal axis, there are determined the work and power of penetration of the screw-type working body into the soil, loosening the soil and overcoming the soil friction. It has been established that the cutting power is proportional to the square root of deepening of the working body ($a^{1/2}$), and the radius of the working body ($R^{1/2}$) is directly proportional to the speed of the unit V. On the basis of a complex of experimental studies, regression dependencies were derived to determine the traction resistance when cultivating the soil with a harrow, equipped with screw-type working bodies. It has been found that the dominant impact upon the value of the traction resistance P_x is exerted by the depth of tillage h, then by the angle of attack β of the battery of the screw-type working bodies, but the least impact is made by the change in the speed of the harrow V. The difference between the calculated and the experimental values of the traction resistance ranges from 9.6...11.2%.

АНОТАЦІЯ
Відновлення родючості ґрунту є важливим завданням для аграріїв України, серед яких зростає попит на застосування технології поверхневого обробітку ґрунту. На основі побудованої математичної моделі поверхні гвинтового робочого органу, який обертається навколо нерухомої горизонтальної осі, визначено роботу і потужність на врізання гвинтового робочого органу в ґрунт, розпушування ґрунту та на подолання тертя ґрунту. Встановлено, що потужність різання пропорційні кореню квадратному від заглиблення робочого органу ($a^{1/2}$) та радіусу робочого органу ($R^{1/2}$) прямо пропорційна швидкості руху агрегату V. На основі проведеного комплексу експериментальних досліджень, виведено регресійні залежності для визначення тягового опору, при обробітку ґрунту бороною із гвинтовими робочими органами. Встановлено, що домінуючий вплив на величину тягового опору P_x має глибина обробітку ґрунту h, далі кут атаки β батареї гвинтових робочих органів і найменше впливає зміна швидкості руху борони V. Різниця між розрахунковими та експериментальними значеннями величини тягового опору коливається в межах 9.6...11.2%.

INTRODUCTION
The present state of development of the transport and technological agricultural machines requires a search for new ways to improve the technological and operational parameters of the working bodies, which can increase productivity, improve the quality of the production processes, and also acquire new operational capabilities for restoration of the soil fertility. The traction resistance of a tillage machine is a value that constantly changes during its operation. All the factors affecting the traction resistance of the machine may be classified into natural and climatic ones (the type and condition of the soil, the relief, rockiness, meteorological conditions); the structural (the type, shape and number of the working bodies, the material from which they are made, and the manufacturing technology, the machine weight, type and design of the running gear); the operational (technical condition of the machine, the correctness of adjustments, the degree of wear of the working bodies, etc.) *(Khaylis*, *1990*; *Hevko et al., 2016*; *Lech, 2001)*.

A number of works are devoted to the study of the functional and operational characteristics of the screw-type soil-cultivating working bodies and their interaction with the soil, in particular *Gevko and Rogatynsky, (1989), Pastushenko et al., (2020), Ivan et al., (2017)*. In *Hevko et al., (2016), Pylypets et al., (2000) Klendiy and Pilipaka, (2016),* there are substantiated the design, kinematic and technological parameters of screw-type soil-cultivating working bodies in terms of their functional purpose. The theory of designing and constructing linear surfaces is reflected in *Klendii et al., (2016)*. The works *Wang, (2012), Hevko et al., (2018), Ivan et al., (2015)* theoretically substantiate the design of a soil-cultivating tool, in which helical surfaces in the form of a part of the unfolded helicoid are used as working surfaces.

The work *Bulgakov et al., (2022),* substantiates the practical possibility and expediency of using a screw-type working body in tillage, and the work *Bulgakov et al., (2021)* reflects experimental research to determine the quality indicators of a harrow with screw-type working bodies. Works *Manjula et al., (2017) Tripathi et al., (2015), Tian et al., (2018)* are devoted to the study of the impact of design and technological parameters of the developed variants of a harrow with screw-type working bodies upon the incorporation efficiency of the plant residues into the soil. The research of agrotechnological indicators of the quality of soil cultivated by a harrow with screw-type working bodies is considered in *Tsarenko et al., (2003), Yao et al., (2014)*.

However, the energy parameters of tillage by a harrow with screw-type working bodies have not yet been fully studied. So the task of determining the work and power that must be consumed when tilling the soil with a harrow with screw-type working bodies is urgent.

The purpose of the work is to study the energy parameters for the soil cultivation by a screw-type working body of a transport-technological agricultural machine, depending on its parameters and operating modes.

MATERIALS AND METHODS

In order to determine the energy parameters of tillage by a harrow with screw-type working bodies, it will be considered in the form of an unfolded helicoid. Then the equation of the surface of the working body of the harrow with an axis parallel to the *Ox* axis has the following form:

$$\begin{gathered} X = h\alpha - u\,\sin\varphi \\ Y = p\,\sin\alpha - u\,\cos\varphi\,\cos\alpha \\ Z = p\,\cos\alpha + u\,\cos\varphi\,\sin\alpha \end{gathered} \tag{1}$$

where: h – the screw helicoid parameter (ratio of helicoid pitch to full revolution), $h = \dfrac{b}{2\pi\cos\beta}$; β – the inclination angle of the axis of the cutting edge of the surface of the helicoid; φ – the elevation angle of the turning edge; u – the length of the rectilinear generatrix from the current point on the helix to the point on the surface; p – the diameter of the cylindrical shaft.

After turning the working body of the harrow at an angle β around axis *Oz* (Fig. 1) and taking into account its rotation around its own axis with an angular velocity ω*,* the trajectory of the movement of the arbitrary point on the surface of the working body will be written down as a function of time:

$$\begin{gathered} x(t) = (h\alpha - u\,\sin\varphi)\,\cos\beta + (u\,\cos\varphi - p)\,\sin\beta\,\sin(\alpha+\omega) \\ y(t) = (h\alpha - u\,\sin\varphi)\,\sin\beta - (u\,\cos\varphi - p)\,\cos\beta\,\sin(\alpha+\omega) \\ z(t) = p\,\cos(\alpha+\omega) + u\,\cos\varphi\,\sin(\alpha+\omega) \end{gathered} \tag{2}$$

The speed of an arbitrary point on the surface is determined by differentiating dependence (2). There will be:

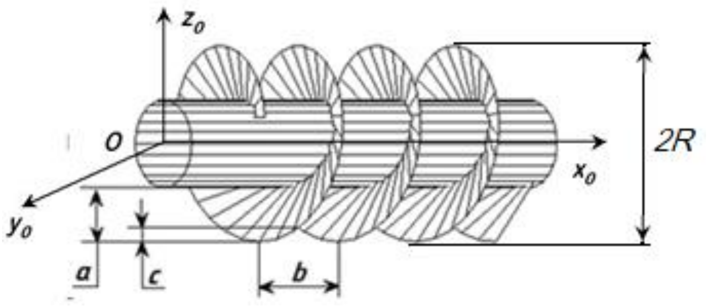
$$\overline{V} = \dot{x}(t)\cdot\bar{\imath} + \dot{y}(t)\cdot\bar{\jmath} + \dot{z}(t)\cdot\bar{k}. \tag{3}$$

The relative speed of the soil movement at the entrance to the working area of the unit in the fixed coordinate system *OXYZ*, associated with the soil $V_0=0$, in the coordinate system of the aggregate will be equal to $V_2 = -\overline{V}$.

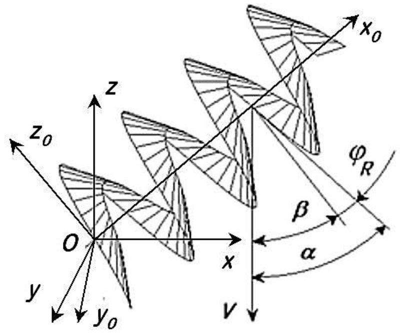
The relative speed of the movement V_{rel} of an arbitrary point of the screw-type working body relative to the soil will be equal to:

$$\overline{V_{rel}} = \overline{V} - \overline{\omega}\times\overline{r}\ , \tag{4}$$

where $\overline{V}$ – the vector of the speed of the aggregate; $\bar{\omega}\times\bar{r}$ – the vector of the speed of the surface element of the working body with angular velocity $\bar{\omega}$ and the radius of rotation $\bar{r}$.



a



b

Fig. 1 - Projections of the soil-cultivating helical surface of the screw-type working body
a – the depth of tillage, *c* – the height of the crests, *b* – the distance between the crests

To determine the loading parameters, the kinematics of turning of the working body will be considered, the axis of which is inclined at an angle β to axis OX of the fixed coordinate system $OXYZ$, associated with the soil, in which axis OY is directed in the direction of the movement of the aggregate, and axis OZ is directed vertically to the soil surface.

When the aggregate is moving at speed V, the passive working body is rolled with penetration into the soil to the tillage depth $h=a$, by the way, without slipping, a cylindrical surface with a radius r_0 will be rolled along a plane, buried from the soil surface to depth h_N :

$$r_0 = R - a + h_N \tag{5}$$

where R – the external radius of the screw-type spiral; h_N – the depth of the neutral layer $h_N < a$.

Accordingly, the angular speed of rotation of the screw-type working body, set at an angle β to the front of processing, is determined as:

$$\omega = \frac{V}{r_0 \cos\beta} \tag{6}$$

Therefore, each point of the working body with a radius less than $r<r_0$ will describe a curve called a shortened trochoid, and with radius $r>r_0$ – a curve called an elongated trochoid of this kind:

$$\begin{cases} y = r_0 - r\,sin\,\alpha\,cos\,\beta \\ z = r_0 - r\,cos\,\alpha \end{cases} \tag{7}$$

Fig. 2 shows the trajectory of the movement of the points of the screw-type working body during its rolling along the neutral layer (z = 0) in accordance with radius $r<r_0$ and $r>r_0$.

Since each point of the screw-type working body in its own coordinate system performs a plane-parallel movement, it is advisable to determine their speeds, using the method of the instantaneous center of velocities, which is located at a distance $z_C = r_0$ from the axis of the working body, and in plane yOz having coordinates $C\,(y_C;\, z_C)$, where $y_C = 0$; $z_C = -r_0$. Determination of the speeds of the implement in relation to the mass of the cultivated soil is necessary to establish the nature of cutting and the distribution of forces on the surface of the implement.

The arm l_A of the arbitrary point *A* of the section of the helix, buried in the soil, the radial parameter and the angular *α* are determined according to the formula:

$$l_A = \sqrt{r^2\cos^2\alpha + (r\sin\alpha + z_0)^2} \tag{8}$$

For the points, placed on the cutting edge, $r = R$, arm l_{RA} will be equal to:

$$l_{RA} = \sqrt{R^2 + 2Rr_0\sin\alpha + z_0^2}\,. \tag{9}$$

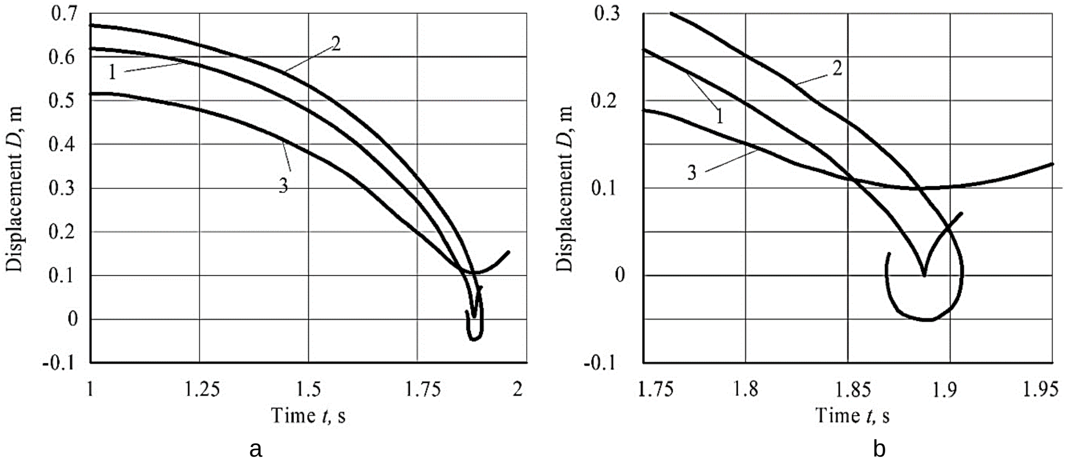


Fig. 2 - The trajectory of movement of the points of the screw-type working body during its rolling along the neutral layer (z = 0) of the soil (a) with the rolling radius

1 – r = 0.3 m, 2 – r = 0.2 m and 3 – r = 0.35 m

Accordingly, the absolute speed V_A of the specified point in the fixed coordinate system $OXYZ$ will be $V_{Ay}= |\omega|l_{RA}$. Its projections on the Oy_0 axis and on the Oz_0 axis, respectively, will be equal to $V_{Ay} = |\omega|l_{RA}$. Its projections on axis Oy_0 and on axis Oz_0, respectively, will be equal to:

$$V_{Ay0} = \omega R \cdot \cos\alpha \tag{10}$$

$$V_{Az0} = -\omega(R \cdot \sin\alpha + r_0) \tag{11}$$

The change in speed and its components is shown in Fig. 3. In the coordinate system of the aggregate, the vertical component will not change, while the horizontal component will expand into the Oy and Oz axes (Fig. 4). In this connection:

$$V_{Ay} = \omega \cdot R \cdot \cos\alpha \cdot \cos\beta \tag{12}$$

$$V_{Az} = -\omega(R \cdot \sin\alpha + r_0) \cdot \sin\beta \tag{13}$$

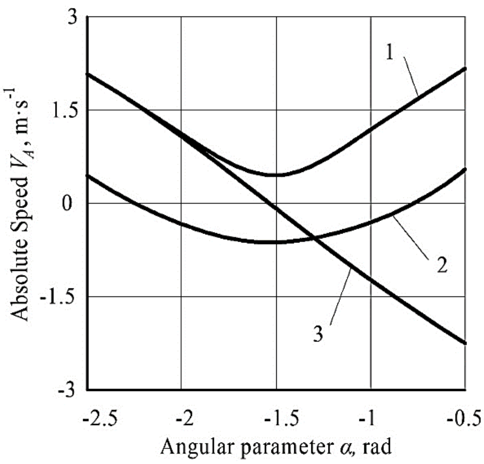


Fig. 3 - Change in the absolute velocity of point V_A at the edge of the screw with radius R = 0.28 m at the aggregate velocity V = 2 m s^{-1} from its angular parameter α

1 – absolute velocity V_A; 2 – projection V_A onto the axis of the system screw Oy_0; 3 – projection V_A onto the axis of screw Oz_0

Let us consider the speed components of the movement of the points of the cutting edge in the direction of the normal to the cutting surface and the tangent.

A normal direction is set by the radius of the vector, directed from an arbitrary point of the edge (point $A(R;\alpha)$) to the axis of rotation of the screw. The tangential component of the speed of point $A(R;\alpha)$ is directed along the tangential cutting surface in the direction of rotation and is directed perpendicular to the radius of the vector and the axis of rotation of the screw. Accordingly, the indicated speed components of point $A(R;\alpha)$ are determined by the following dependencies:

$$V_{An} = V_{Ay} \cdot \cos(\alpha) + V_{Az} \cdot \sin(\alpha); \tag{14}$$

$$V_{At} = -V_{Ay} \cdot \sin(\alpha) + V_{Az} \cdot \cos(\alpha). \tag{15}$$

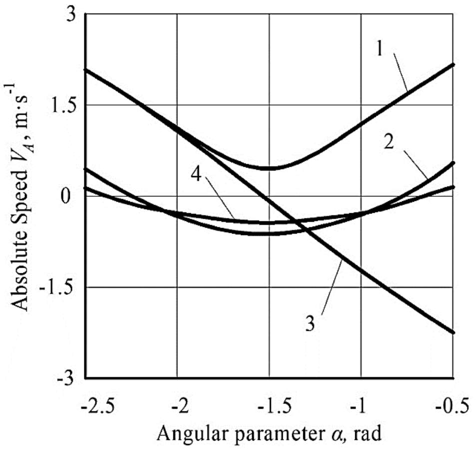


Fig. 4 - Change in the absolute velocity of point V_A on the edge of the propeller with radius R = 0.28 m at the aggregate velocity V = 2 m·s^{-1} from its angular parameter α

1 – absolute velocity V_A; 2 – the projection of V_A onto axis Oy; 3 – projection of V_A onto axis Oz; 4 – projection of V_A onto axis Ox

The change in speeds on the cutting edge is shown in Fig. 5 and Fig. 6.

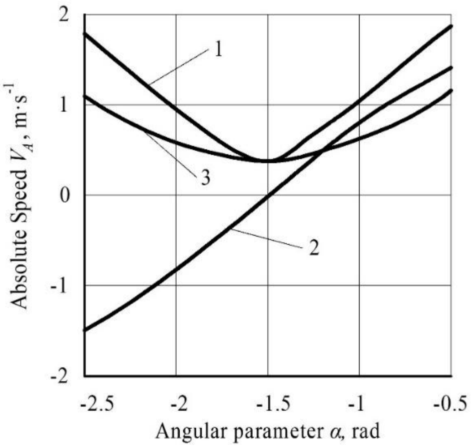


Fig. 5 - Change in absolute velocity V_A of the screw with radius R = 0.28 m at the speed of the aggregate V = 2 m·s^{-1} from α

1 – the absolute velocity V_A; 2 – the normal component V_{An}, perpendicular to the soil surface of the screw axis; 3 – the tangential component of V_{At}, tangential to the soil surface of the axis of the screw system

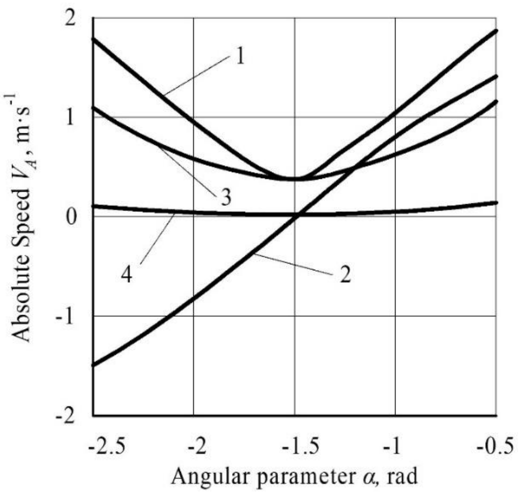


Fig. 6 - Change in the absolute speed V_A of the screw with a radius R = 0.28 m at an aggregate speed V = 2 m·s^{-1} from α to the line of the helical edge

1 – the absolute velocity V_A; 2 – the normal component V_{An} to the line of the screw-type edge; 3 – the tangential component $V_{A\tau}$ to the line of the screw-type edge; 4 – the binormal component V_{Ab} to the line of the screw-type edge

The tangential component of an arbitrary point $A(R;\alpha)$ is decomposed into a component in the direction of the blade (tangential to the edge line) $V_{A\tau}$ and a shear component along the soil (along the binormal to the edge line) V_{Ab}:

$$V_{A\tau} = V_{At}\cdot\cos(\varphi_R) \tag{16}$$

$$V_{Ab} = V_{At}\cdot\sin(\varphi_R) \tag{17}$$

Let us consider interaction of the passive screw-type working body with the soil. A screw with an outer radius R and an inner radius r_0 deepens into the soil to depth a, forming a submerged helical segment cut off by a plane $z=a$.

Area S of the section of the helical surface, buried by value a is defined as the integral over angle α in the coordinate system of the section y_0Oz_0, normal to the axis of the helix, running the value from $\alpha_1 = \pi + \arccos(1–a\cdot R^{-1})$ to $\alpha_2 = 2\pi–\arccos(1–a\cdot R^{-1})$. Considering the symmetry of the screw-type segment, the area of the recessed section will be equal to:

$$S = \int_0^{\arccos(1-a/R)} \left(R\sqrt{R^2+b^2} - \frac{R-a}{\cos\alpha}\sqrt{\frac{(R-a)^2}{\cos^2\alpha}+b^2} \right) d\alpha \tag{18}$$

The working helical surface is affected by the distributed pressure force directed along the normal and the corresponding friction forces from the mutual displacement of the soil relative to the helical surface, the direction of which is opposite to the relative force vector. Taking into account expression (1), the normal to the surface of the straight helicoid in vector form is defined as follows:

$$\bar{n}_{uv} = \sin\alpha_p \sin v\bar{i} - \sin\alpha_p \cos v\bar{j} + \cos\alpha_p \bar{k} \tag{19}$$

where $\alpha_p = arctg[T/(2\pi u)]$ – the elevation angle of the helix with a running radial parameter $u=r;$ T–spiral step, $T = 0.2$ m.

The projections of the total forces from the normal pressure $p = p(r;\alpha)$ are equal, on plane y_0Oz_0 they are an integral part of the axial load onto the screw, and the projections on plane x_0Oz_0 are the component of the force that are turning the working passive body. Similarly, the projections of the contacting distributed forces $|\tau| = \mu|p|$ on these planes is the second component of the resulting forces. Here μ is the coefficient of friction of the working body to the soil surface.

Since it will be taken into account that tillage is carried out on the soil that has already been pre-treated, and in this case a relatively small depth of tillage is used, in the further study the distributed value of soil pressure will be replaced with its indirect value $p(r;\alpha) = p_c = \text{const}$. Accordingly, the projections of the total forces on planes y_0Oz_0 and x_0Oz_0 will be equal:

$$P_{yOz} = p_c\cdot S_{yOz} \tag{20}$$

$$P_{xOz} = p_c\cdot S_{xOz} \tag{21}$$

where S_{yOz} and S_{xOz} – projections of the working area of the screw (screw segment) onto the corresponding coordinate planes of system $Ox_0y_0z_0$.

Next, S_{yOz} and S_{xOz} are defined. The surface of the helical segment onto plane y_0Oz_0 is projected into a circular segment, the arc of which is equal to l_α, and the chord, defining the boundary of the soil, is l_y. They will be respectively equal:

$$l_\alpha = R\cdot\alpha_r = 2R\arccos(1 - a\cdot R^{-1}) \tag{22}$$

$$l_y = \sqrt{2Ra - a^2} \tag{23}$$

The area of the circular segment S_{yOz} will be equal to:

$$S_{yOz} = R^2 arc\cos\left(1-\frac{a}{R}\right) - (R-a)\sqrt{2Ra-a^2} \tag{24}$$

The surface of the helical segment onto plane x_0Oz_0 is projected into a segment, limited by a sinusoid and line $z=a$, the chord of which is equal to:

$$l_T = 2b\cdot\arccos(1 - a\cdot R^{-1}) \tag{25}$$

The area of the indicated segment S_{xOz} of the cosine wave is equal to:

$$S_{xOz} = 2R\cdot\cos[\arccos(1 - a\cdot R^{-1})] - 2b(R - a)\cdot\arccos(1 - a\cdot R^{-1}) \tag{26}$$

Dependencies (24) and (26) are inconvenient for engineering calculations, so they are simplified by applying them to the functions, describing the curves into which a helix is projected onto the indicated planes by expanding them into a Maclaurin series.

The helix (1) on the coordinate plane y_0Oz_0 is projected into a circle, the coordinate plane and x_0Oz_0 – in a cosine wave, the equations of which, respectively, will be equal to:

$$z_k = -\sqrt{R^2 - y^2} \tag{27}$$

$$z_c = -R\cos(y/b) \tag{28}$$

Let us expand the circle equation (27) as a function of $z_k(y)$ in the Maclaurin series:

$$Z_{KM} = -R + \frac{y^2}{2R} + \frac{y^4}{8R^3} \tag{29}$$

Figure 7 shows a graph of function (1), with which the equation of the circle (29) is replaced with a radius r = 0.25 m for the buried area of the soil, with a depth of a = 0.1 m.

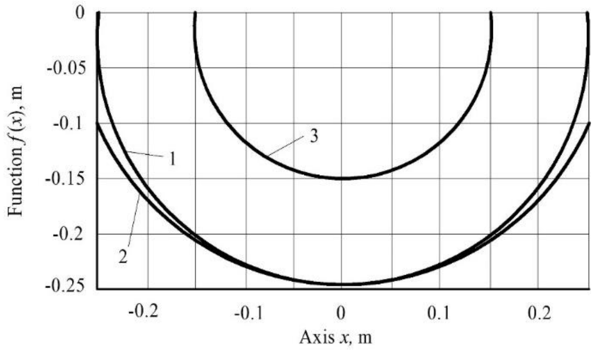


Fig. 7 - Graphs of functions, describing the outer circle with a radius *R* = 0.25 m – the projections of the helical surface onto the normal plane y_0Oz_0 (1), its approximation by a parabolic function in the Maclaurin series expansion (2), and the inner circle of the projection of the helix of the horizontal soil level line

The Maclaurin series expansion of the cosine equation (28) gives:

$$z_{cM} = -R + \frac{Ry^2}{2b^2} - \frac{Ry^4}{24b^4} + ... + O(y^6) \tag{30}$$

Fig. 8 shows a graph of function (29), with which will be replaced the cosine equation (30) for the working body with a radius of r = 0.25 m and a step of T = 0.2 m for a buried area with a depth of a = 0.1 m (Fig. 8 a), and a working body with a radius of r = 0.28 m and a pitch of T = 0.25 m (Fig. 8 b) for a recessed area with a depth of a = 0.12 m.

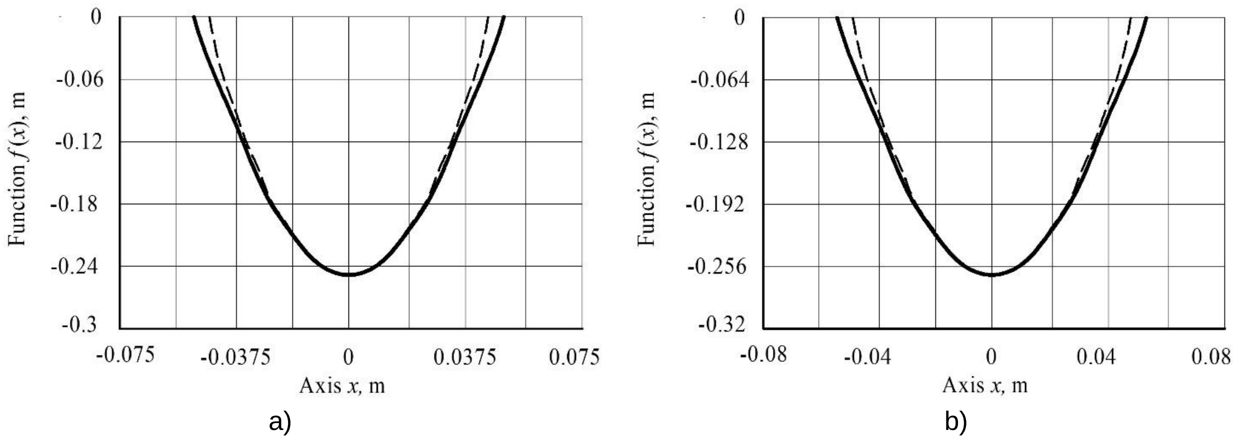


Fig. 8 - Graphs of functions that describe a section of the sinusoid – a projection of the outer edge of the screw (helix) on the vertical longitudinal plane x_0Oz_0 (a solid line), its approximation by a parabolic function by expansion in the Maclaurin series (dashed line), and the horizontal line of the working body with an outer radius *R* = 0.25 m, step *T* = 0.2 m (a) and *R* = 0.28 m, step *T* = 0.25 m (b)

The analysis of dependences (29) and (30) shows that, with sufficient accuracy for practical calculations, one can restrict oneself to two terms of the expansion, thus approximating these dependences by square parabolas.

Accordingly, the chords of the projection of the helix onto planes y_0Oz_0 and x_0Oz_0 will be equal to:

$$l_{yM} = k_1\sqrt{Ra} \tag{31}$$

$$L_{xM} = k_2 b\sqrt{\frac{a}{R}} \tag{32}$$

where k_1 and k_2 – consolidated digital coefficients, respectively, for each of the projections.

Using the dependence to determine the areas that are limited by second-order parabolas, the dependences for the projection areas (24) and (26), respectively, will assume the form:

$$S_{xOzM} = \frac{4\sqrt{2}b}{3\sqrt{R}}a^{\frac{3}{2}} = 1{,}9\frac{b}{\sqrt{R}}a^{\frac{3}{2}} \tag{33}$$

$$S_{yOzM} = \frac{4\varepsilon\sqrt{2R}}{3}a^{\frac{3}{2}} = 1{,}7\sqrt{R}a^{\frac{3}{2}} \tag{34}$$

In Fig. 9 and Fig. 10 there is shown correspondence of the curves with the dependences (24) and (33) for the projection onto plane y_0Oz_0 (Fig. 9) and dependences (26) and (34) for plane x_0Oz_0 – Fig. 10.

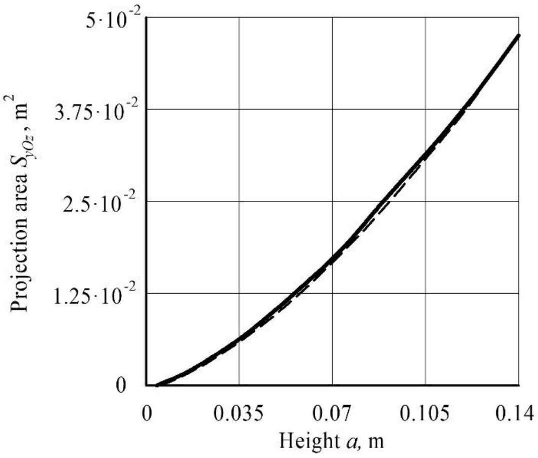


Fig. 9 - Dependence of the projection area S_{yOz} of the helical segment onto the normal coordinate plane y_0Oz_0 (solid line) upon height *a* and its approximation (dashed line) by dependence (33) for a screw with outer radius *R* = 0.28 m

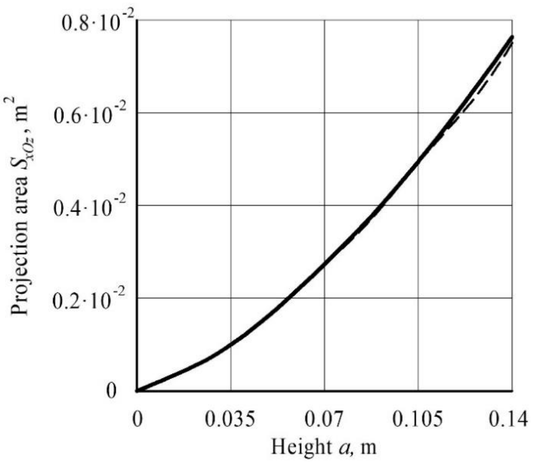


Fig. 10 - Dependence of the projection area S_{xOz} of the helical segment onto the longitudinal coordinate plane x_0Oz_0 (solid line) and its approximation (dashed line) by dependence (34) for a screw with outer radius *R* = 0.28 m, pitch *T* = 0.25 m

Accordingly, the chord of the screw segment, formed by the surface of the screw-type working body, immersed into the soil, will be equal to:

$$l_{\max M} = k_1 R \sqrt{1+\frac{k_2^2 b^2}{k_1^2 R^2}} \cdot \sqrt{a} \tag{35}$$

The chord (34) is located in the plane, on which the projection of the helical sector area will be maximum:

$$S_{\max M} = \frac{2k_1}{3} \sqrt{1+\frac{k_2 b^2}{k_1 R^2}} \cdot a^{\frac{3}{2}} \tag{36}$$

The indicated area projection practically corresponds to the area of the helical segment, immersed into the soil, and dependence (35) with an error of not more than 2% can be used to calculate the area instead of dependence (12).

When the helical section is inclined at an angle β to the front of the movement of the aggregate, the area of the helical segment, the area of which is determined by dependence (12) or approximated (36), is projected onto the frontal coordinate plane xOz of the coordinate system of the aggregate $Oxyz$ and, accordingly, plane xOz of the fixed coordinate system $OXYZ$, connected with the soil, into a paraboloid segment, the chord of which will be equal to:

$$l_{x\beta} = l_x \cos\beta + l_y \sin\beta = k_1 \sqrt{Ra} \sin\beta + k_2 b \sqrt{\frac{a}{R}} \tag{37}$$

Dependence (37) can be represented as:

$$l_{x\beta} = \frac{\sqrt{Ra}}{\sqrt{1+\frac{k_2^2 b^2}{k_1^2 R^2}}} \sin\left(\varphi_\beta + \beta\right) \tag{38}$$

parameter, which is determined by the angle.

Accordingly, the area of the frontal surface of the working zone of the coil on plane XOZ, which has the shape of a paraboloid segment, will be equal to:

$$S_{XOZ} = \frac{2}{3} l_{x\beta} \cdot a = \sqrt{\frac{R}{1+\frac{k_2^2 b^2}{k_1^2 R^2}}} \cdot a^{\frac{3}{2}} \sin\left(\varphi_\beta + \beta\right) \tag{39}$$

The cutting forces act upon the cutting edge of the helical surface. Their normal components, directed perpendicular to the edge in the plane of the helical working surface and directed towards its axis, are characterized by a load, distributed along the edge with intensity $q_n = q_n(\alpha)$, and the contacting components are characterized by a distributed load with intensity $q_t = q_t(\alpha)$, which are directed along the tangent to the edge and directed in the direction of rotation of the passive screw-type working body. Cutting into the soil passes along the leading edge of the helical segment, the arc length of which is determined according to expression (15). Expanding this dependence $l_\alpha = l_\alpha(\alpha)$ into a descending Maclaurin series, a simplified approximate dependence l_α is obtained:

$$l_\alpha = 2(2a \cdot R)^{1/2} \cdot (1 + a \cdot (12R)^{-1}) \tag{40}$$

For the screw-type working bodies with a radius $R \leq 0.3$ m, dependence (22) with an error of less than 1% can be written as:

$$l_\alpha = 5.7(aR)^{1/2} \tag{41}$$

Considering that the edge of the screw-type working body cuts into the soil both in the normal and tangential directions and the speed of movement of the edge in these directions according to (14) – (16) is commensurate (Fig. 5, 6), then the cutting has a complex character with normal and tangential movement of the blade. Let us assume that the intensity of the distributed normal cutting components is constant and proportional to the value of the bearing resistance (hardness) of the soil σ_{lim}, $q_n = K_q \sigma_{lim} . V_{n.}$, where the resulting speed of the edge blade is given, which is 2/3 of the maximum value V_{An} determined by dependence (14). Here K_q depends on the sharpness of the edge blade. Then the power, consumed for cutting the cutting edge of the screw along the normal, taking into account its entire length of its cutting section will be equal to:

$$N_{p.n} = q_n\, l_\alpha V_{n.\sigma} = 2.85\, K_q \sigma_{lim}\, V_{n.\sigma} (aR)^{1/2} \tag{42}$$

The power from the tangential components of the cutting force of the edge blade is $N_{p.\tau} = \mu N_{p.n}$, where μ is the coefficient of the soil friction along the edge.

Accordingly, the total power at the edge (blade) of the screw is:

$$N_{p.} = K_p \sigma_{lim}(1+\mu)V_{n.\sigma}(aR)^{1/2} \tag{43}$$

where K_p – the integral cutting factor, K_p = 2.85 K_q.

The power, consumed for the resistance of the soil to its movement by the passive working body, is determined mainly by the friction forces along the helical surface since the normal speeds V_{Ab} are insignificant (Fig. 6), but the normal component forces are partially mutually compensated by the rotation of the passive working body.

Accordingly, the power to move the soil will be proportional to the area of the screw sector, the coefficient of friction *f* (taking into account the soil sticking to the working surfaces of the screw) and the hardness of the soil.

Taking into account (34), the power to move the soil will be written in the following form:

$$N_{n.} = K_n \sigma_{гр} V_{n.\tau}\, a^{1/2} \cdot a^{3/2} = K_n \sigma_{гр} V_{n.\tau}\, a^2 \tag{44}$$

where $V_{n.\tau}$ – the reduced value of the average speed of the screw moving relative to the soil, in the first approximation equal to 3/4 of value $V_{a\tau}$, determined from the dependence (16).

The analysis of dependences (42) and (43) shows that the cutting power is proportional to the square root of the deepening of the working body ($a^{1/2}$), and the radius of the working body ($R^{1/2}$) is directly proportional to the aggregation speed V. The power to move the soil is non-linearly proportional to the tillage depth ($a^{1/2}$), the radius of the working body ($R^{1/2}$) and is directly proportional to the aggregation speed V.

Since for the passive working bodies the analytical determination of the components of the load on the screw working body is laborious, in particular, it is difficult to determine the center of instantaneous speeds, then for preliminary calculations of the energy consumption for tillage by a harrow with screw-type working bodies, it is possible to carry out simplified calculations.

In particular, the integral work of displacement, cutting in and compaction can be determined from the displaced volume using Fink's formula:

$$dA_1 = p_{cp} \cdot \ln(1+\varepsilon) dV_1 \tag{45}$$

where p_{cp} is the average pressure on the screw-type working body; ε – the linear soil compaction in the direction of movement of the aggregate up to 0.1; dV_1 – elementary volume undergoing compaction.

Accordingly, the power for moving, cutting in and compacting:

$$N_1 = p_{cp} \cdot (1+\varepsilon) \cdot B \cdot h \cdot V \tag{46}$$

where B is the grip width; h – the processing depth; V – the speed of the aggregate.

The work, spent to provide kinetic energy to the soil particles by a screw-type working body at the loosening stage, is equal to:

$$dA = \rho_v \cdot v_v^2 \cdot dV_2 \tag{47}$$

where ρ_v – the bulk density of the soil; dV_2 – the elementary volume gaining speed V_2.

The power, spent for loosening and providing soil particles with kinetic energy, is equal to:

$$N = \rho_v \cdot k_v \cdot V_{2c}^2 \cdot B \cdot h \cdot V \tag{48}$$

where k_v – the coefficient of reduction of the particle velocities to the average k_v = 1.05…1.10.

The work, spent to overcome the friction of the soil against the screw-type working body, is equal to:

$$dA_3 = p_{cp} \cdot \mu \cdot l_w \cdot dS \tag{49}$$

where μ – the friction coefficient; dS – the surface element of the screw; l_w – the length of the movement (path) of the soil along the surface of the working body.

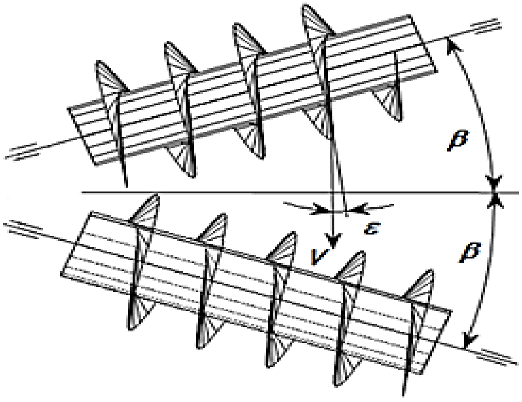
Accordingly, the power consumed to overcome the frictional resistance is equal to:

$$N_3 = \mu \cdot p_{cp} \cdot S_c \cdot V_{rel} \tag{50}$$

where S_c – the total area of the particle of the screw-type working body, buried in the soil; V_{rel} – relative speed of the movement according to (14).

In Fig.11, on a scale, there are built the frontal and the horizontal projections of the screw-type working body for surface tillage to a depth of a = 0.10 m, with a pre-set distance between the ridges b = 0.2 m, with the designation of the rear angle ε. The design characteristics of this working body are: radii – R = 0.25 m, r = 0.15 m, the screw parameter – h = 0.0416. As a result of interaction with the soil, a reaction force arises, which will put pressure on the working surface of the coil.

The component of this force will try to shift the working body to the side, perpendicular to the direction of its movement. To balance this moment of force, it is advisable to arrange the aggregate in the form of two working bodies, as shown in Fig. 11. The surface of the second working body must have a turn rib with the opposite direction of winding and the direction of rectilinear generatrices, as shown in Fig. 11. The cylindrical shaft for the tool is chosen taking into account the pre-set depth and tillage. Also, with this option it is possible to reduce the height of the ridges *c* and the distance *b* between the ridges (Fig. 3).



a)

b)

Fig. 11 - A soil-cultivating harrow, consisting of two screw-type working bodies

a – a structural diagram; b – a general view

To avoid clogging of the inter-coil space with soil and plant residues, it is proposed to make the cylindrical shaft lattice.

The working body works like a disc soil-cultivating tool, that is, the profile of the cultivated field has ridges and depressions. At the moment of contact of the blade with the field surface, there are angles, similar to the angles of attack and roll for the disc tillage implements. It is possible to change the angle of roll by changing the inclination of the rectilinear generatrix of the surface with respect to its axis.

The developed working body has a simple design and low metal consumption. Unlike the disc tillage implements, it does not require individual bearing assemblies to mount individual tillage discs. Installation of one section of the screw tillage body is carried out using two bearing units, located at the ends of the section.

To determine the impact of the design, kinematic and technological parameters of the developed versions of the harrow with screw working bodies (independent factors (x_i) on the energy-power indicators of the aggregate displacement, experimental studies were used on the manufactured pilot plant, a general view of which is shown in Fig. 12.

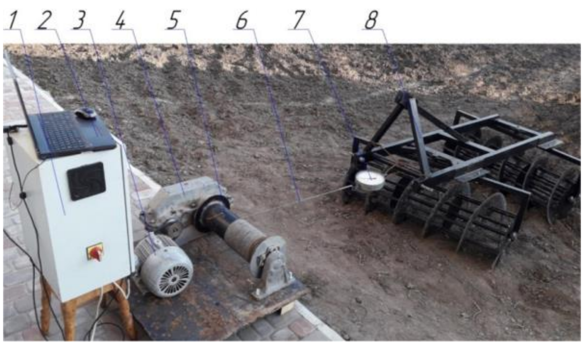


Fig. 12 - General view of the experimental setup and equipment for determination of the traction resistance of a harrow with screw-type working bodies

The harrow with a screw-type working body *8* was set in motion with the help of a cable *6,* which, in the process of moving, was wound on a drum *5*, fixed on a low-speed gearbox shaft *4*, driven by an electric motor *3*.

The Altivar 71-1 frequency converter and the Power Suite v.2.5.0 software, contained in PC 2, were used to start the engine and adjust its speed. The electric motor *3* and gearbox *4* are rigidly fixed at the beginning of the soil channel in order to be stationary, and only the harrow was movable.

After the completion of the process of moving the harrow with screw-type working bodies in the Power Suite window on the computer display, data were obtained about the change in torque and engine power over time.

The scheme of the experiment: the implementation of the technological process by the aggregate for the purpose of surface loosening of the soil, closing moisture, planting seeds, destroying weeds, as well as for leveling the microrelief, created by pre-treatment. The number of repetitions is three. The minimum length of the path of the aggregate was 25 m. It was determined from the conditions that the permissible error does not exceed 2%, and the reliability is equal to 0.95.

In experimental studies, a planar method was used, which ensures the determination of the resulting force, acting between the electric motor with a gearbox and the harrow in one plane (longitudinal-vertical). Before each stage of the experiment the harrow with a screw-type working body was located in the extreme right position, the soil in the channel was preliminarily prepared according to the readings of the hardness tester.

The results of the research in the soil channel of the proposed harrow with a screw-type working body were illuminated in the computer display window.

Further, according to the peak values, the results obtained were recorded in tables.

The experimental research program included research into the change in the value of the horizontal component P_x of the resistance forces from the speed of the harrow V at various values of the angle of attack of the screw body β and the depth of processing h. To obtain the values of the studied quantity, there were used the peak (maximum) values, obtained from the data studies.

To determine the impact of the parameters of the technological and kinematic processing and the design parameters of a harrow with screw-type working bodies upon the traction resistance of the experimental version of the harrow (optimization parameter P_x), a full-factor experiment PFE-3^3 was performed, that is, determination of the dependence of the horizontal component P_x of the resistance forces on the changes in the three main speed factors of the harrow movement V, km·h^{-1}, angle of attack β of a battery of the screw-type working bodies, deg., and the processing depth h, m, i.e. $P_x = f\,(V, \beta, h)$. Since during the experiments the variable independent factors are heterogeneous and have different units of measurement, and the numbers, expressing the value of these factors, are of a different order, they were led to a unified system of calculations by moving from real values to encoded ones, presented in Table 1.

After coding the factors a plan-matrix of the corresponding multifactorial experiment of the PFE type 3^3 was compiled for the number of experiments $N = 3^3$. Experiments were performed with five-fold repeatability.

Table 1

The results of coding the factors and the levels of their variation in the study of the traction resistance of a harrow with a screw-type working body

Factors	Designation		Interval of variation	Levels of variation, natural/coded		
	Parameter value indicated as a code	Parameter value in the form of its natural value				
Speed of the harrow, *V*, km·h^{-1}	X_1	x_1	3	4/–1	7/0	10/+1
Angle of attack of the screw-type body, *β*, deg.	X_2	x_2	15	10/–1	25/0	40/+1
Depth of tillage, *h*, m	X_3	x_3	0.02	0.08/–1	0.1/0	0.12/+1

A general view of the regression equation of the traction resistance of a harrow with a screw-type working body, depending on the change in the speed of the harrow V, km·h^{-1}, the angle of attack β of the battery of the screw-type working bodies, deg., and the processing depth h, m, i.e. $P_x = f\,(V, \beta, h)$, has the form:

$$P_x = 423.64 + 821.58h + 219Vh + 0.296\beta^2 - 12.21\beta h + 46726h^2 \,. \qquad (51)$$

The obtained regression equation (51) may be used to determine the traction resistance of a harrow with a screw-type working body P_x, depending on the change in the speed of the harrow V, the angle of attack β of a battery of the screw-type working bodies and the tillage depth h, when tilling the soil.

RESULTS

Using the Statistica-6.0 software for the PC, a graphical reproduction of intermediate general regression models was built in the form of quadratic response surfaces and their two-dimensional sections of the traction resistance of a harrow with a screw-type working body P_x (force that acts in the horizontal plane) as a function of two variable factors $\boldsymbol{x}_{\boldsymbol{i}(\mathbf{1},\mathbf{2})}$ at a constant level of the corresponding third factor $\boldsymbol{x}_{\boldsymbol{i}(\mathbf{3})} = \text{const}$.

Graphical values of the results of the dependence of traction resistance, obtained by using Statistica-6.0, are shown in Fig. 13.

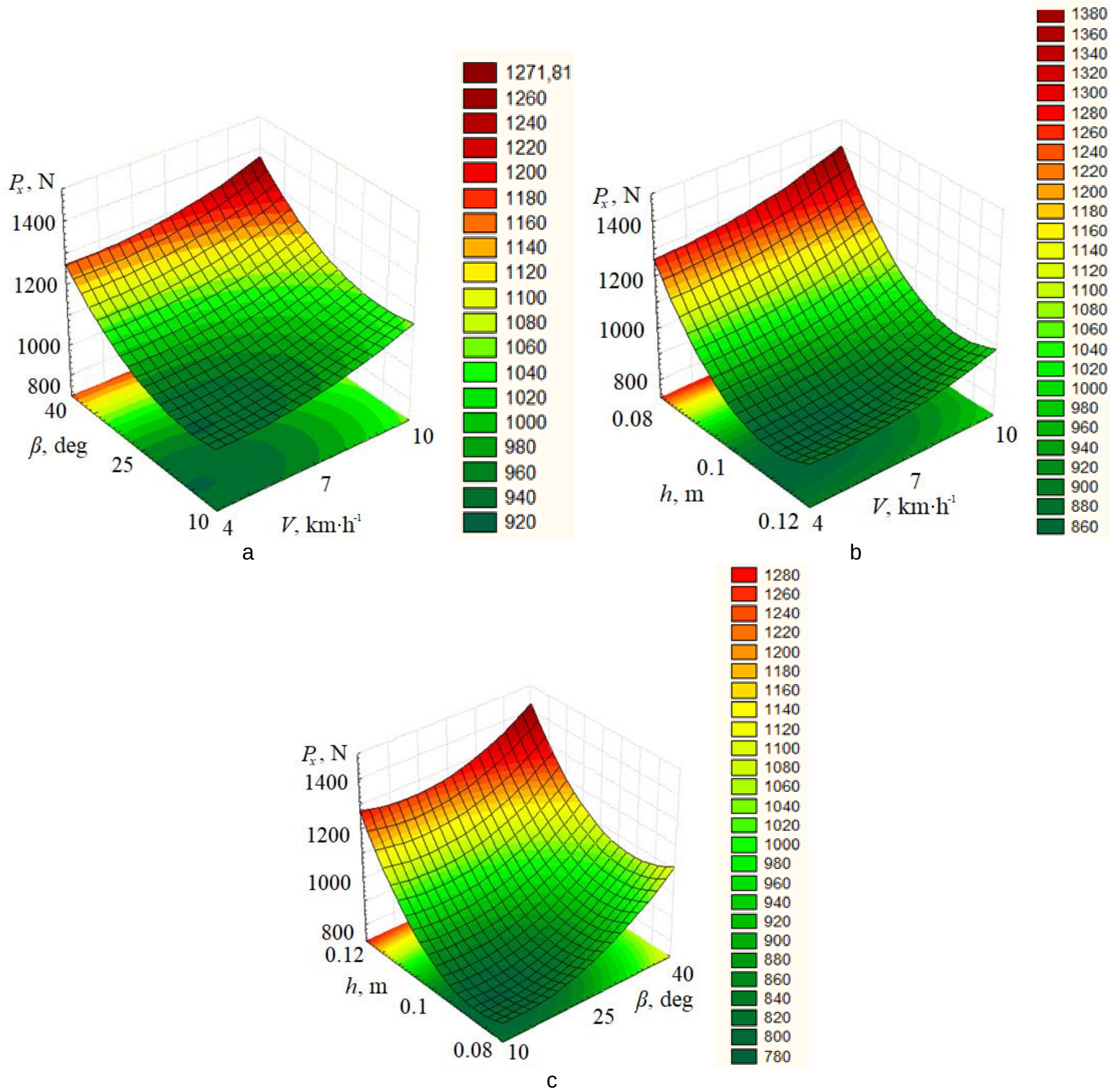


Fig. 13 - The response surface of the dependence of the traction resistance of a harrow with a screw-type working body, when tilling the soil:
a – P_x (V, β); b – P_x (V, h); c – P_x (β, h)

Analysis of the regression equations shows that the following factors have the greatest impact upon the change in traction resistance: the depth of tillage h and the angle of attack β of a battery of screw-type working bodies. In general, an increase in traction resistance is caused by all factors: h, β and V. It is evident from Fig.13 that, with an increase in the factors h, β and V, the value of traction resistance increases. It has been found that an increase in the speed of the harrow V from 4 m·s^{-1} to 10 m·s^{-1} leads to an increase in traction resistance P_x by 9.8%. Increasing the angle of attack β from 10 deg. to 40 deg. leads to an increase in traction resistance P_x by 26.3%. An increase in the working depth *h* from 0.08 m to 0.12 m leads to an increase in traction resistance P_x by 29.8%. The angle of attack of a battery of screw-type working bodies β and the speed of the harrow V have a less significant effect.

CONCLUSIONS

1. It has been established that the cutting power of the soil by a screw-type working body of a transport-technological agricultural machine is proportional to the square roots of the penetration of the working body ($a^{1/2}$) and the radius of the working body ($R^{1/2}$) and is directly proportional to the speed V of the transport-technological agricultural machine. The power to move the soil depends on the depth of processing ($a^{1/2}$), the radius of the working body ($R^{1/2}$) and is directly proportional to the speed V of the machine.

2. Regression dependencies have been obtained to determine traction resistance when cultivating the soil a harrow with screw-type working bodies. It was found that the depth of tillage h has a dominant influence upon the value of traction resistance P_x, then angle of attack β of a battery of screw-type working bodies, but the change in the speed of the harrow V has the least impact. The constructed response surfaces of the dependence of traction resistance P_x during tillage by a harrow with screw-type working bodies, using the software "Statistica-6.0" for Windows, showed that an increase in the speed of the harrow V from 4 km·h^{-1} to 10 km·h^{-1} leads to an increase in traction resistance P_x by 9.8%. An increase in the angle of attack from 10 deg. to 40 deg. leads to an increase in traction resistance P_x by 26.3%. An increase in the tillage depth a from 0.08 m to 0.12 m leads to an increase in traction resistance P_x by 29.8%.

3. The difference between the calculated and experimental values of traction resistance ranges from 9.6...11.2%, which confirms the adequacy of the mathematical model.

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Basic parameters

Current number	Name of the parameter	Symbol of the parameter	Unit of measurement
1.	the screw helicoid parameter (ratio of helicoid pitch to full revolution)	q	m
2.	the inclination angle of the cutting edge axis of the helicoid surface	β	deg
3.	the elevation angle of the turning edge	φ	deg
4.	the length of the rectilinear generatrix from the current point on the helix to the point on the surface	u	m
5.	the diameter of the cylindrical shaft	p	m
6.	the angle of rotation of a point around the axis of the surface during its movement on a helical line located on a cylinder of radius *p*	γ	deg
7.	angular speed of the working body	ω	s^{-1}
8.	the depth of tillage	a	m
9.	the height of the crests	c	m
10.	the distance between the crests	b	m
11.	angle of attack of the working body	α	deg
12.	helix line elevation angle	φ_R	deg
13.	the vector of the speed of the aggregate	$\overline{V}$	$m \cdot s^{-1}$, $km \cdot h^{-1}$
14.	the relative speed of the movement of an arbitrary point of the screw-type working body relative to the soil	V_{rel}	$m \cdot s^{-1}$, $km \cdot h^{-1}$
15.	the tillage depth	h	m
16	the depth of the neutral layer	h_N	m
17.	cylindrical surface with a radius will be rolled along a plane, buried from the soil surface to depth h_N :	r_0	m
18.	external radius of the screw-type spiral	R	m
19.	the relative speed of the soil movement at the entrance to the working area of the unit	V_2	$m \cdot s^{-1}$
20.	spiral step	T	m
21.	the power, consumed for cutting the cutting edge	$N_{p.n}$	kW
22.	the power from the tangential components of the cutting force	$N_{p.\tau}$	kW
23.	the reduced value of the average speed of the screw moving relative to the soil	$V_{n.\tau}$	$m \cdot s^{-1}$
24.	the average pressure on the screw-type working body	p_{cp} –	MPa
25.	the linear soil compaction in the direction of movement of the aggregate up	ε	$MPa \cdot m^{-1}$
26.	the total area of the particle of the screw-type working body, buried in the soil; is the relative speed of movement according to	S_c	m^3
27.	the friction coefficient;	μ	-
28.	the length of the movement (path) of the soil along the surface of the working body	l_w	m
29.	the bulk density of the soil	ρ_v	$kg \cdot m^{-3}$
30.	consolidated digital coefficients	k_1 and k_2	-
31.	the grip width	B	m
32.	the coefficient of reduction of the particle velocities	k_v	
33.	force that acts in the horizontal plane	P_x	N
34.	the integral cutting factor	K_p	-
35.	the power for moving, cutting in and compacting	N_1	kW
36.	the power, spent for loosening and providing soil particles	N_2	kW
37.	the power consumed to overcome the frictional resistance	N_3	kW
38.	the work of displacement, cutting in and compaction	A_1	kJ
39.	the work, spent to provide kinetic energy to the soil particles	A_2	kJ
40.	the work, spent to overcome the friction	A_3	kJ