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STUDY OF THE PROCESS OF SOIL STRIP TILLAGE BY VERTICAL MILLING ADAPTER

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Об'єкт досліджень – процес смугового обробітку ґрунту вертикально-фрезерним адаптером розробленої конструкції. Предмет досліджень – визначення впливу кінематичних параметрів адаптера на показники якості обробітку. Виконані аналітичні дослідження дії адаптера на ґрунт та проведені експерименти за складеною методикою. Результати досліджень свідчать про можливість отримання заданих показників якості обробітку шляхом регулювання кінематичних параметрів

Ключові слова: смуговий обробіток ґрунту, вертикально-фрезерний адаптер, робоче середовище, кінематичні параметри

Объект исследований – процесс ленточной обработки почвы вертикально-фрезерным адаптером разработанной конструкции. Предмет исследований – определение влияния кинематических параметров адаптера на показатели качества обработки. Выполнены аналитические исследования действия адаптера на почву и проведены эксперименты по составленной методике. Результаты исследований свидетельствуют о возможности получения заданных показателей качества обработки путем регулирования кинематических параметров

Ключевые слова: ленточная обработка почвы, вертикально-фрезерный адаптер, рабочая среда, кинематические параметры

1. Introduction

Nowadays agricultural production is a major industry, which provides the internal consumer market and its saturation with foreign currency earnings through export. The agricultural sector is the most attractive for foreign and domestic investment. However, stable profitability in the sector is provided by extensive methods of management, and the introduction of new technologies is not becoming widely spread. This negative phenomenon is caused by a weak feedback between science and industry.

One of the new and promising technologies is the tripper strip soil tillage, which in the international practice became known as Strip-till. This method is the cultivation of the strip, into which crops will be sown, while the spaces between them will remain untilled, which combines the benefits of zero (No-till) and traditional technologies.

Therefore, a relevant problem of modern agricultural mechanics is the study of this technology, development of appropriate soil tillage tools, determining their effect on the environment and the substantiation of optimum parameters of cultivation process. This will make it possible to provide the agricultural sector with efficient equipment and to increase production intensity.

2. Literature review and problem statement

One of the main ways of influence on the natural environment in order to obtain products of plant growing is the change in volumetric mass (density) of soil by mechanical influence. To increase the volume of agricultural production in the middle of the last century, more than 50 % of Ukraine's territory was ploughed, which is one of the highest of ploughness in Europe. For example, the ploughness in Poltava Region makes up 62 % or 80.6 % of the territory of agricultural lands. Such development of lands causes a number of ecological problems, particularly the degradation of agricultural land that is related to wind and water erosion (deflation). Erodibility creates conditions for breaking the soil structure, a decrease in the content of humus and elements of mineral nutrition of plants [1, 2].

Soil erosion is characteristic for developed agricultural regions in the world. Thus, in the United States of America, this problem became apparent in the middle of the last century. Since then, the technologies of soil tillage have been transformed into transfer to preservation of nutritious residues at the field surface to prevent erosive phenomena. The concept, which involved the rejection from ploughing, originated in the USA in the 1970s, the implementation of which was possible due to improving planting tools and application of herbicides. Such an approach required not only the development of new technical solutions of soil tillage implements, but also the changes in the style of controlling processes and solving economic problems [3].

Initially, the zero tillage technology (No-till), became very popular in the USA, which had a positive effect: better moisture retaining due to an increase in infiltration and a decrease in evaporation. However, this also had negative consequences – due to excessive ground humidity, corn seeding was delayed that negatively influenced the vegetation of plants and crops. Development of the Strip-till technology was aimed at providing for the conditions of shoots development of agricultural crops in spring. Tillage in autumn or in spring helps remove excessive soil humidity of soil and increase its temperature. So, Strip-till should combine the benefits of traditional cultivation in the area of seed germination, preventing this erosive phenomena.

To perform technological operations, they started the development and production of appropriate technical devices, the design of which differs depending on the manufacturer. The basic complete equipment of such implement contains disk working bodies of various shapes for soil strip tillage and a blade to prepare it to fertilization. Strip tillage is carried out both in autumn and in spring, but in both cases the quality of tillage must meet the requirements that will provide a uniform sowing and creating conditions for further germination and vegetation of plants. It is the quality of the soil strip tillage that determines the expediency of applying the Strip-till technology.

When choosing a soil tillage technology, it is necessary to evaluate it in terms of the impact on environment. The expediency of using the Strip-till technology decreases when cultivating the fields on steep slopes, which is caused by water erosion of such lands. However, with a slight fields slope it is possible to decrease the probability of this phenomenon by cultivating the fields on the contour, but not along the slope. When compared with zero soil tillage, the application of the Strip-till technology may carry a risk of formation of a soil skin that affects the moisture retention in the plants nutrition zone and makes their germination difficult. However, if we compare the Strip-till technology with the traditional soil tillage, it presents a significant step forward in terms of dealing with erosive phenomena. The plant residues in untilled areas retain near-ground wind, reducing the wind erosion. And on condition of taking into account the rose of winds when choosing the direction of tillage, the negative effect of the wind erosion can be reduced to minimum. In addition, water erosion decreases, as the increasing moisture infiltration is provided and the plant residues retain the motion of surface waters [3–5].

Obviously, in the USA, the Strip-till technology is a soil protective instrument, whereas Ukrainian producers find it attractive due to the possibility of savings fuel and lubricants. Today this technology has not yet gained widespread acceptance, but the practice of its application in the agricultural holding «Kernel» is well known. In this case, special machinery is not applied, it has to be replaced with the re-equipped deep-scarifier, in which the working bodies are installed through one. It is obvious that such decision cannot provide for meeting the agrotechnical requirements for growing a variety of crops, on which the harvest formation depends, and as a result, the profitability of production.

The rotary working bodies are used for the strip soil tillage for sowing raw crops, in particular sugar beets. It is known that there is a research into the operation of the strip tillage soil cultivator in a combination with a precision drill [6]. The work of rotary working bodies with different designs of blades, used in the process of growing rice with minimum tillage, was explored. In this paper, the influence of the geometry of blades on the tillage quality and the required torque were studied [7]. Similar research was conducted in article [8], but the object of study was the influence of the angle of sloping of rotary working bodies to the vertical on the parameters of the created furrow. A complex problem was solved in [9], where the influence of the geometry of blades of working bodies and their rotation velocity on the quality of soil strip tillage was studied. The research results indicate the increasing indicator of soil crushing with a growth in angular velocity of the working bodies. The negative phenomenon of soil dispersion does not depend on the geometry of working bodies and increases with an increase in angular velocity. However, a low angular velocity of working bodies does not provide the proper soil crushing.

The rotary cultivator operation for the zero tillage technology was studied. The experiments were conducted on the stubble background and involved determining the impact of kinematic parameters on the tillage characteristics, namely the depth and width of a furrow, an area of the scarified soil and the cross intersection of furrow [10]. As for the strip soil tillage technology, there are some known research in the optimization of geometrical parameters of angled blades on rotary working bodies based on a mathematical model that included the following parameters: velocity of translational movement of the unit, angular velocity of rotors, depth and the width of soil cutting, rotor radius, rotation angle, specific resistance and density of soil [11]. The study of the rotary cultivator operation during the soil strip tillage included field tests at a rotation velocity of rotary working bodies 370 rev/min and translational motion velocity 5.4 km/h. The essence of the research was to determine the optimal width of the tilled strip. It was found that the wider the strip, the higher the soil temperature and the lower the moisture content in it. However, the thickness and length of stems of cultivated plants were larger at maximum tillage width. It was established that on the condition of optimization of indicators of efficiency and of fuel consumption, it is advisable to perform the soil tillage at strip width of 22.5 cm [12].

The known studies explore structural and technological parameters of rotary equipment for the strip tillage of soil, concerning the working bodies with the horizontal rotation axis, mainly, the rotors of with angled blades. There have not been found any studies devoted to the influence of working bodies with the vertical rotation axis on the working medium, for the purpose of crushing and stirring soil and plant residues.

3. The aim and tasks of the study

The aim of present work is to study the process of strip tillage of soil by the vertical milling adapter.

To achieve the aim of the study, the following tasks were to be solved:

– identifying and substantiating the expedience of developing technical solution of the vertical milling adapter and the subsequent analytical study of the impact of changes in its kinematic parameters on the character of motion of the particle of working medium;

– conducting experimental research into the process of soil tillage by vertical milling adapter according to the developed technique;

– analysis of the results of experimental research and establishment of relationships between kinematic parameters of the adapter and obtained quality of tillage.

4. Determining and substantiating the expediency of developing a technical solution and studying the operation of vertical milling adapter

The expediency of applying the strip tillage of soil is determined by the parameters of quality of its performance, which is achieved when using the soil tilling implement. The most common soil tilling implement by Strip-till technology implies using self-driven rotary working bodies of different structures that mostly have a horizontal rotation axis and perform the soil tillage at the desired depth. According to the desired width of tillage, the working bodies are mounted alone or in pairs, they are combined or united in sections. Working bodies with a horizontal axis of rotation have sufficiently high effectiveness, because only from 1/3...1/2 of the surface area of the working body contact with soil, a part of the energy is consumed for throwing the fractions of soil, which contributes to erosive phenomena [13].

Such working bodies may have the structure of spherical, cut out, wavy or needle-like disks. Such structures create an effect of throwing of plant residues from the tilled area. In this case, the intersection of the tilled layer is triangular with its apex at the bottom and the working area surface is pectinate. Such phenomena do not allow a rational use of biological potential of working medium.

Thus, crushing, working and uniformed placing of plant residues in the tilled layer will allow the creation of additional resource of nutrition of cultivated plants due to the mineralization of residues. In addition, further decomposition of plant residues in a layer of the tilled soil provides for the maintenance of optimal volumetric mass for a longer period, which creates favorable conditions for the development of cultivated plants. In fact, it is known that volumetric mass of soil is one of the influential factors of forming high crops [14].

Uneven surface profile of the tilled zone causes an increase of evaporation area, which negatively affects the moisture content available for plants, which is especially dangerous in the initial period of vegetation.

The use of self-driven rotary working bodies does not allows regulating the tillage parameters depending on the conditions of its performing, instead, active working bodies have such possibility and soil milling provides for a longer maintenance of it optimal volumetric mass [15].

Thus, common soil cultivation implement for the strip tillage does not provide for an increase in quality indicators which imply the qualitative soil tillage and shredding plants residues resulting in their uniformed mixing in the tilled layer, as well as an even surface profile.

An analysis of the known soil tilling working bodies indicates that the active working groups with the vertical rotation axis meet these conditions [13, 16–18]. However, the known rotary working bodies with vertical rotation axis are not intended for the strip tillage. Therefore, it is relevant to develop the structure of vertical milling adapter for the strip soil tillage, the operation of which would satisfy the requirements of quality and would consider specific features of development of cultivated plants when growing them by the Strip-till technology.

To solve the set problem, a technical solution of the vertical milling adapter for the strip soil tillage was developed, which is protected by the patent of Ukraine for the invention [19]. According to the patent, the vertical milling adapter includes the driving outer and inner shafts with vertical rotation axis, where outer and inner disks are mounted, which are set into forced rotary motion in opposite directions. The cutting elements with active angle of attack within α_1=1...35° and with outer sharpening of cutting edge are mounted onto the outer disk; and cutting elements with passive angle of attack within the α_2=1...35° and inner sharpening of cutting edge are mounted on the outer holder. In this case, the length of cutting elements is selected so as to perform the tillage in the same depth, which is determined by biological features of development of root systems of cultivated plants. The diameters of the circles that are described by outer and inner holders are determined from the following relationships:

$$D_{o.d.} = D_{r.s.} \cdot k_{p.m.p.}, \tag{1}$$

where $D_{o.d.}$ is the diameter of the circle, described by the outer disk during rotation, mm; $D_{r.s.}$ is the diameter of distribution of root system of cultural plants in the period of rooting and sustainable vegetative development, mm; $k_{p.m.p.}$ is the coefficient, which takes into account physical and mechanical soil properties.

$$D_{i.d.} = D_{o.d.} - 2\Delta k, \tag{2}$$

where $D_{i.d.}$ is the diameter of the circle, described by the inner disk during rotation, mm; Δk is the magnitude that takes into account the lateral soil deformation by cutting elements of the outer and inner holders and depends on physical and mechanical properties of soil.

Depending on tillage conditions, the kinematic mode of operation of vertical milling working body is regulated, that is, the ratio of angular velocity of holders rotation and the longitudinal velocity of the working body motion.

5. Analytical study of the process of soil tillage by the vertical milling adapter

In accordance with the specified technical result of developing of the vertical milling adapter construction, it is necessary to provide for the uniformed mixing of plant residues in the tilled soil layer and regulating the tillage parameters depending on the conditions of its performance and the assigned quality indicators. For this it is necessary to explore the process of stirring the particles of working medium under the influence of adapter.

The soil is an elastic-plastic medium and the leading scientists in agricultural mechanics were involved in studying the ways it is influenced [14, 15, 20–25]. Considering the kinematics of motion of the vertical milling adapter, we should note the following: the rotating front part of the outer rotor is involved in the destruction of unploughed soil, whereas the rear part only stirs and crushes the soil that has been already destroyed. This means that the total length of the destruction is equal to half the perimeter of the outer disc. The inner rotor takes part in crushing undestroyed lumps and plant remains.

Let us consider the scheme of operation of vertical miling adapter by the zones of influence on the working medium (Fig. 1).

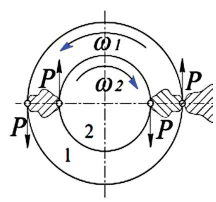

Fig. 1. Zones of working medium according to interaction with vertical milling adapter: 1 — soil twisting; 2 — soil crushing

In zone 1 (Fig. 1), the plots of soil are exposed to the influence of twisting. We will calculate angular rotation velocity in the case when working disks rotate in different directions. The plot of soil performs two moves: spins around its axis with angular velocity of ω_1 and moves translationally with the velocity of V_1. If the adapter's holder did not rotate, the velocities of the holders would be the same and would equal to V_1, which is physically impossible. Possible rotation leads to the fact that the relative velocity of an outer holder increases, and that of the inner holder decreases by the magnitude $\omega_1 R_1$, the linear velocity on the soil plot circle is presented in Fig. 2, and described by the equations

$$V_1 = V + \omega_1 R_1,$$

$$V_2 = V - \omega_1 R_1, \qquad (3)$$

hence:

$$V = \frac{1}{2}(V_1 + V_2); \quad \omega_1 = \frac{V_1 + V_2}{2R_1}.$$

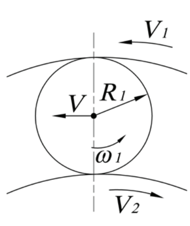

Fig. 2. Scheme of displacement of soil plot under the influence of outer and inner holders of vertical milling adapter

If disks rotate in one direction, we will have:

$$V = \frac{1}{2}(V_1 + V_2); \quad \omega_1 = \frac{V_1 - V}{2R_1}.$$

When substituting initial data, we obtain $\omega_1 = 12{,}6\ s^{-1}$ for the case of discs rotation in different directions, and $\omega_1 = 6{,}2\ s^{-1}$ if they rotate in the same direction. Rotating at the velocity ω_1 and moving at the velocity V, the soil breaks into individual lumps that are mixed in this zone.

Let us consider this motion, taking the displacement of one lump as an example. As it was already noted, the sliding line during destruction is on the cylinder of a conical screw line (by helicoids). Then the surface, which describes the motion of sliding lines, rotates around the vertical axis with constant angular velocity ω_1 (Fig. 3).

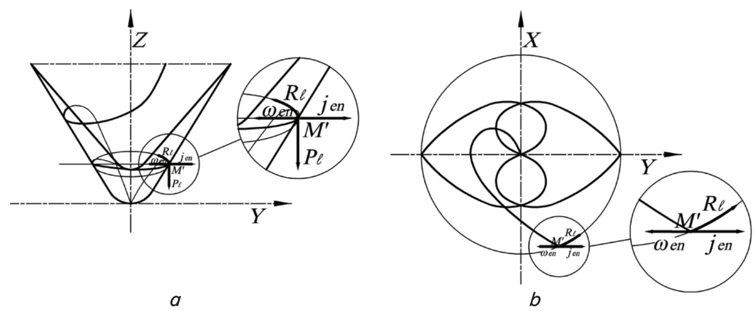

Fig. 3. Scheme of soil lump sliding under the influence of vertical milling adapter: *a* — front projection; *b* — view from above

Under the influence of centrifugal force that occurs during rotation of the soil plot, the lump obtains horizontal velocity V_0.

Axes ZY rotate along with the plane of sliding lines, which can be divided into the relative, towards the surface, and the portable, together with the surface around the vertical Z axis.

Let us draw a lump in position ω(Z, Y) at the assumption that it is the motion upwards along the surface, we will designate the lump's weight as P.

The lump is influenced by forces: P_l the weight of a lump, R_l is the normal strength of reaction of the sliding surface, centrifugal force, the Coriolis force of inertia j_c and the Coriolis force $P_C = m\omega\sin\xi$ which is perpendicular to the ZOX plane and is projected onto the axis 0Z to the point and equals zero (in Fig. 3, it is not shown).

At the uniformed rotation of the lump at the angular velocity ω_1, its angular acceleration equals zero. Therefore, the portable rotating acceleration of the lump $\omega_{e\tau}$ and the rotary force of inertia in the portable motion $j_{e\tau}$ is equal to zero. Portable central acceleration $\omega_{e\tau}$ of the lump is directed horizontally to the left, and: $\omega_{en} = y\omega_1^2$. That is why the centrifugal force of inertia in the portable motion j_{en} is directed horizontally to the right and by the module is equal to: $j_{en} = \frac{P_r}{g} y\omega_1^2$.

The Coriolis acceleration $\vec{\omega}_c = 2\vec{\omega}_1 \times \vec{V}_r$ is directed perpendicular to the plane of the figure from us ($\vec{V}_r$ and $\vec{\omega}_1$ are collinear vectors, which, according to accepted assumption, is directed upwards tangentially to the lumps at point M). Therefore, the Coriolis force of inertia $\vec{j}_c$ is directed perpendicular to the plane of the figure to us and by the module is equal to $j_c = 2\frac{P_r}{g}\omega_1 \vec{V}_r \sin\xi$, where ξ is the angle formed by positive direction of axes z and τ. Differential equation of relative motion of a lump in the projection on the tangent to the lump in point M:

$$\frac{P_r}{g}\cdot\frac{dV_r}{dt}=\frac{P_r}{g}y\omega_1^{\ 2}\sin\xi-P_r\cos\xi,$$

(forces $\vec{R}_r$ and $\vec{j}_c$ are projected onto axis τ). Considering that

$$j_{en}=\frac{P_r}{g}y\omega^2 \text{ and } \omega_{r\tau}=\frac{dV_r}{dt},$$

we find:

$$\frac{dV_r}{dt}=\omega_1^{\ 2}y\sin\xi-g\cos\xi. \qquad (4)$$

Since $\frac{dy}{dz}=\mathrm{tg}\xi$, it is evident that $\sin\xi=\frac{dy}{d\sigma}$, a $\cos\xi=\frac{dz}{d\sigma}$. In addition,

$$\frac{dV_r}{dt}=\frac{dV_r}{d\sigma}\cdot\frac{d\sigma}{dt}=V_r\frac{dV_r}{d\sigma}.$$

Now equation (4) takes the form: $V_r dV_r=\omega_1^{\ 2}y-gdz$.

After the integration we obtain: $V_r^{\ 2}=\omega_1^{\ 2}y^2-2gz+c$.

Then, according to condition $y^2=2az$, we will have:

$$V_r^{\ 2}=2(a\omega_1^{\ 2}-g)z+c. \qquad (5)$$

Let us define the velocity of lump V in relative motion, knowing that at the initial point the lump is at rest in the position M_0 with absciss z_0.

Substituting into equation (5) $z=z_0$, $V_r=0$, we will obtain that $c=-2(a\omega_1^2-g)z_0$.

Thus, equation (5) takes the form: $V_r^2=2(a\omega_1^2-g)(z-z_0)$, and after transformations:

$$V_r=\sqrt{2(a\omega_1^{\ 2}-g)(z-z_0)}. \qquad (6)$$

Having examined formula (5), we can draw conclusions about the direction of the lump's motion.

During the motion of the lump upwards along the sliding surface, $z>z_0$. As the radicand in formula (6) is positive, then $a\omega_1^2>g$, that is, angular velocity of lump rotation must satisfy the condition $\omega_1^2>\frac{g}{a}$, a – parameter. During the motion of the lump downwards along the sliding line, $z<z_0$. Hence, $\omega_1^2<\frac{g}{a}$.

At the relative rest of a lump, that is, $V_r=0$, we will obtain that $a\omega_1^2=g$, from which it follows that a lump will be on the surface in relative rest, if the angular velocity of rotation of a lump satisfies the condition: $\omega_1^2=\frac{g}{a}$.

We will determine at which point of the surface the lump should rise, if at the initial moment it is at the coordinates origin, and it was set into motion horizontally to the right by velocity V_0.

Substituting into equation (5) $z=0$, $V_r=V_0$, we obtain $C=V_0^2$. Therefore, equation (5) takes the form: $V_r^2=V_0^2+2(a\omega_1^2-g)z$, hence

$$V_r=\sqrt{V_0^{\ 2}+2(a\omega_1^{\ 2}-g)z}.$$

At the highest point of a lump rising, $V_r=0$, which is why:

$$z_{max}=\frac{V_0^{\ 2}}{2(g-a\omega_1^{\ 2})}. \qquad (7)$$

Considering that $y^2=2az$, we find:

$$y_{max}=\sqrt{2az_{max}}=\sqrt{\frac{aV_0^{\ 2}}{g-a\omega_1^{\ 2}}}. \qquad (8)$$

For zone 1 (Fig. 1) at rotation in different directions $\omega_1=12.6\ s^{-1}$, $a=6.5\cdot10^{-2}$ m, we will obtain 160>151, that is, the lump will move upwards. Further away from the sliding surface, the rotation rate decreases, the lump may remain at the same height or even go down. In addition, the transversal displacement (by tangential lines) also contributes to stirring.

Therefore, our analytical analysis of operation of the vertical milling adapter and its impact on working medium indicates the qualitative crushing and stirring of soil and plant residues providing the possibility to regulate the parameters of the process depending on the tillage conditions and the assigned indicators of quality.

5. Materials and methods of studying the strip soil tillage by the vertical milling adapter

Experimental studies were conducted in accordance with the methodology developed on the basis of regulations and guidelines for testing rotational soil tillage implement known from the scientific and technical sources. The duration and terms of conducting research were determined by the KND 46.16.02.16 «Agricultural machinery. Duration and agroterms of testing».

Laboratory and field studies were carried out on the basis of SOU 74.3-37-155:2004 «Testing agricultural machinery. Machines and equipment for soil tillage». Before starting the research, the conditions of testing were determined according to GOST 20915-75 «Agricultural machinery. Methods for determining testing conditions». The type of soil and its name by the aggregate composition were determined from the ground map of farming [26].

Moisture content and soil density were determined prior to the beginning of research by standard methods. Soil hardness was determined at the experimental plots in places for moisture determination by the soil hardness gauge of Reviakin according to DSTU 5096:2008 «Soil quality. Determining soil hardness by the soil hardness gauge of Reviakin».

To carry out experimental research of efficiency of the vertical milling adapter under field conditions, the research installation, which included two working bodies, was designed, which allows objective assessment of operation quality of the vertical milling adapter.

The experimental installation (Fig. 4) includes bearing frame 1, onto which the hydraulic motor 2 was mounted. On supports of mounting 3, vertical milling adapters 4 were mounted. The torque is transmitted to adapters 4 from hydraulic motor 2 through pass transmission, which includes driven 5 and drive 6 pulleys, tension roller 7 and toothed gear 4.

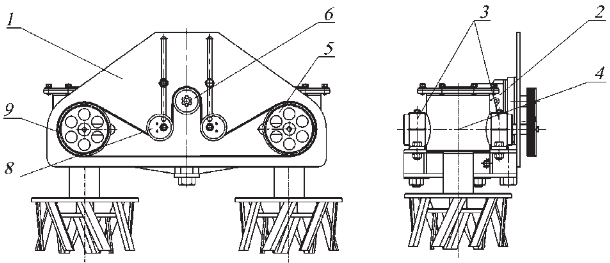

Fig. 4. Structural scheme of the experimental installation with rotating bodies for spacing tillage: 1 — bearing frame; 2 — hydraulic motor; 3 — supports of mounting of working bodies; 4 — working body; 5 — driven pulley; 6 — drive pulley; 7 — tension roller; 8 — toothed gear

The experimental installation is designed so that it is possible to regulate the values of angular velocity of rotation of adapter disks 4, in accordance with the conditions of research, the control cock was mounted onto hydraulic motor 2, which adjusts the pressure of the working fluid. Carrying out field studies implied mounting and aggregating the experimental installation with the power device and installing appropriate equipment to control parameters of its operation. According to the program of experimental research, the following parameters of the installation operation were supposed to be controlled: angular velocity of rotation of the adapter's disks, translational velocity of the aggregate of the experimental installation, installed on plough beam.

Control of translational velocity of the installation was made with the help of distance-measuring wheel, which was mounted to the footrests on the tractor with the inductive frequency meter D4V-1, installed on it. Calibration factor is 9, according to the number of spokes of the distance-measuring wheel. The sensors have passed calibration. The signal acceptance and recording was made by the information-measuring system based on the tensor-intensifier «SPIDER-8» with the software CatMan Express 4.5 for personal computer; data were stored in the format «*.xls» and simultaneously control parameters were determined.

The use of «Spider-8» and the optimum plan of the experiment allowed performing experimental research in one day, with minimum consumption of labor and time for settings the explored parameters of the experimental installation, with the exception of the influence of changes in testing conditions on the results of the study.

Setting up of the experimental installation was carried out within pre-substantiated limits, namely: angular rate of rotation of the drives of rotary bodies was ω=50...250 min^{-1}; translational velocity of the plant was V=1.2...3.2 m/s.

Before each try, the adapters were set into rotating motion before reaching specified values of angular velocity that were controlled using the frequency meter D4V-1. The results of research established that significant changes in the parameters of tillage quality at varying the given parameter within the assigned limits were recorded at three levels of significance, the following values were defined by the control points of angular velocity: 50 min^{-1}, 100 min^{-1}, 250 min^{-1}.

According to theoretical substantiation as for the optimal kinematic mode of rotary bodies [27], translational velocity of the unit was changing at levels: 1.2 m/s, 2.22 m/s, 3.2 m/s.

After determining the values of regulated parameters, in accordance with the plan of the experiment, the adapters were lowered and plunged into soil to working depth of (8....12 cm). Then the installation with the plunged rotation bodies passed the distance of approximately 7...10 m before starting the tillage of the experimental plots. It was necessary for the engine and the experimental installation to reach a sustainable mode of operation. This period corresponded to the least correlation values of the signals recorded by the information-measuring system «Spider-8».

Soil crushing was determined every 1.5 hour, by soil sampling at the tillage depth form the experimental plots of the area of 0.25 m^2, repeated 4 times. Selected samples were sifted through a set of sieves, placed in order of decreasing of the holes diameter. Then with careful fluctuating movements, the soil was sifted through the sieves on the appropriate faction. The content of each sieve was weighed with error ±20 g.

The content of erosion-dangerous particles in the layer of 0...5 cm was determined by measuring at three experimental plots before and after the passage of the installation. In this case, a sample of weight 2.5...3.0 kg was taken with the shovel. The samples were brought to the air dry condition, sifted through a sieve with the holes diameter of 1 mm and weighed. Results of measurements and calculations of the mass fraction of erosion-dangerous factions of soil were entered into the register

The soil density was determined in the following way. A special drill was plunged perpendicularly without soil compaction at the end of the plunge in places at the experimental plots, selected in the same way as for determining humidity and hardness. The drill was rotated several times and pulled out of the soil, the excessive part of the soil was cut with a blade on the edge of the screw surface of the drill. The drill cap was removed, closed with the lid and weighed under laboratory conditions on the laboratory balance VLTK-500 with accuracy 0.01 g (GOST 24104 «Laboratory balance. General technical requirements»). Then the soil sample was removed from the cap, mixed, weighed and dried to constant mass in the drying chamber SSh-3 at 105 °C.

The stage of plant residues shredding was performed similarly to the definition of soil crushing, but with the previous sifting of plant residues from soil.

The uniformity of stirring plant remains in the tilled soil layer was determined by visual inspection after plunging a transparent plate with width and length of not less than the geometric parameters of the tilled layer and further shoveling of soil from one side.

6. Results of experimental research into the process of strip tollage of soil by vertical milling adapter

6. 1. Results of determining the testing conditions

Before conducting the research, the testing conditions were defined by the method described above; the results are presented in Table 1.

The choice of parameters of testing conditions was determined according to the requirements, defined in SOU 46.2-37-155:2004. Thus, soil hardness affects plunging of a seeder, and therefore the stability of sowing depth and density affects the development of cultivated plants.

Table 1

Characteristics of testing conditions for the vertical milling adapter for soil tillage by resource saving technology

Parameter name	Parameter value
Make	Experiment installation
Kind of work	Strip pre-seeding tillage
Soil type and name according to mechanical composition	Chernozem, deep, medium loam, low in humus
Relief	Plain without slopes
Microrelief	Weekly leveled
Soil humidity, % by layers, cm: from 0 to 5 inclusive above 5 to 10	 18.5 19.8
Soil hardness, MPa, by layers, cm: from 0 to 5 inclusive above 5 to 10	 0.77 1.53
Soil density, g/cm^3 from 0 to 5 inclusive above 5 to 10	 2.0 2.4
Characteristics of turf: – turf thickness, cm – turf connectivity, kg/m^2	 10.6 0.7
Pre-tillage, previous crop	Deep plowing, winter wheat

6. 2. Results of experimental research into the vertical milling adapter operation

In terms of analytical studies, we will consider the results of experimental research into influence of translational and angular velocities on the degree of soil crushing, soil density and shredding of plant residues.

For this purpose, in accordance with the procedure of testing, the experiments were conducted at three different velocities of advance motion, which corresponds to transmission of the tractor at the translational change in angular velocity of rotation of the adaptor's disks. According to the results of determining the fractional composition, the following diagrams are built (Fig. 5).

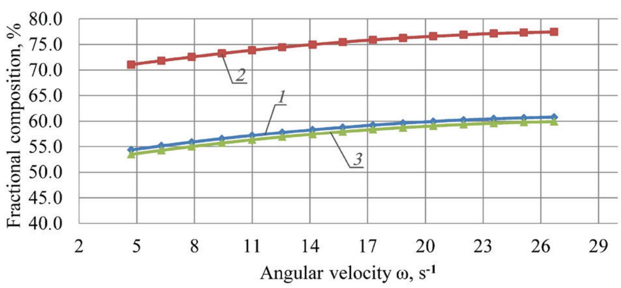

Fig. 5. Dependence of fractional composition of soil on angular velocity at the following values of rate of translational motion: 1 – $V_{a.m.}$ = 1.2 m/s; 2 – $V_{a.m.}$ = 2.2 m/s; 3 – $V_{a.m.}$ = 3.2 m/s

From the diagram in Fig. 5 it is obvious that the content of particles with diameter from 0.001 to 0.005 m and from 0.01 to 0.005 m reaches maximum values with increasing angular velocity and the velocity of translational motion $V_{a.m.}$ = 2.2 s^{-1}. The resulting fractional composition meets the requirements of quality cultivation and provides favorable conditions for the development of cultivated plants, preventing the formation of erosion-dangerous particles with diameter less than 0.001 m.

Another important indicator of the quality of tillage is the density (volumetric mass) obtained as a result. The influence of change in angular velocity on the soil density after tillage at different values of forward speed was determined (Fig. 6).

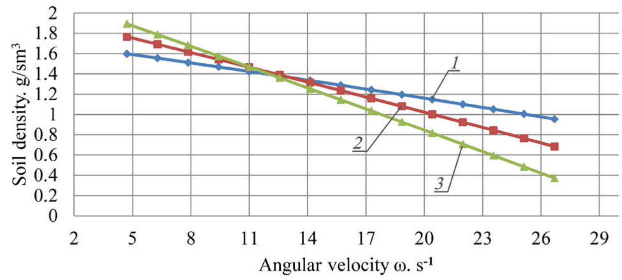

Fig. 6. Dependence of soil density on angular velocity at different values of velocity of translational motion: 1 – $V_{a.m.}$ = 1.2 m/s; 2 – $V_{a.m.}$ = 2.2 m/s; 3 – $V_{a.m.}$ = 3.2 m/s

From Fig. 6 we can see that the optimum density of 1.2...1.25 g/cm^2 is achieved at angular rotation velocity of the disks of adapter 14...16 s^{-1}, at different values of translational velocity 1.2...3.2 m/s.

Dependence of degree of shredding plant residues on angular velocity is shown in Fig. 7.

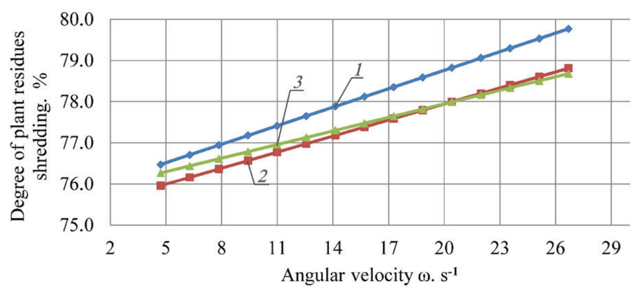

Fig. 7. Dependence of degree of plant residues shredding on angular velocity at different values of velocity of translational motion: 1 – $V_{a.m.}$ = 1,2 m/s; 2 – $V_{a.m.}$ = 2,2 m/s; 3 – $V_{a.m.}$ = 3,2 m/s

In this case, we determined the content of plant residues from 0.005 to 0.03 m that do not exert negative influence on the development of cultivated plants and are suitable to the rapid mineralization in the soil layer. Diagram in Fig. 7 shows that the content of plant residues of the optimal size will increase with an increase in the value of angular velocity, and will reach 79 % at the velocity of translational motion 1.2 m/s.

7. Discussion of results of studying the operation of the vertical milling adapter

In the present work, studies of the process of soil tillage by the vertical milling adapter of the developed construction were carried out. According to the technical solution, the separation of a soil chunk from unbroken furrow is performed with the front part of the adapter disk with its following crushing and stirring with the help of the rear part of the disk and inner rotor. This provides an increase in the degree of soil crushing and shredding plant residues for creating favorable conditions for the development of cultivated plants, especially during germination and at the initial period of the growing season.

However, when using this technical solution, there is a risk of excessive soil crushing and of formation of fractions with diameter less than 0.01 m, which are erosion-dangerous. The degree of soil crushing and plant residues shredding is affected by the ratio of angular rotation velocity of the adapter disks and the velocity of translational motion of the plant. This ratio determines the kinematic mode of operation, which is the ratio of a circular and translational velocity. It is known that under the kinematic mode which is less or equal to one (which is typical for self-driven working bodies) the degree of soil crushing does not meet the requirements of favorable conditions of cultivated plants development, namely the share of soil fractions of more than 0.25 m reaches 30 %. Such fractional composition causes acceleration of the loss of moisture and makes germination of cultivated plants difficult.

Therefore, it was important to determine the interrelationship between kinematic parameters of the adapter (angular and translational velocities) and the parameters of the soil tillage quality.

According to the methods of soil mechanics we established an analytical relationship between the kinematic parameters of the adapter and motion of the particle of the working medium in the cultivated layer. The possibility to influence this process by regulating the kinematic parameters will make it possible to evenly distribute the plant residues in the cultivated layer, providing a rational use of the biopotential and the retention of optimal characteristics of soil, such as density and fractal composition for a longer period.

The influence of kinematic parameters of the quality parameters of tillage, specified above, was investigated. It was found that at angular rotation velocity of the adapter disks 26.5 s^{-1} and the velocity of translational motion of the unit 2.2 m/s, the maximum content of the factions of optimal diameter is achieved. In this case, the factions of diameter from 0.001 to 0.005 m and from 0.005 to 0.01 are considered optimum. It is known that the optimum soil density is 1.2...1.25 g/cm^3 [14]. It is achieved at the angular velocity of rotation of adapter disks 14...16 s^{-1} at the defined levels of variation in velocity of translational motion of the unit.

The degree of shredding plant residues is not a less important parameter, because the large-sized residues will prevent cultivated plants from germination and will not mineralize fast enough, which will decrease the biopotential of working media and will not provide an additional source of plants nutrition. The residues with dimensions of 0.005 to 0.03 m are optimal. According to the results of experiment, it was found that the maximum content is achieved at the angular velocity of rotation of adapter disks 26.5 s^{-1} and at the velocity of translational motion 1.2 m/s.

Thus, the identified dependencies will allow the optimization of kinematic parameters of vertical milling adapter according to the indicators of the soil tillage quality. This is achieved through the development of appropriate computer software, which would allow taking into account initial characteristics of the soil condition, such as humidity, hardness, turfness, and connectivity.

The use of vertical milling adapter is restricted to sandy and sandy loam soils, because their crushing takes place under smaller deformable influences on them. The application of developed technical solution will be expedient for heavy and medium chernozems, and clay soils.

The obtained results can be considered as a verification base of expediency of the practical application of vertical milling adapter at the enterprises of agro-industrial production. Among them, it is worth mentioning LLC «Promin» from Karlivsky region and PP «Agroecology» from Shishatsky region, Poltava Region, Ukraine, where a special attention is paid to the implementation of new soil protective technologies.

In future, it is planned to investigate the influence of kinematic parameters on power characteristics of the operation of vertical milling adapter and their optimization, along with the indicators of tillage quality. This is possible by using the methods of mathematical statistics, compiling and solving systems of equations, which would take into account the above mentioned influential factors and controlled indicators.

8. Conclusions

1. The technical solution of the vertical milling adapter for the strip soil tillage, which was protected by the invention patent, was developed. According to the technical solution, the adapter contains the driving outer and inner shafts with vertical rotation axis, where outer and inner disks with working elements are mounted, the disks are set into forced rotary motion in opposing directions.

2. Conducted analytical studies of the influence of change in kinematic parameters of the vertical milling adapter on the nature of moving of particle of working medium proves high quality crushing and stirring of soil and plant residues with the possibility of regulating the process parameters depending on the tillage conditions and the assigned quality parameters.

3. A technique of conducting laboratory and field study of operation of the experimental installation with vertical milling adapters within predefined limits was substantiated: angular velocity is from 50 min^{-1} to 250 min^{-1} and velocity of translational motion is from 1.2 to 3.2 m/s.

4. According to the results of experimental research, the influence of parameters of the vertical milling adapter on the quality indicators of soil tillage was established, namely:

– the maximum content 77.5 % of fractions with optimal diameter from 0.001 to 0.005 m and from 0.005 to 0.01 m in the cultivated layer is achieved at angular velocity of rotation of adapter disks 26.5 s^{-1} and velocity of translational motion 2.2 m/s;

– the optimal value of soil density 1,2...1,25 g/cm^3 is achieved at angular velocity of rotation of adapter disks of 14...16 s^{-1} and different values of velocity of translational motion;

– the maximum content of plant residues 79 % of optimum size from 0.005 to 0.03 m is achieved at rotation velocity of adapter disks 26.5 s^{-1} and velocity of translational motion 1.2 m/s.

The results of experimental research testify to the high quality of performance of technological process of strip soil tillage by the vertical milling adapter, which provides optimal conditions for the development of cultivated plants. Thus, the theoretical positions, given in analytical study of the vertical milling adapter performance for high-quality crushing and stirring of soil and plant residues, are proved.

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