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IMPROVING THE SOIL BIN FOR STUDYING ROTARY TOOLS TAKING INTO ACCOUNT THE KINEMATIC FEATURES OF INTERACTION WITH THE SOIL

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The object of this study is experimental equipment in the form of a soil bin intended for scientific and educational investigation of rotary tools.

The task solved was to clarify the specificity of rotary tools operation and to design a small-sized soil bin taking into account this specificity. The data collected during experimental research and theoretical analysis confirmed the determining influence of the kinematic parameter on the indicators of interaction between the rotary tool and soil.

As a result of the research, a concept was proposed and a soil mini channel was designed, which makes it possible to investigate the process mechanics and to perform graphic modeling.

The result relates to the fact that the mediator of motion transmission during the experiments was a ground trough, and the drive belt is rearranged in engagement with pulleys of different diameters. This provides a different ratio of linear movement of the trough and rotation of the working body.

The peculiarity of the design is the combination of variable movable troughs and graphic screens with a stationary position of the rotor. The design provides simplicity and visibility of the assignment of different values of the kinematic parameter.

A special feature is the modularity of the structure. This makes it possible to conduct research with variable troughs with different soil composition and immediately acquire a graphic interpretation of the kinematic mode on the screen. This implementation of the soil mini bin simplifies the observation and recording of the result of interaction between the rotor and model environment.

The field of practical use is scientific research in the area of agricultural engineering. The data obtained can be used to improve existing tools. The research process is part of the educational process at the agricultural university

Keywords: soil bin, rotary implement, kinematic parameter, trajectory, soil-tool interaction, tillage

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1. Introduction

Improving technical means for farming, in order to improve their efficiency, requires an in-depth scientific study of the patterns of processes in the cultivated environment. The result of scientific research is determined in a certain way by the level of equipment for experiments. In addition to standard equipment, there is a need for specialized equipment, in particular in soil bines. The first step in the design and improvement of soil bines is an analytical study of existing equipment and patterns of processes between the working body and the treated environment. The level of scientific results is largely determined by the perfection of scientific experimental equipment.

Thus, the design and improvement of specialized experimental equipment, in the form of a soil bin for the study of rotary tools, is an urgent task.

2. Literature review and problem statement

Construction of theoretical models of the interaction between tools and soil is based on the preliminary examination and verification of models under real conditions, in particular, in soil bines. Thus, in study [1], the authors combine the construction of a mathematical model of the state of soil under the influence of a wedge with experiments in a soil bin. But the study concerns passive working bodies.

The equipment for studying the working bodies of rotary machines based on the soil bin is presented in monograph [2]. The equipment includes a control system, equipment for video recording and recording of sensor signals. With the help of the equipment, a significant amount of experimental materials were acquired, used in the design of milling and traction-drive machines. The advantage of [2] is that the structure involves the possibility of establishing the kinematic coefficient. An unsolved issue is the achievement of clarity of kinematic modeling, as well as the complexity and energy consumption of the equipment.

In study [3], a soil bin is proposed, which includes equipment for soil conditioning, computerized motion control, data collection and analysis. The coordinating mechanism of the translational movement of the wheel and drive of its rotation was realized by the hardware method. The disadvantage of the equipment is the complexity and obscurity in establishing the kinematic parameter.

Investigating [4] the interaction of the soil with a concave chisel-shaped tooth included designing a new soil bin aimed at achieving instantaneous movement of the carriage. The advantage of study [4] is that the results of soil destruction had confirmed the theoretical model [5]. It was found that the speed of movement did not have a significant effect on the parameters of the working body.

Work [6] considers measurement tools and data recording devices related to a soil bin; they are used in the study of traction devices (wheels and tracks). The advantage of the proposed structure is the presence of chain transmission, which ensures mechanisms alignment, as well as a unified data collection system for different converters. The disadvantage of the equipment is its bulkiness and significant construction costs. Research [6] focuses on the design of innovative installations for measuring and recording the parameters of interaction between working elements and soil.

In study [7], the effect of the velocity ratio of the active-passive tillage tool was investigated in the soil bin. The experiments made it possible to establish indicators of optimal system settings from the point of view of increasing energy consumption. However, the soil bin used had significant dimensions, and the equipment consumed significant electricity, which complicates its use.

In work [8], the rational value of the speed ratio coefficient was determined in the field according to the maximum productivity of soil cultivation with minimal energy consumption of the active-passive combined disk harrow. Thus, the determining influence of the speed ratio coefficient on energy consumption was emphasized.

Study [9] proposed a calculation method based on the obtained geometric relationships between the operating parameters of a rotary cutter for determining the height of ridges that occur in the lower part of the soil treatment layer. Analytical materials from work [10] were used to derive appropriate dependences. The theoretical results reported in these works require experimental verification.

From the above studies, a conclusion can be drawn regarding the importance and influence of the "speed ratio" or "kinematic coefficient" parameter on the performance of the rotary tool.

A significant problem associated with using known equipment is its complexity, significant material and energy consumption, and, as a result, high cost. This prevents the spread of this means of research.

Regarding the specificity of studying the operation of rotary tools, the disadvantage is that the selection and registration of kinematic parameters of the working body, which influence energy consumption and the quality of tillage, are difficult and ambiguous.

Thus, the soil bin remains a modern means of scientific research. The trend in the development of soil bines is saturation with measuring and recording equipment. The technical solutions in the mechanical part remain more stable, which is explained by the insufficient theoretical understanding of peculiarities in the study of rotary tools.

An option for overcoming related difficulties may involve designing new research equipment that implements theoretically justified dependences. This is the approach used in works [5, 11]. However, work [5] considers passive tools while study [11] focuses on the factors affecting the index of combing the bottom of the furrow. The basis for improvement may be work [1], which takes into account solutions from work [10]. All this gives reason to assert that it is expedient to carry out research and to design improved equipment taking into consideration the specificity of rotary tools.

3. The aim and objectives of the study

The purpose of our research is to improve the equipment for experimental investigation of rotary tillage tools taking into account their kinematic features. The use of such equipment will make it possible to simplify and speed up the establishment of cause-and-effect relationships between the kinematic parameters of the working body and the bin formed in the soil.

To achieve the goal, the following tasks were set:

– to investigate the structural and technological features of soil bines, related to the specificity of the study of rotary tillage tools;

– to investigate the operation of rotary needle tools under field and laboratory conditions;

– to theoretically analyze the mechanism of interaction between the soil and needle of the rotary tool;

– to design a prototype of a soil mini bin, the structure of which enables establishing the kinematic parameters and a graphic representation of the movement of rotary working bodies.

4. The study materials and methods

The object of our research is a soil bin as a specialized means for researching the process of interaction between rotary working bodies and soil.

The main hypothesis of the research assumes that the improvement of the soil bin for the study of rotary tools should be based on the features of the process of their interaction with the soil. It is assumed that the feature of non-driven working bodies is that the real rolling radius is not equal to the distance from the axis of rotation to the end of the needle, and it decreases during work because of soil sticking.

For field research, a needle rotary working body with needles on a hub, installed on a simplified attachment of a wheeled tractor, was used. The working body operates under the mode of free rolling. Soil moisture and hardness were measured with standard instruments according to a standard procedure.

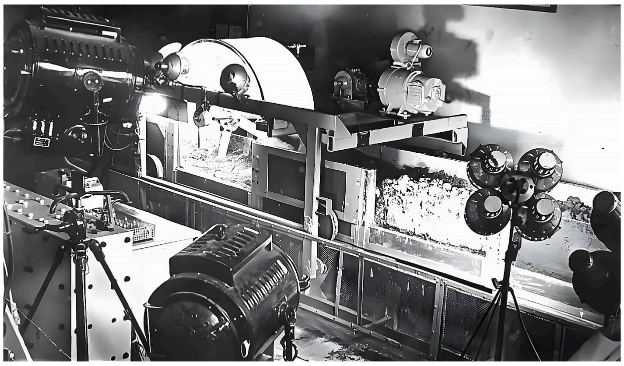
For laboratory research, a mock-up of a soil bin and a mock-up for graphic and kinematic modeling were fabricated and used.

At this stage, for simplification, needle rotary tools are studied as having a simple cylindrical shape of the working part and a rectilinear shape of the working edge.

5. Results of designing a modular soil mini bin for the study of rotary tools

5. 1. Investigating the structural and technological features of soil bines related to the specificity of rotary tillage tools

The study of structural and technological features of soil bines was carried out on full-scale samples (Fig. 1), based on the review of literary sources and technical documentation.



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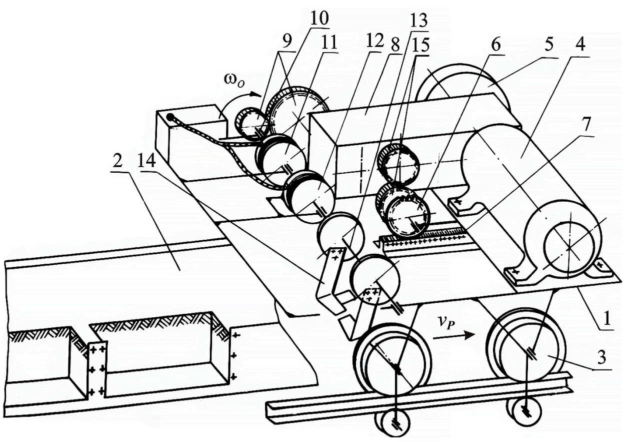


b

Fig. 1. Experimental installation for the study of kinematic and energy characteristics of rotary tillage machines [2]: *a* — general view of the installation; *b* — schematic diagram

The installation (Fig. 1) was driven by a direct current motor, which made it possible to continuously change the speed of movement and rotation of the rotor in a wide range. The installation has a control system for starting and stopping the rotor. The tillage working body is rotated at different moments of the cart's movement along the soil hopper. Start and braking of the working body is carried out by electromagnetic clutches. The operation of the electromagnetic couplings is controlled by the track switches located along the carriage path. In order to record the effect of the experimental working body on the soil, one of the walls of the soil bunker is made transparent, and the installation includes equipment for high-speed filming.

The matching mechanism, which coordinated the translational movement of the carriage and the rotation of the rotor, contains a toothed rack, a system of toothed wheels, and a gearbox.

The experimental installation [3] with a soil bin includes equipment for soil conditioning, computer components for motion control, measurement, registration, and data analysis (Fig. 2). The installation is mechanically complex and full of electronic equipment. Unlike the installation shown in Fig. 1, the coordination mechanism of the translational movement of the wheel along the soil surface and the wheel rotation drive was implemented by the hardware method.

Shown in Fig. 3, the soil bin, with a single wheel tester and equipment to measure the interaction of the tire with the soil, is significant in size, which of course requires suitable premises and capital investment. The bin is equipped with various instruments. The carriage is driven by a chain transmission, which provides movement for a length of several meters.

It was established that an essential feature of soil bines for studying rotary working bodies, in contrast to the equipment for investigating passive working bodies, is the presence of devices for coordinating the longitudinal movement and rotation of the working body around the axis. Such devices are implemented in the form of multi-stage mechanical transmissions or sophisticated hardware and software. The disadvantage of existing bines is the significant material and energy consumption, which limits their use, including for educational purposes.

Fig. 2. Installation with a soil bin for measuring parameters in the operation of agricultural wheels [3]

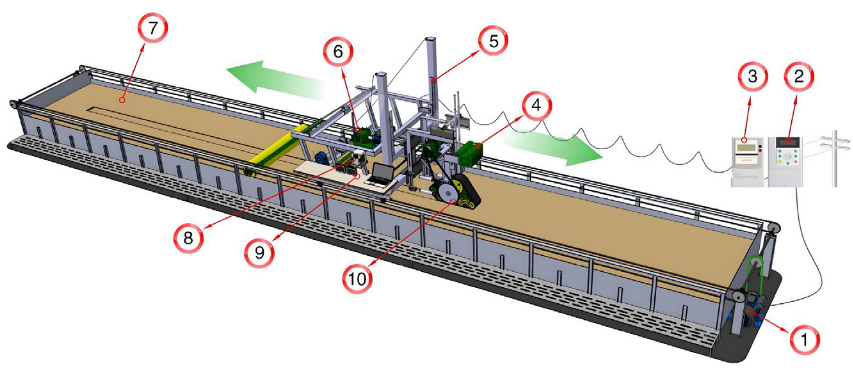


Fig. 3. Soil bin for studying interaction between the tire and soil [6]: 1 — drive electric motor; 2 — mobile inverter; 3 — three-phase power source; 4 — static load; 5 — wheel tester height adjustment mechanism; 6 — bevameter; 7 — soil; 8 — single test wheel/bevameter/penetrometer; 9 — data recorder; 10 — prototype of a crawler motor

5. 2. Investigating the operation of rotary needle tools under field conditions

The purpose of this stage of the research was to determine in the field the factors that most influence the parameters of tillage and furrow formation. During research, we used a rotary needle tool designed to introduce a liquid substance into the root system of crops. The tool consists of needles on a hub, which, through a bearing unit and a bracket, is attached to the beam of the tractor hitch (Fig. 4, *a*).

During operation, the needle of the rotary tool performs translational-rotational movement due to adhesion with the soil massif. As a result of the variability of the state of the soil, and, accordingly, its density, humidity, and composition, the ratio of the speed of translational and rotational movements changes.

Factors affecting machining performance include the linear speed of translational movement of the tool and the angular speed of rotational movement of the hub with needles. The quality of soil treatment is considered to be the size of the formation of holes and the presence of other changes around them. The density and moisture values of the soil were also recorded. It should be noted that for tools of this type, the formation of a significant furrow is not a positive phenomenon.

It was found that when the tool is working for one hour, with a linear speed in the range of 3.5÷6 km/h, the depth of the hole decreases by an average of 27 % from the value of the depth at the beginning of work. At the same time, the indicators of soil condition (moisture and density) remained unchanged.

As a result of observations in the field, it was established that the kinematic characteristics of the working body of the rotary tillage tool have a variable character. When the speed of forward movement of the tool increases above a certain value, the phenomenon of rolling of the working body with accelerated rotation occurs. The rolling mode with accelerated rotation is also observed as a result of soil sticking to the needles, that is, with a decrease in the real rolling radius of the tillage working body. As a result, the dynamic removal of the soil by the ends of the needles of the working body to the surface of the field is observed (Fig. 4, *c*).

Investigating the movement of the model of the needle tool in the soil bin (Fig. 5) showed that the penetration into the soil with the drilling of the needle is also accompanied by the removal of soil particles from the depth of the layer. Small-sized mounds of soil (Fig. 5, *b*) formed after the passage of the working body were recorded by photo-registration. The embankments are placed on the opposite side of the hole, from the direction of forward movement of the rotary tool.

Graphical-kinematic modeling of the process was carried out using a mock-up of a needle rotary working body. The model was driven by a flat belt, which was fixed around a sector of a certain radius. The equipment included a graphic tablet that was driven in longitudinal motion relative to the axis of rotation of the model of the working body.

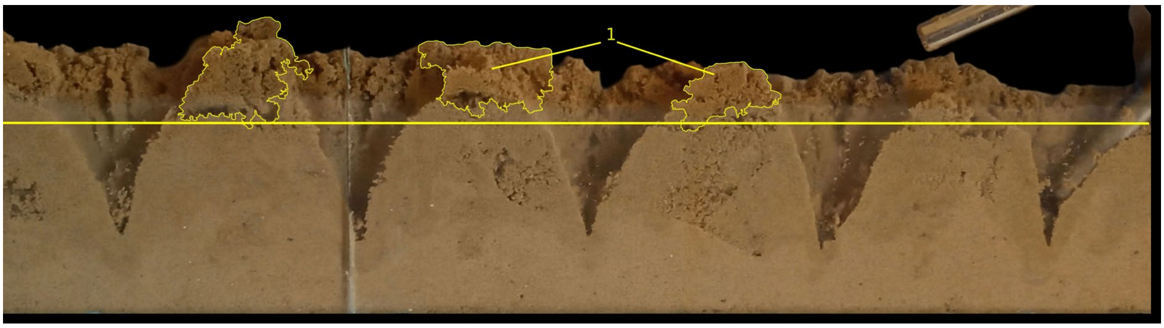
The system of geometric parameters of the working body was modeled (Fig. 6), developed based on the materials of previous studies [12]: d_N – needle diameter N; R_N is the outer radius of the needle wheel; R_{R1}; R_{R2}; R_D – respectively, intermediate radii of rotation/rolling of the needles; h_{R1}, h_{R2}, h_R, $h_{\max}$ are the depths of penetration of needles N into the soil.

The peculiarity was that the axis of rotation of the model of the working body was stationary, and the plane-parallel movement was carried out by a graphic tablet that simulated the relative movement of the working body along the surface of the field. It is important that the prototype of the working body did not move relative to the observer, which simplified the observation and recording of data.

Several successive positions of the needle, in the process of its relative movement, were outlined on a sheet of paper. The acquired data were processed by graphic methods and analyzed. The analysis process was simplified by the fact that the data were recorded directly during the experiment. Shown in Fig. 6, *b*, the example corresponds to the case when the radius of rotation/rolling of the needle working body is equal to the radius R_{R2}.

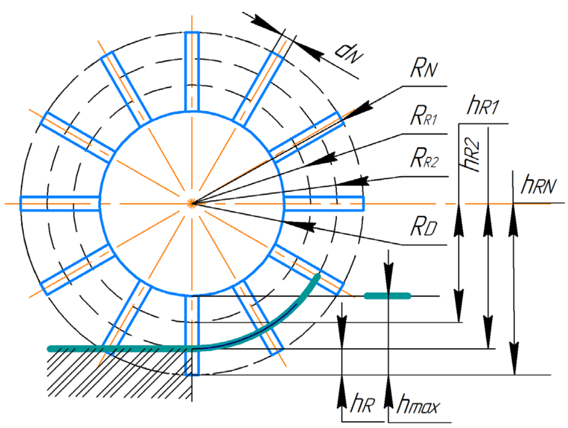
Fig. 4. Investigating the operation of a rotary needle tool under field conditions:
a – general view of the installation; *b* – the effect of soil sticking to the needles; *c* – appearance of holes in the soil

a



b

Fig. 5. General view of the soil layer after the passage of the model of a rotary needle tool in the soil bin: *a* — appearance of the processed soil layer; *b* — the type of soil release on the day surface



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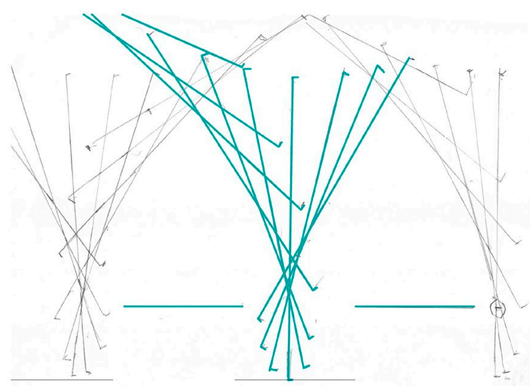

b

Fig. 6. Scheme of graphic-kinematic modeling of the rotary needle working body operation: *a* — schematics of parameters; *b* — acquired graphic data

5. 3. Theoretical analysis of the mechanism of interaction between the soil and needle of the rotary tool

During the working process, there is a complex movement of each needle relative to the treated soil layer, namely, translational movement relative to the field surface and rotation. The rotational motion of the needle also has two components: rotation relative to a point coinciding with the disk axis and rotation/rotation around another point located in the thickness of the soil layer. The resistance of the soil occurs due to the immersion of the needle, as well as due to the rotation of the needle in the soil. The position of the conditional point around which the needle rotates is determined by the balance of soil resistance forces and affects the real radius of rotation of the rotary tool when rolling along the soil layer.

The working surface of the needle *N* is represented by two moving parts and a relatively stationary zone separating them (Fig. 7). In the process of work, the needle *N* rotates around the axis *A* of the working body and rotates around the conditional point A_N in the soil layer. The driving force *R* is applied to the axis *A* of the working body, and can be decomposed into components, transverse R_1 and longitudinal R_p. The longitudinal force component R_p arises as a result of resistance to the immersion of the needle. The action of the driving force *R* is accompanied by deformation of the soil by the working surfaces N_1 and N_2 and causes a corresponding reaction from the soil.

The distributed soil reaction forces applied to the working surfaces N_1 and N_2 can be replaced by equivalent forces R_2 and R_3. The system also has needle-soil friction forces along the surface of the needle and the force of resistance to needle immersion R_p (with a "minus" sign) at the end *P* of needle *N* (not considered in this model).

The first part N_1 of the working surface is located closer to the rotation axis *A*, oriented in the *long* direction of the tool movement. The second part N_2 of the working surface is located further from the axis of rotation 1, oriented back relative to the *long* direction of the tool movement. The zone delimiting parts N_1 and N_2 of the working surface, and the corresponding point A_N carries the content of the instantaneous center of rotation of the needle in the soil layer.

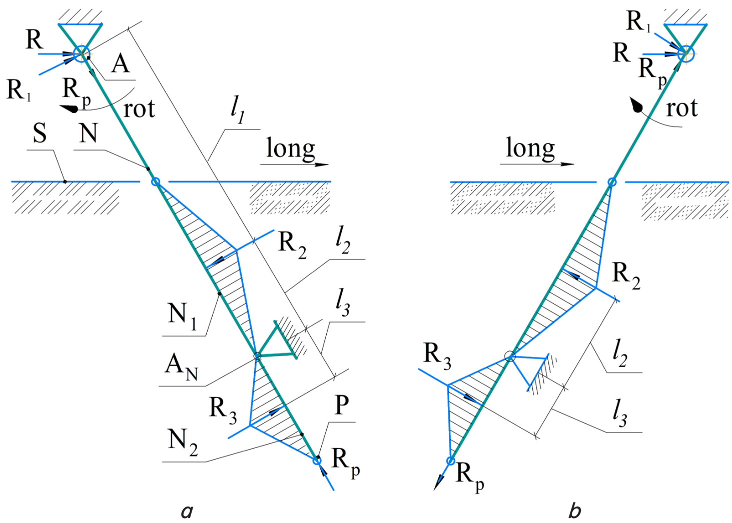

Fig. 7. Scheme of forces acting on a needle in the soil (the needle is conditionally represented as a beam): *a* – the phase of needle immersion in the soil layer; *b* – the phase of needle exit from the soil layer

The equilibrium equation of the system relative to the instantaneous center of rotation A_N takes the following form:

$$R_1 l_1 - R_2 l_2 - R_3 l_3 = 0. \qquad (1)$$

The force R_3, which causes the soil to be thrown onto the field surface, is equal to:

$$R_3 = (R_1 l_1 - R_2 l_2)/l_3. \qquad (2)$$

Our analysis has made it possible to divide the working part of the needle into at least three functional parts:

– the upper zone of the working surface is directed in the direction of movement of the tool;

– the lower zone of the working surface of the needle;

– the separation zone of the working surface, the so-called "point of turning of the needle".

The introduction into the analysis of the equilibrium of the system of the concept of "point of turning of the needle" and the instantaneous center of rotation of the needle in the soil layer makes it possible to explain the origin of the phenomenon of soil ejection on the field surface.

5. 4. Designing a soil mini bin

The equipment (Fig. 1) for the experimental study of rotary tillage tools was taken as a prototype. The equipment includes a frame, guides, a hopper with soil, a rotating working body installed on a shaft, with the possibility of longitudinal movement relative to the soil surface, a leading rotor, and a drive.

The leading rotor is kinematically connected to the longitudinal movement of the working body [2].

The technical task is to simplify the establishment of the kinematic parameters of rotation of the rotary tillage tool during the experiment, to ensure the clarity of such establishment, to facilitate investigating the result of the action of the tillage working body on the soil, which is also important in the educational process.

The improved equipment for the experimental study of rotary tillage tools is schematically shown in Fig. 8–11.

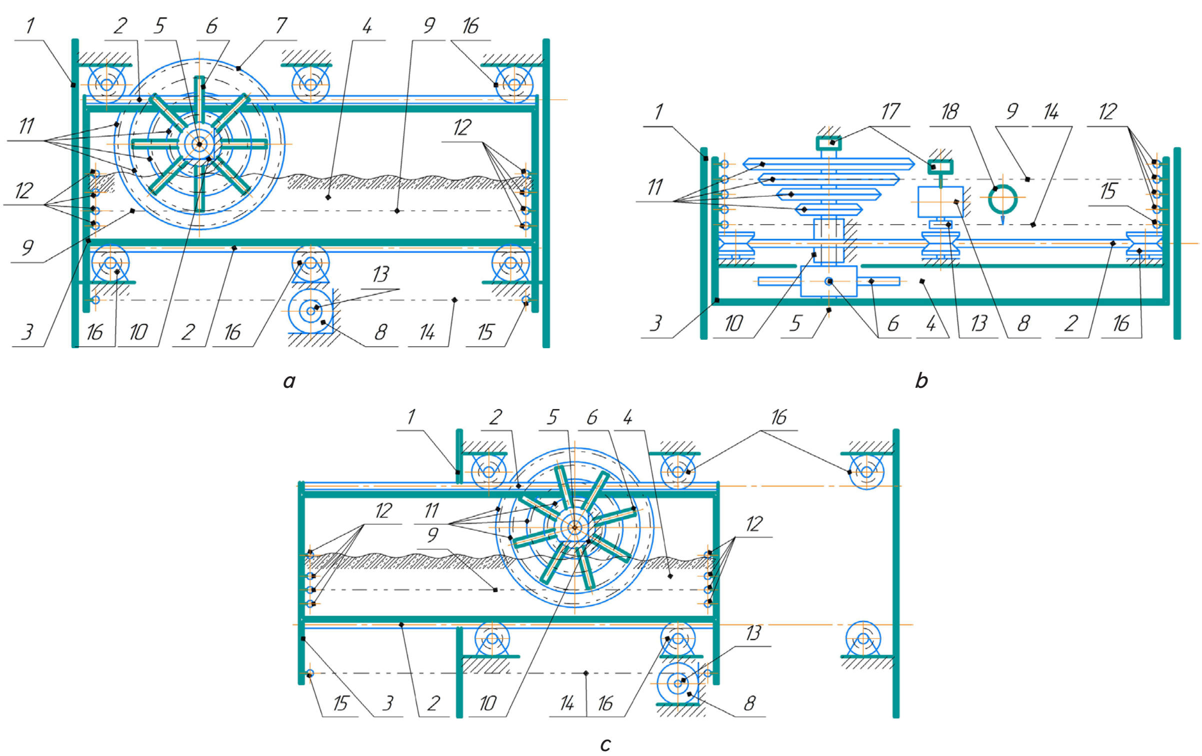

Fig. 8. Schematic view of the equipment: *a* – front view; *b* – top view; *c* – view of the equipment with a hopper with soil moved to the left, where: 1 – frame, 2 – guides, 3 – hopper, 4 – soil, 5 – shaft, 6 – rotating soil working body, 7 – leading rotor, 8 – drive, 9 – belt, 10 – support, 11 – pulleys, 12 – belt attachment points, 13 – pulley, 14 – belt, 15 – belt attachment points 14, 16 – support rollers, 17 – angular displacement sensors, 18 – linear displacement sensor

The equipment consists of frame 1, guides 2, hopper 3 with soil 4 mounted on shaft 5, a rotating soil-processing working body 6, leading rotor 7, and drive 8. The leading rotor 7 is kinematically connected to the longitudinal movement of hopper 3 by belt 9. The longitudinal movement of working body 6, relative to the surface of soil 4, is realized due to moving hopper 3 with soil 4.

Support 10 of shaft 5 of the rotation of working body 6 is fixed motionless relative to frame 1, and hopper 3 with soil 4 is installed with the possibility of forced movement with the help of drive 8 along guides 2. Driving rotor 7 is made in the form of pulleys 11 of different diameters with the possibility of connection with hopper 3 by pass 9 at connection points 12. When examining some modes, pass 9 is disconnected from hopper 3.

Drive 8 through pulley 13 is connected by belt 14 to hopper 3 at attachment points 15. Support rollers 16 have a V-shaped profile, are fixed on frame 1, and engage with guides 2. To control the speed of rotation of rotor 7 and pulley 14 of drive 8, the installation includes angular 17 and linear 18 movement sensors.

In a specific design, a standard roller chain or toothed belt can be used as belts 9 and 14. Pulleys 11 and 13 have the corresponding profile.

Bunker 3 has several connection points 12 of belt 9 according to the diameter of pulleys 11. When examining the mode of free rolling of working body 6 on ground 4, belt 9 was disconnected from connection points 12 and removed from the installation.

During the operation of the equipment for the experimental study of rotary tillage tools, hopper 3 with soil 4 is set in motion by drive 8 due to the attachment of belt 14 to hopper 3 and its coupling with pulley 13. Due to the kinematic connection of hopper 3 and rotor 7 with the help of belt 9, longitudinal movement hopper 3 leads to forced rotation of rotor 7.

Installed on common shaft 5, drive rotor 7 and working body 6 rotate with the same angular speed ω. The longitudinal movement *L* of working body 6 relative to soil 4, with the simultaneous rotation of working body 6, leads to the formation of a furrow of a certain shape and parameters in soil 4. The parameters of furrow and loosening of soil 4 depend on the ratio of the speed *VL* of the longitudinal linear movement *L* of hopper 3, and accordingly of soil 4 and the tangential speed *VT* of points *P* of working body 6 (Fig. 9).

During the experiment, belt 9 can be rearranged at attachment points 12, and accordingly engage with pulleys 11 of different diameters *D*1, *D*2, *D*3, *D*4. Pass 9 can also be removed from the equipment. Thus, with the same linear speed *VL* of the longitudinal movement of soil 4 in hopper 3, working body 6 can rotate with a different angular speed ω.

At a certain angular speed ω, the points *P*1, *P*2, *P*3 of working body 6 move with different tangential speeds *VT*, respectively, *VT*1, *VT*2, *VT*3. In the variant of engagement of belt 9 with pulley 13 of diameter *D*2, the tangential *VT* and linear *VL* speeds of point *P*2 coincide with each other, that is, $VT2 = VL2$. For this variant, the kinematic parameter λ is equal to one, $\lambda = 1$.

For points *P*1 and *P*3 of working body 6 and soil 4, there is a ratio of tangential speed *VT* and linear speed *VL*, respectively, $VT1 > VL1$, $VT3 < VL3$. That is, at point *P*1 there is a so-called accelerated rotation, and at point *P*3 there is a decelerated rotation, which corresponds to a different value of kinematic parameter λ. Thus, three modes of interaction of working body 6 with soil 4 are simulated:

– free rolling ($\lambda = 1$);
– accelerated rotation ($\lambda > 1$);
– retarded rotation ($\lambda < 1$).

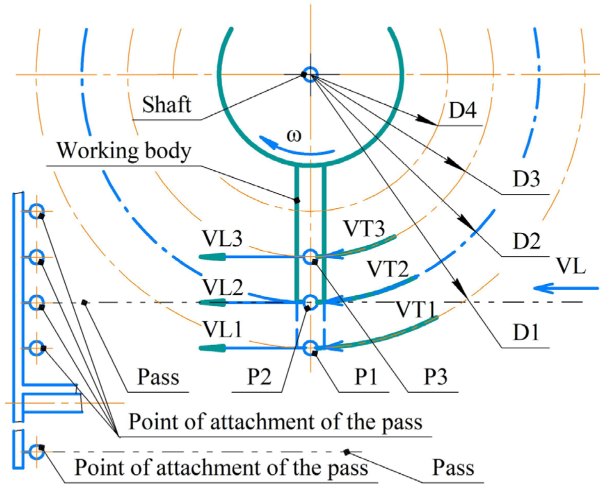

Fig. 9. Scheme of rotational speeds and linear movement of conditional points of the soil and the working body, where: *D*1, *D*2, *D*3, *D*4 — diameters of pulleys, *VL* — direction of linear speed of the bunker, ω — direction of angular speed, *VT*1, *VT*2, *VT*3 — tangential speed of points, *P*1, *P*2, *P*3 — points of the working body, *VL*1, *VL*2 *VL*3 — linear speed of the points

During the study under the free rolling mode, pass 9 is removed from the equipment. Hopper 3 is driven by drive 8, working body 6 rotates due to traction with soil 4.

Working bodies 6 of various types of rotary tools can be installed on shaft 5 of the equipment. For example, types of cutters, needle wheels, toothed rotary harrow, smooth disk, and others. During the experimental study, the shape and other parameters of the furrow in soil 4 are recorded.

Under the graphic modeling mode, the equipment is equipped with a graphic screen (Fig. 10).

During equipment operation under the mode of graphical modeling of the operation of rotary tillage tools, cart 3 with screen 4 is set in motion by drive 8 due to the attachment of belt 14 to cart 3 and its coupling with pulley 13.

Due to the kinematic connection of cart 3 and rotor 7 by means of belt 9, the longitudinal movement of cart 3 in the direction *L* leads to the forced rotation of rotor 7 in the direction ω. Installed on common shaft 5, drive rotor 7 and working body 6 rotate with the same angular movement. Thus, the rotation of working body 6 and the longitudinal movement *L* of screen 4 relative to working body 6 occur at the same time. The contact of screen 4 and the set of recorders 17 leads to the formation on screen 4 of an image of a set of lines n, *m*, *l*, *k*, respectively, the trajectories of the movement of individual points *p*1, *p*2, *p*3, *p*4 of working body 6 (Fig. 11).

The shape and parameters of the lines depend on the ratio of the longitudinal linear movement *L* of cart 3 and the angular movement φ of the points *p*1, *p*2, *p*3, *p*4 of the model of working body 6 relative to screen 4. The value of the mentioned ratio determines the value of kinematic parameter λ. The kinematic parameter λ is changed by rearranging belt 9 in engagement with pulleys 11 of different diameter *D*. Such rearranging with the same linear movement of cart 3 ensures different angular rotation of working body 6.

In the course of modeling, belt 9 can be rearranged at connection points 12, and accordingly engage with pulleys 11 of different diameters *D*1, *D*2, *D*3, *D*4. Working body 6 rotates with angular displacement φ and longitudinal displacement *L* according to different lengths of circles with diameters *D*1, *D*2, *D*3, *D*4. The image in Fig. 11 corresponds to the coupling of belt 9 with pulley 11 of diameter *D*3 and the rotation of the model of working body 6 by half a revolution, that is, the angular displacement $\varphi=\pi$.

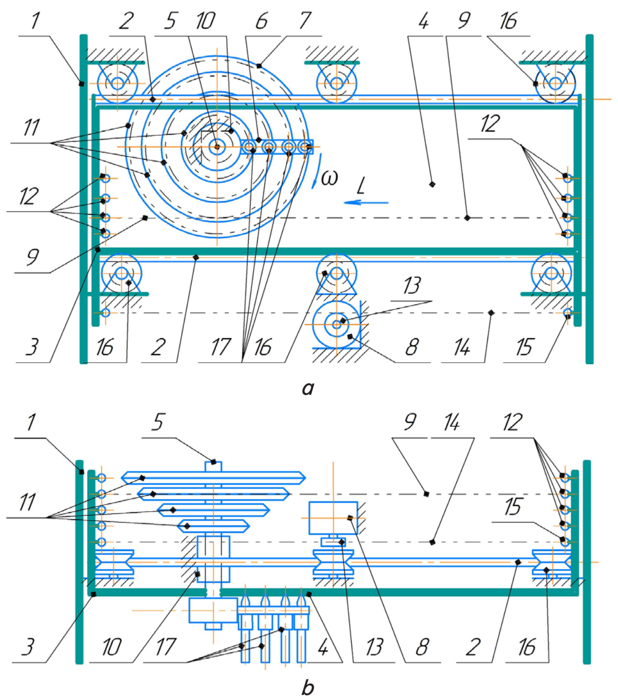

Fig. 10. Schematic view of the equipment under the graphical modeling mode: *a* – front view; *b* – top view; where: 1 – frame; 2 – guides; 3 – bunker; 4 – graphic screen; 5 – shaft; 6 – rotary tillage working body; 7 – leading rotor; 8 – drive; 9 – pass; 10 – support; 11 – pulleys; 12 – belt attachment points; 13 – pulley; 14 – pass; 15 – belt attachment points 14, 16 – support rollers; 17 – recorders

Points $p1$, $p2$ perform accelerated rotation ($\lambda>1$) and form trajectories recorded by recorders 17 on screen 4 as lines *n*, *m*.

Point $p3$ moves with the kinematic parameter $\lambda=1$, and forms a trajectory recorded by recorder 17 as line *l*.

Point $p4$ executes a retarded rotation ($\lambda<1$) and forms a trajectory recorded by recorder 17 on screen 4 as line *k*.

Thus, the structure of the designed equipment provides simulation at different ratios of longitudinal movement and rotation of the working body, i.e., at different values of the kinematic parameter λ set by the researcher in the modeling process.

Registration of the trajectories of movement of various points of the working body is provided by a set of recorders 17 installed on the model of working body 6 and their interaction with screen 4.

Simplification of modeling the movement of various points of the working body with different kinematic parameters of rotation of the rotary tillage tool is ensured by the ease of repositioning belt 9 in engagement with pulleys 11 of different diameter *D*.

Investigating the result of the action of the working body is facilitated by the possibility of visual observation and assessment of trajectories in the movement of the points of rotary working body 6 at different values of the kinematic parameter, simultaneously with the graphic registration of the trajectories on screen 4 by recorders 17. The graphic information obtained on screen 4 is suitable for further study without additional processing but, if necessary, it can be processed by quantitative methods. Such visualization is important both for the research scientist and in the educational process at educational institutions.

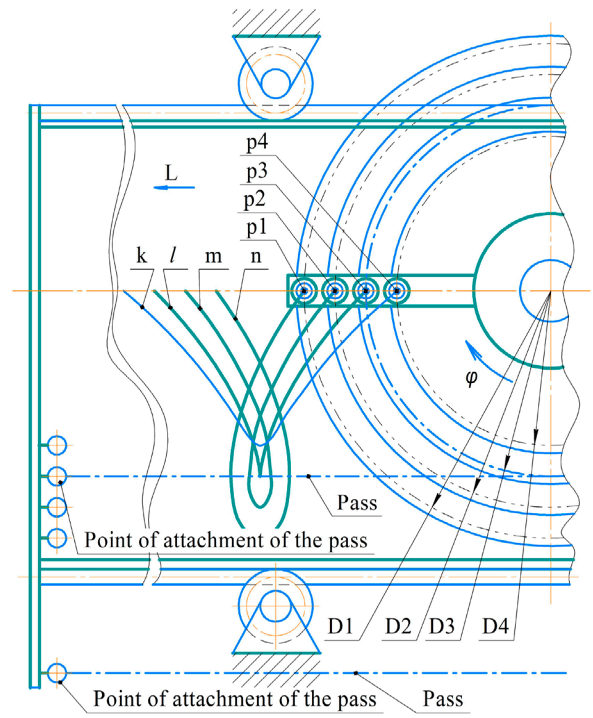

Fig. 11. Schematic representation of a piece of equipment with a graphic representation of the recorder trace on the screen; where: *p*1, *p*2, *p*3, *p*4 – points of the working body; *n*, *m*, *l*, *k* – trajectories of movement of points; *p*1, *p*2, *p*3, *p*4 – directions of rotation; *D*1, *D*2, *D*3, *D*4 – diameters of rotation of points; φ is the direction of angular movement; *L* is the direction of longitudinal movement

Studying the result of the action of the working body is facilitated by the fact that the rotary working body does not move along the frame and, accordingly, relative to the observer.

6. Discussion of results based on the design of an improved modular soil mini bin for studying rotary tools

In the current work, we have designed improved equipment for the experimental study of rotary tillage tools, which makes it possible to establish cause-and-effect relationships between the kinematic parameters of the working body and the parameters of the furrow formed in the soil. In comparison with known models of soil bines, the improved soil mini bin makes it possible to provide visibility by obtaining instant reflections of the movement of rotary working bodies, with the establishment of relationships between kinematic parameters and action on the soil.

In contrast to the equipment in [1], in which the work of passive working bodies is studied, our result (Fig. 8, 9) allows one to coordinate the longitudinal movement and rotation of the working body around the axis. This becomes possible thanks to the use of multi-stage mechanical transmissions.

When managing the work of a tillage working body (Fig. 1), it is important to coordinate the translational and rotational movement of the working body due to the operation of the gearbox mechanisms and gear wheels. It is also possible to ensure control over the work of the coordinating mechanism through computer equipment (Fig. 2) [3]. The presence of a chain transmission (Fig. 3) [6] makes it possible to ensure the smoothness of the mechanism, but at the same time, this mechanism is bulky and requires significant capital investment. The equipment proposed in this paper is simpler and the result of the experiment is directly visible.

In study [13], a device for graphic modeling and determination of geometric parameters of blades is proposed, taking into account the ratio of translational and rotational speeds of rotary tools. Owing to the features of the designed equipment, the possibilities of graphic (Fig. 10, 11) and physical (Fig. 8, 9) modeling are combined.

Study [14] theoretically analyzes volumetric deformations of soil under the action of a needle. Experiments in the soil bin demonstrated the process of piercing the soil with a needle and turning out a part of the soil from the depth of the layer (Fig. 5). The complex movement of the needle of the rotary working body includes its rotational component, that is, rotation relative to the axis of the rotary disk and rotation relative to some point located in the soil layer (Fig. 7). The derived general equation of the balance of needle in the process of rotation showed the existence of a force causing the soil to be ejected onto the field surface. Thus, in contrast to study [14], it has been shown that the needle has two functional parts that determine the action of the tool.

The structure of the proposed soil mini bin simplifies establishing the kinematic parameters of rotation of the rotary tillage tool while providing visibility. This facilitates the study of various trajectories of the movement of needles of the rotary working body and its impact on the soil both during experiments and in the educational process. The novelty of the proposed solutions is substantiated in the materials of two applications for inventions submitted to the patent office.

The limits of application of the proposed solutions are preliminary laboratory studies and the educational process at educational institutions. Limitations are related to the use of materials simulating the soil environment and the scaling effect of the working body model. During the experiment, as a result of interaction with the model of the working body, the model soil environment loses its monolithic nature, which requires the presence of a significant number of variable bunkers with the model soil environment.

The disadvantage is the need for quantitative processing of the acquired graphic information.

However, this simulation allows for a simplified and visual determination of the kinematic coefficient. Thus, our results are useful for improving existing research on rotary tillage tools and soil bines as means of these studies.

Further research should be focused on clarifying the kinematic characteristics of the working body of the rotary tillage tool, which arise in the process of soil sticking to the needles of the rotary working body. This will make it possible to carry out a quantitative assessment of the acting forces in the needle-soil system and to propose effective methods for reducing the phenomenon of soil ejection onto the field surface.

7. Conclusions

1. Soil bines, intended for studying rotary tillage tools, include mechanisms for coordinating the longitudinal movement and rotation of the working body. Such mechanisms are structurally designed as chain gears or gear sets for speed switching, which does not always ensure visibility and ease of setting kinematic parameters.
2. Investigating the operation of rotary needle tools under field and laboratory conditions has confirmed the determining influence of the kinematic coefficient on the nature of interaction with the soil and performance indicators of the rotary tool. Work under the mode of accelerated rotation leads to the negative phenomenon of the removal of soil particles to the surface of the field.
3. The theoretical analysis of the mechanism of interaction between the soil and the needle of the rotary tool has made it possible to explain the origin of the phenomenon of the removal of soil particles to the surface of the field, observed under laboratory and field conditions. The results of the analysis are the basis for the design of an improved modular soil mini bin for studying rotary tools.
4. An improved soil mini bin has been designed, which makes it possible, during research, to establish kinematic parameters and a graphic representation of the movement of rotary working bodies. The structure provides the possibility of adjusting the rotation speeds and linear movement of soil points and the working body at the researcher's choice. Owing to the small size and simplicity of the improved soil bin, its use in scientific research and the educational process is facilitated.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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