

SYNTHESIS OF TILLAGE MACHINES AND EXPERIMENTAL RESEARCH ON AGRO TECHNOLOGICAL INDICATORS FOR TILLAGE QUALITY

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Abstract. An important issue in the design of tillage machines is the search for improved machine designs to achieve high levels of productivity and quality of tillage operations, as well as the expansion of technological capabilities. One way of solving the problem of creating new machine designs for soil tillage is to implement progressive methods of searching for new technical solutions in the early stages of design preparation of production. This can be achieved by using morphological analysis, which in the fourth step involves the synthesis of object variants, which, based on the morphological matrix compiled, produces the full number of solutions. The article presents a synthesis of tillage mechanisms and machines using morphological analysis, which has led to improvements in the design of tillage machines. Hierarchical group synthesis using morphological analysis generated workable designs for alternative tillage machine variants. A method of structuring machine design for tillage and a method of their improvement based on the study of the properties of their structure elements, according to the theory of synthesis of hierarchical groups using morphological analysis, are proposed. To determine the agro-technological efficiency of the harrow with helical working tools, we conducted field tests of a rotary tool BDN-1,3 and an experimental sample of a harrow. The article presents the results of comparative tests of the disc harrow BDN-1,3 and the harrow with screw working tools. According to the results of studies, it was found that the density of the cultivated soil with the proposed helical working tools meets agricultural requirements and is $1.21 \text{ g}\cdot\text{cm}^{-3}$, which is 4.0% less than the variant with a disc harrow, and 36.3% less, compared to the agricultural background. According to the results of studies, it was found that the density of the cultivated soil with the proposed helical working tools, meets agricultural requirements and is $49.8 \text{ kN}\cdot\text{m}^{-2}$, which is 15.2% less compared to the disc harrow tillage, and 43.0% less compared with the background and the standard value. The volumetric crush coefficient of the proposed harrow variant is 51.4% lower than the background and the standard value, which varies between $1\text{...}2 \text{ N}\cdot\text{cm}^{-3}$ (for a plowed field).

Keywords: tillage machines, screw harrow, synthesis, quality of tillage.

Introduction

The current state of development of transport-technological agricultural machinery requires the search for new ways to improve the technological and operational parameters of working bodies, allowing to increase productivity and improve the quality of production processes and acquire new operational capabilities. An important issue in the design of tillage mechanisms is the search for their improved designs to achieve high productivity and quality of tillage operations, as well as the expansion of technological capabilities. Tillage machines, in which technological operations are performed by helical working tools, are characterized by simple design, ease of use, high technological reliability and efficiency [1-3]. Screw working elements of tillage machines are a component of comprehensive mechanization and automation of production.

High-performance work of departments and companies depends on the optimal selection of individual types of these devices and their design characteristics. Papers [4; 5] consider designs of helical tillage implements, in which helical surfaces of working tools are straight helicoids (augers), which cannot provide cutting of tillage tools into the soil, lifting of soil and its loosening, qualitative crushing of soil and its mixing with crop residues, levelling of surface layer of soil and its rolling, and axial movement. Based on the analysis of technological processes using screw conveying and technological mechanisms [6; 7], it can be argued that there is a significant field for further research, which is associated with the need for energy-saving, high-tech screw conveying and technological mechanisms that ensure effective performance of various functional operations.

The mechanical behaviour of agricultural soils has a large role in determining the performance of agricultural implements and the resulting soil tithes [8-10]. Seasonal wetting and drying of these soils induce drying stresses that alter the soil physical state and its properties. The performance of a simple vertical tine was investigated in a clay-loam soil subjected to three different levels of drying stress in a soil bin. Results showed that changes in most soil properties caused by tillage depended on drying stress. Soil bulk density decreased after tillage, although it was not significantly affected by drying stress. Soil shear strength, tine draft and aggregate size increased significantly with drying stress. Dried soils subjected to high drying stress broke in a less periodic manner and into larger masses than unwetted soil. Also, one of the ways to solve the problem of creating new designs of machines for tillage is the implementation of progressive methods of searching for new technical solutions at the early stages of design preparation of production. This can be achieved by using morphological analysis, which involves the synthesis of variants of the object.

The aim of the study is to improve the quality of performance of the technological process of tillage by synthesizing tillage machines by hierarchical grouping using morphological analysis to obtain new designs of their working bodies and their further field experimental studies.

Materials and methods

An important issue in the development, design and construction of machines for surface tillage is the search for their improved designs to achieve high performance and quality performance of the technological process, as well as to expand technological capabilities.

One of the ways to solve the problem of creating new designs of machines for tillage is the implementation of progressive methods of finding new technical solutions in the early stages of design preparation. This can be achieved by using morphological analysis, which in the fourth stage involves the synthesis of variants of the object, making it possible to obtain the full number of solutions on the basis of the composed morphological matrix [8]:

$$N = \prod_{j=1}^n K_j . \quad (1)$$

Nevertheless, the number of variants obtained as a result of this synthesis is very large, which makes it difficult to find the most rational solutions. Therefore, it is advisable to use the method of synthesis of hierarchical groups with the help of morphological analysis. It involves dividing a mechanical system into a certain number of hierarchical levels (usually 3), attributed to each individual structural element of the system. This method involves dividing the general problem into partial ones and searching for a rational solution in partial search areas, followed by their layout. So, to the first hierarchical level should be included those structural elements of the mechanical system, which have a direct impact on the quality and performance of the technological process (elements of the first order). To the second hierarchical level should be included design elements that help implement the functions of the corresponding mechanical system and have an indirect impact on the implementation of the technological process (elements of the second order). The third hierarchical level should include design elements that are necessary for the mechanical system, but do not affect the implementation of the technological process (elements of the third order). When laying out a mechanical system, these structural elements should be chosen primarily on the basis of economic feasibility (their price and cost of operation). Generation of alternatives by the proposed advanced method involves the generation of alternatives at individual hierarchical levels or within individual structural elements, starting from higher levels. At the next stage to the structural solutions selected at these levels a selection of possible alternatives for the structural elements from the lower levels is made, which provides the most rational structural solutions at a much lower cost of effort and time than when using the morphological analysis. When using the proposed method of synthesizing hierarchical groups with the help of morphological analysis, the number of variants will be determined by the formula:

$$N_{II} = \sum_{z=1}^l \prod_{i=1}^m K_i , \quad (2)$$

where z – hierarchical level;
 l – number of hierarchical levels;

K_i – alternative to the design feature of a hierarchical level subgroup element;
 m – number of design feature alternatives of the hierarchical level subgroup elements.

To carry out the synthesis of tillage machines, a morphological table was developed, in which, according to the proposed grouping, the following design elements should be assigned to the first hierarchical group: 1 – type of tillage machine; 5, 6, 7, 8 – types of working tools; to the second hierarchical group: 9 – working tool installation scheme; 10 – types of rollers; 11 – roller placement; to the third hierarchical group: 2 – type of tillage by depth; 3 – method of aggregation with tractor; 4 – working tool drive.

In structural synthesis and design of tillage machines, as well as their optimization, it is necessary to generate a set of layouts of these machines that correspond as much as possible to the functional purpose of the machine at a minimum cost. At the same time, for the performance of many functional operations using tillage machines, the determining factor is the tillage capacity of the working body, which is determined by the productivity, length and complexity of the technological process.

In order to facilitate the creation of original layouts of tillage mechanisms satisfying the performance of functional operations, the functions were coded: “A” – soil crumbling; “B” – crushing crop residues; “C” – mixing soil with crop residues; “D” – soil crumbling; “E” – soil loosening; “F” – “closing” moisture; “G” – weed cutting; “J” – embedding crop residues into the soil.

When several functional operations are performed by separate layouts, they are recorded with a combination of symbols, for example: crumbling soil and shredding crop residues – “AB”, shredding crop residues, mixing soil with crop residues and “closing” moisture – “BCF”, etc. The design contains several identical structural elements. It is advisable to write their number in the appropriate degree, for example: two working bodies – $(6_{12})^2$, and if there are several different structural elements of the same kind, it is reasonable to write them as follows: two troughs – $(1_7 \cup 1_9)$.

If we use the traditional method of morphological analysis in the synthesis of design alternatives, the number of alternatives will be

$$N = \prod_{j=1}^n K_j = 1935360$$

variants, which is 380 times more than when using the proposed method of synthesizing hierarchical groups using morphological analysis

$$N_{IT} = \sum_{z=1}^l \prod_{i=1}^m K_i = 5080.$$

This indicates the feasibility of using the proposed method, which greatly facilitates the selection of the best of the alternative.

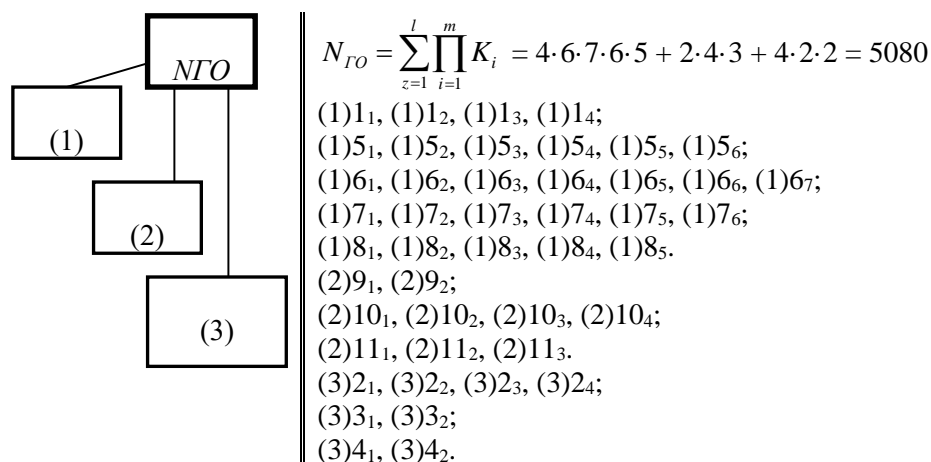


Fig. 1. Model of the mechanical system “Machine for soil processing”: (1) – first hierarchical level; (2) – second hierarchical level; (3) - third hierarchical level

As a result of generating design alternatives, at the first hierarchical level, the following alternatives are obtained (Fig. 2): (1)7₁ to (1)7₆ (Fig. 2).

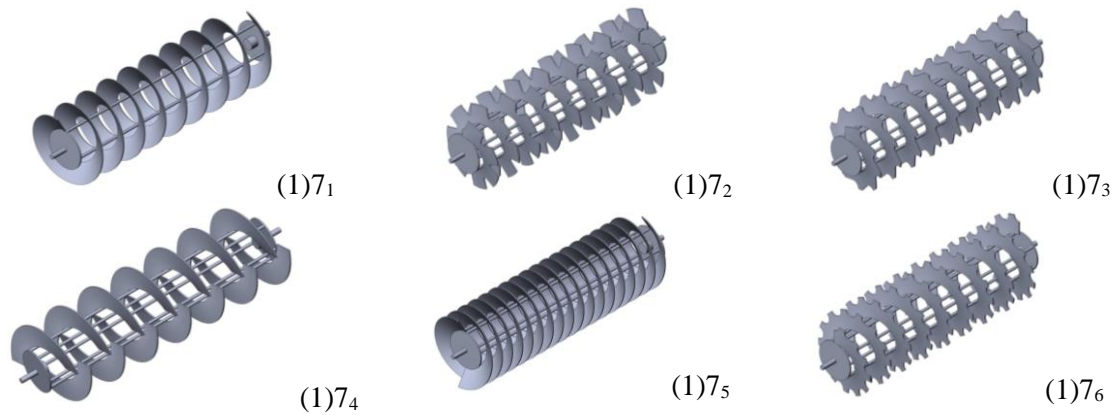


Fig. 2. **Design variants of helical working tools:** (1)7₁ – solid blade; (1)7₂ – screw with trapezoidal notches; (1)7₃ – screw with asymmetrical notches; (1)7₄ – propeller screw; (1)7₅ – fluted blade screw; (1)7₆ – round cut screw

To determine the agro-technological indicators of the quality of tillage with a harrow with a helical working body, field experimental studies of a prototype harrow were conducted, the general view of which is shown in Fig. 3.



Fig. 3. **General view of the screw harrow**

Soil cultivation quality indicators were determined for three variants: basic – agrofon: stubble of cereal crops; comparative, as a basic variant of cultivation – was performed by a disk harrow BDN-1,3; a comparable variant – tillage by a tillage tool with the proposed screw working tools (SWT). Type of soil, on which field experimental studies were conducted – gray ashy soil.

Indicators of the structural state of the soil were evaluated by the coefficient of structurality K

$$K = \frac{A_A}{B_A}, \quad (3)$$

where A_A – sum of macro aggregates with dimensions 0.25...10.0 mm;

B_A – sum of aggregates with size < 0.25 mm and lump with size > 10 mm.

A_A and B_A were determined by the method of fractionation of soil samples in the air-dry state at the installation for determining the structural and aggregate composition of the soil by dividing it into fractions: > 10; 10...7; 7...5; 5...3; 3...2; 2...1; 1...0.5; 0.5...0.25; < 0.25 mm. With the help of a hardness tester, the hardness of the soil P and the volumetric shrinkage coefficient q were determined:

$$P = \frac{cy}{A_s}, \quad (4)$$

where c – spring stiffness, $N \cdot m^{-1}$;

y – middle ordinate of the chart at the selected depth, m;

A_s – cross-sectional area of the plunger, m^2 .

$$q = \frac{P_g}{V} = \frac{cY_A}{A_s \lambda}, \quad (5)$$

where P_g – resistance of the soil, which corresponds to the limit of proportionality, N;
 V – volume of compacted soil that corresponds to the limit of proportionality, cm³;
 Y_A – ordinate corresponding to the limit of proportionality, m;
 λ – deformation corresponding to the limit of proportionality, m.

The absolute humidity W of the soil was determined by the formula:

$$W = \frac{a_b}{b_g} \cdot 100\% , \quad (6)$$

where a_b – mass of moisture evaporated, g;
 b_g – mass of a completely dry soil sample, g.

The density of the soil was determined by the formula:

$$d_v = \frac{M_g}{V_g} , \quad (7)$$

where M_g – mass of completely dry soil in a certain volume of the studied sample, g;
 V_g – volume of the studied sample, cm³.

Profiling of the surface of the treated soil and the bottom of the furrow was performed using a coordinate rail by the method of graphic copying of the relief. The indicator of the distribution of plant residues according to the depth of cultivation in kg was determined by the formula:

$$k_g = \frac{M_{5...10}}{M_n} \cdot 100\% , \quad (8)$$

where M_n – mass of plant remains on the surface of the field before the passage of the tillage tool;
 $M_{5...10}$ – mass of plant remains in the soil layer of 5...10 cm after the passage of the tool.

The distribution of plant remains in the soil layers of 0...5cm, 5...10cm and 10...12cm was determined by washing a soil monolith with an area of 0.1 m² of the appropriate thickness through a sieve with a hole diameter of 3.1 mm and 0.25 mm.

Results and discussion

As a result of the synthesis of hierarchical groups, using morphological analysis, workable designs of alternative variants of machines for tillage were generated, one of which is shown in Fig. 4.

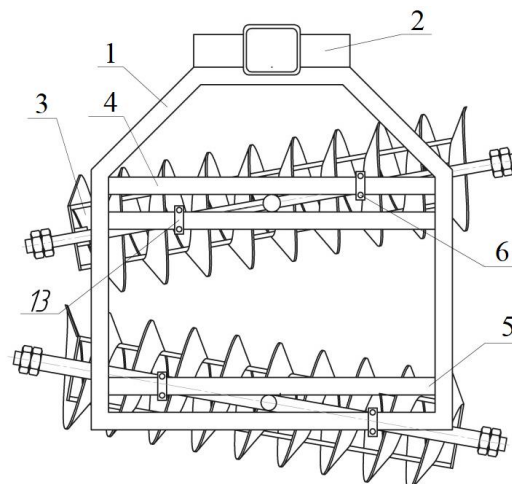


Fig. 4. Synthesized design of the machine for tillage with helical working tools:
 1 – frame; 2 – automatic coupling; 3 – batteries of helical working tools; 4, 5 – guides;
 6 – fixing elements

The results of comparative field experimental studies are presented in Table 1.

Table 1

Results of comparative field experimental studies

Quality of tillage indicators	Variant agro background	Variant disk harrow	Variant screw working tools harrow
Value of the soil texture coefficient	0.94	1.49	1.68
Surface area of the field with full embedding of crop residues into the soil, %	–	73	81
Value of resistance to soil crushing (hardness), $\text{kN}\cdot\text{m}^{-2}$	87.4	58.7	49.8
Value of the coefficient of volumetric soil compression, $\text{N}\cdot\text{cm}^{-3}$	1.4	0.7	0.7
Absolute soil humidity, %	16.0	15.3	15.6
Soil density, $\text{g}\cdot\text{cm}^{-3}$	1.90	1.26	1.21
Micro-relief of the field surface, cm	–	0...5.3	0...5.2

According to the results of the field experiments it was found that the absolute soil moisture in the layer of 0...12 cm was higher by 1.9% when cultivated with a soil tillage machine with screw working tools compared to disc tools and it corresponded to agricultural requirements. The density of the cultivated soil with the proposed helical working tools meets the agricultural requirements and is $1.21 \text{ g}\cdot\text{cm}^{-3}$, which is 4.0% less than the variant with a disc harrow and 36.3% less compared to the agricultural background (Fig. 5). It was found that during tillage with a harrow with a helical working tool, the resistance to soil crushing is minimal and amounts to $49.8 \text{ kN}\cdot\text{m}^{-2}$, which is less by 15.2% compared to tillage with a disc harrow and 43.0% less compared to the background. Volumetric soil compression coefficient of the proposed variant is 51.4% less compared to the background (Fig. 6) and the standard value.

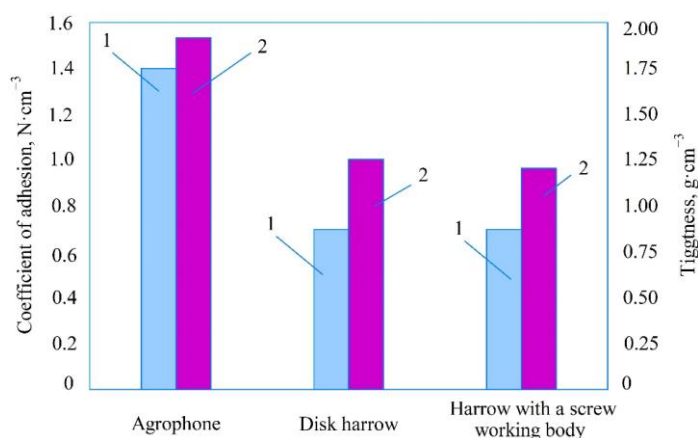


Fig. 5. Indicators of soil tillage quality: 1 – volumetric compression coefficient; 2 – density

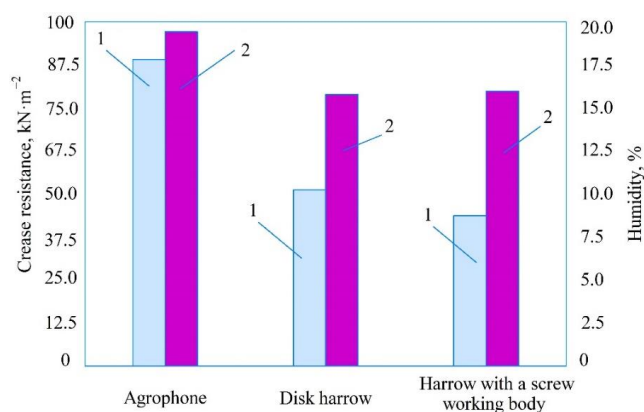


Fig. 6. Indicators of soil tillage quality: 1 – hardness; 2 – moisture

Statistical indicators of the quality of tillage are shown in Table 2.

Table 2

Statistical indicators of the quality of tillage

Indicator	Characteristics of the indicator	Variant agro background	Variant disk harrow	Variant screw working tools harrow
Absolute soil moisture, %	Average value	16.0	15.3	15.6
	Dispersion D	0.0043	0.0059	0.0002
	Mean square deviation σ	0.066	0.077	0.0153
	Coefficient of variation v , %	0.35	0.5	0.1
Soil density, $\text{g}\cdot\text{cm}^3$	Average value	1.9	1.26	1.21
	Dispersion D	0.02	0.001	0.001
	Mean square deviation σ	1.144	0.033	0.032
	Coefficient of variation v , %	7.67	2.62	2.64
Soil hardness, $\text{kN}\cdot\text{m}^2$	Average value	87.4	58.7	49.8
	Dispersion D	1.52	1.38	1.21
	Mean square deviation σ	1.23	1.17	1.10
	Coefficient of variation v , %	1.41	1.99	2.2
Indicator of earning plant residues, %	Average value	-	73	81
	Dispersion D	-	1.33	1.42
	Mean square deviation σ	-	1.15	1.19
	Coefficient of variation v , %	-	1.58	1.47
Coefficient structure	Average value	0.941	1.493	1.679
	Dispersion D	0.018	0.02	0.024
	Mean square deviation σ	0.134	0.141	0.155
	Coefficient of variation v , %	14.26	9.34	9.22

The proposed rotary tillage tools meet the requirements for sowing of agricultural crops without performing additional technological transitions.

Analysis of the results of field experimental studies on the quality indicators of tillage allows us to conclude that there is a positive impact on the structural and agro-technological state of the tillage machine with a screw working tool compared to the standard rotary working elements of the disc harrow.

Conclusions

A method of structuring of tillage machine designs and a method of their improvement based on the study of the properties of the elements of their structure, according to the theory of synthesis of hierarchical groups by means of morphological analysis, are proposed. Workable designs of alternative machine designs for tillage were generated.

To determine the agro-technological efficiency of the harrow with helical working tools, we conducted field tests of the rotary tool BDN-1,3 and an experimental sample of harrow. According to the results of studies, it was found that the density of the cultivated soil with the proposed helical working tools meets agricultural requirements and is $1.21 \text{ g}\cdot\text{cm}^{-3}$, which is 4.0% less than the variant with a disc harrow, and 36.3% less, compared to the agricultural background. It was found that the density of the cultivated soil with the proposed helical working tools, meets agricultural requirements and is $49.8 \text{ kN}\cdot\text{m}^{-2}$, which is 15.2% less compared to disc harrow tillage, and 43.0% less compared with the background and the standard value. The volumetric crush coefficient of the proposed harrow variant is 51.4% lower than the background and the standard value, which varies between $1\text{...}2 \text{ N}\cdot\text{cm}^{-3}$ (for a plowed field).

Author contributions

All the authors have contributed equally to creation of this article.

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