Assessment of self-adjustment of tillage working bodies to soil conditions

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Abstract. Assessment of self-adjustment, that is, automatically adjusting parameters of tillage working bodies as a result of soil exposure, is an urgent task, since it is associated with the problem of developing energy-efficient tillage units. The purpose of the research is to assess the self-adjustment of typical and dynamic tillage working bodies to specific soil conditions during their functioning. The objects of research are a dynamic tillage working body with an energy-storage transmitting device and a typical tillage working body for continuous surface treatment of various soil types. The subject of research was the indicators of self-adjustment of tillage working bodies to soil conditions. During the research, methods of mathematical modeling, strain measurement of tillage working bodies, analysis and generalization of experimental data were used. The scientific novelty of the work is represented by the selected criteria for assessing the self-adjustment of working bodies and the patterns of their change from the movement speed. As criteria for assessing the self-adjustment of tillage working bodies, the following were selected: the coefficient of terradynamic resistance, the specific traction resistance per unit of its active frontal area, the number of degrees of freedom of the tillage working body and indicators for assessing the tillage quality. Based on the proposed evaluation criteria, it was experimentally established that the dynamic tillage working body developed by the authors with an energy-storage transmitting device is more efficient and adapted to changing soil conditions in comparison with a typical working body, which provides a reduction in traction resistance by an average of 20% and an increase in the degree of soil loosening by an average of 8.4-8.8% compared with typical working bodies.

1. Introduction
The development of energy-efficient working bodies and machines is an urgent task. The energy efficiency of tillage machines largely depends on the design and technological parameters and their movement speed. At the same time, working bodies and machines must ensure high quality of processing in accordance with agrotechnical requirements.

To substantiate the research strategy to improve the efficiency of tillage working bodies, we provide a brief analysis of the literature.

Studies [1] have established that the increase in soil resistance with an increase in speed is not infinite and does not exceed 2.0-2.5 times. At the same time, the increase in soil strength with an increase in the rate of deformation is explained by the transition from a plastic state to a brittle one.

The authors of the work [2] proposed a refined dependence for determining the traction resistance of chisel plows and the values of the empirical coefficients included in it. It was found that, on
average, the calculated values of the reduced traction resistance of chisel plows obtained using the proposed formula differ from the experimental data by no more than 2.5%.

The dependences of the load change on the machine-tractor unit on the soil hardness have also been investigated [3].

The value of the cutting resistance of the soil layer depends on the thickness of the coulter edge and changes in accordance with the change in soil hardness. Humidity has the greatest effect on soil hardness and cutting resistance. Increased soil moisture leads to a decrease in resistance during plowing. The optimal moisture content of viscous clay soil when plowing at a rate of 2.0-2.5 m/s is 18-24% [4].

Studies [5] have established that the traction resistance of the chisel working body, made in the form of a rectilinear vertical rack, in the lower part of which a flat-shaped chisel is fixed, varies depending on the scheme of its interaction with the soil. Formulas are proposed for calculating the traction resistance of the chisel working body depending on the schemes of its interaction with the soil and movement speed.

The influence of the shape of the blades of serial and experimental disks (round disks with a diameter of 0.40 and 0.45 m and hexagonal disks with an area equal to round disks) on the energy performance of their work has been established. It was revealed that the traction resistance of hexagonal disks is 21.2-21.3% lower than round ones [6].

The study of the operation of a curved working body for layer-by-layer tillage showed that its energy efficiency compared to a typical working body. It has been found that the greatest influence on the growth of traction resistance is exerted by an increase in the angle of chisel crushing [7].

The improvement of the plane-cutting working body makes it possible to reduce the energy intensity of the tillage process, retaining 80% of the stubble, which ensures moisture retention in the arid zone of agriculture [8].

It is established that the magnitude of the traction resistance of the shovel depends on the nature of the interaction of the blade and the soil. Sliding cutting is characterized by the fact that the friction force reaches a maximum but is not able to balance the component of normal pressure, and therefore the sliding of soil aggregates along the blade is observed [9].

In the work [10], the general laws of the impact of working bodies on the soil are described, the soil resistivity is selected as a complex indicator for calculating the soil reaction to the working body. The study of the para ploughing process showed that the process of soil elastic deformation and the process of crack development are separated in time and the resistance has a periodic component. The emerging pulsating stress components in the soil make it possible to use the effect of self-oscillations in the structures of working bodies, which provides a reduction in traction resistance and an improvement in the quality of processing [11].

The paper [12] outlines the fundamental possibility of changing the soil hardness by developing combined tillage working bodies with five degrees of freedom, continuous change of approach angles, cutting of the soil and the shape of the working body.

In the developed methodology for substantiating the design scheme of the duckfoot shovel for better adaptation of the machine system to operating conditions, it is proposed to improve the flowability of the working surfaces and the cutting perimeter based on the use of bionics methods [13].

In the work [14] a brief analysis of vibrating tillage machines is provided. The authors of this work noted that the role of vibration in the analyzed vibrating tillage machines is to improve the quality of tillage, and not to reduce their traction resistance.

At the University of South Australia, a deep tiller was developed, which had two working oscillating (vibrating) teeth. The authors of the work investigated the influence of the oscillation angle of the teeth on the tillage machine performance. Research results have shown that negative oscillation angles can reduce the traction resistance by up to 50% [15].

The authors' study [16] reflects the results of evaluating the traction force of tillage machines, a model for calculating the traction force and the required power of a disk plow is developed.
The paper [17] presents the results of studies to determine the energy consumption for tillage. It is established that large ranges of tractor traction, fuel consumption and tractor efficiency indicate significant energy savings that can be achieved when choosing energy-efficient tillage machines, as well as the correct alignment of tractor dimensions and operating parameters of tillage tools.

The authors of the article [18] identified the main disadvantages of cultivators with serial working bodies on soils affected by wind erosion. Based on the conducted research, a new design of the cultivator's working body is proposed, comparative laboratory studies of the cultivator shovels are carried out, the scheme of the new working body for compliance with the basic requirements of soil-protective, environmentally safe, resource-saving agriculture is substantiated.

Along with the deepening and expansion of the already established theory of tillage, the historical development of science leads to the emergence of new areas of research on this problem. A brief analysis of the research allows to conclude that the development of tillage working bodies using new design principles can ensure an increase in their self-adaptability to soil conditions, and therefore, energy efficiency and quality of their functioning.

For this purpose, dynamic tillage working bodies were developed at the Institute of Agroengineering and Environmental Problems of Agricultural Production - a branch of the FSBSI FSAC VIM and their comparative experimental studies with standard working bodies were carried out [19, 20, 21].

2. Materials and methods

During the research, mathematical modeling methods were used based on the study of physical patterns occurring in the process of interaction of working bodies with the soil; experimental studies of tillage working bodies, analysis, and generalization of experimental data.

The common purpose of the research is to assess the self-adjustment of typical and dynamic tillage working bodies to specific soil conditions during their functioning.

The objects of research are a dynamic tillage working body with an energy-storage transmitting device and a typical tillage working body for continuous surface treatment of various soil types (Figure 1).

![a) b) Figure 1. Dynamic with energy-storage transmitting device (ESTD) (a) and standard (b) tillage working bodies.](image)
A comparative energy assessment of typical and dynamic tillage working bodies was carried out using the IIK-IAEP measuring and information complex, consisting of a mounted installation with strain gauge trolleys and the IP-264 RosNIITiM measuring and information system (Figure 2).

Experimental studies were conducted on the territory of the experimental production base of the Institute under the following conditions:
- soil type - sod-medium podzolic; soil - medium loam on a moraine loam; field relief, deg – 1-2;
- field surface ridge, cm - 3-4; soil hardness before processing in a layer of 10-20 cm - 1.4 MPa; depth of tillage 12 cm; average soil moisture in a layer of 0-10 cm - 18%, in a layer of 10-20 cm - 20%.

The experimental data obtained were processed according to the method of statistical processing of empirical data described in the work [22].

The correlation coefficients of the considered indicators for assessing the self-adjustment of tillage working bodies to the soil conditions of their functioning varied within the range of $R=0.932-0.985$.

3. Results and discussion
Theoretical and experimental studies conducted by us in 2017-2020 have shown that dynamic tillage working bodies, depending on the hardness and density of the soil, allow automatically to reduce the frontal projection area, cutting and crumbling angles within certain limits set by the design.

The use of energy-storage transmitting devices in the structures of tillage working bodies ensures the formation of inertia and kinetic energy by high-frequency dynamic impact on the treated soil layer, which in turn suggests an additional reduction in traction resistance and an increase in the degree of soil loosening compared to existing types of working bodies.

The reduction of the frontal projection area, cutting and crumbling angles in dynamic working bodies will be short, since soil hardness (density) in the context of the cultivated fields has a random character.

Dynamic tillage working bodies can automatically adjust the cutting angle, the area of the frontal projection and other design parameters depending on soil resistance, within the specified permissible limits and thereby adapt better to soil conditions. The ability to self-adjust allows them to improve the efficiency and quality of tillage machines compared to domestic and foreign analogues.
Analysis of the design features of tillage working bodies has shown that as criteria for assessing their self-adaptability, it is necessary to choose the most significant indicators characterizing the properties of their dynamism.

As one of the significant indicators for assessing the self-adaptability of tillage working bodies to soil conditions, it is proposed to use the coefficient of terradynamic resistance, considering the streamlining of working bodies. It also depends on the shape, surface quality of the working body and soil hardness (density).

This coefficient is one of the main indicators by which it is possible to assess the ability of tillage working bodies to self-adjust to soil conditions.

The coefficient of terradynamic resistance of the tillage working body of the machine can be expressed by the formula:

\[ K_t = \frac{2R_{ro}}{T_s \cdot V_w^2 \cdot F_{ro}}, \]

where 
- \( R_{ro} \) is the traction resistance of the tillage working body, N; 
- \( T_s \) - soil hardness, kg/cm²; 
- \( V_w \) - movement speed of tillage working body, m/s; 
- \( T_s \cdot V_w^2 \) – dynamic pressure (or pressure velocity) on the tillage working body is a kinetic energy value having a pressure dimension, kg/cm²; 
- \( F_{ro} \) - active area of the frontal projection of the tillage working body at a given processing depth, cm².

Another significant indicator for assessing the self-adjustment of tillage working body is the specific traction resistance \( R_{ud} \) per unit of its active frontal area, which can be determined by the formula:

\[ R_{ud} = \frac{R_{ro}}{F_{ro}}, \text{ kN/m}^2 \]

It should be noted that the active frontal area of the \( F_{ro} \) tillage working body depends on its design parameters and tillage depth.

The third indicator of self-adjustment assessment is the number of \( m_{df} \) degrees of freedom of the tillage working body. The number of degrees of freedom of the tillage working body can be determined by the Chebyshev-Grabler-Kutzbach formula:

\[ m_{df} = 3(n - 1) - 2f, \]

where \( m_{df} \) is the number of degrees of freedom of the tillage working body; 
- \( n \) is the number of links of the mechanism (including one fixed link - the base); 
- \( f \) is the number of kinematic pairs with one degree of freedom.

The degree of dynamism of the tillage working body depends on the number of degrees of its freedom. That is, the greater the number of degrees of freedom, the higher the degree of dynamism (self-adjustment) of the working body to soil conditions.

After the considered indicators, the criteria for assessing the self-adjustment of tillage working bodies can be formulated as follows:

- minimum coefficient of terradynamic resistance \( K_t \to min \); 
- minimum specific traction resistance \( R_{ud} \to min \) per unit of active frontal area; 
- maximum number of \( m_{df} \to max \) degrees of freedom.

Unilateral tolerant (permissible) limits for changing the criteria for assessing the self-adjustment of working bodies to soil conditions are established in accordance with agrotechnical indicators (or criteria) for assessing the quality of tillage.
As criteria for assessing the quality of surface tillage, it is necessary to consider such quality assessment indicators as the cultivation depth, the degree of soil loosening, the degree of weed destruction and the levelling of the field after tillage.

In general, considering the above, it can be concluded that it is advisable to assess the self-adaptability of tillage working bodies to soil conditions according to a system of criteria that include energy, quality and structural and technological indicators.

The final opinion on the expediency of choosing a soil-cultivating working body that is effective in terms of the degree of self-adjustment can only be formed because of evaluation according to the above criteria.

We will move to the presentation of the analysis of the research results. In the process of tillage, generalization and analysis of experimental data, indicators for assessing the self-adjustment of tillage working bodies were determined.

Table 1 shows the values of the coefficient of terradynamic resistance, specific traction resistance per unit of the active frontal area of the typical (Figure 1b) and dynamic (Figure 1a) tillage working bodies, depending on the speed of their movement, calculated by expressions (1), (2) and (3).

Table 1. Values of the coefficient of terradynamic resistance, specific traction resistance per unit of active frontal area of typical and dynamic tillage working bodies, depending on the speed of their movement.

| Name of tillage working body | Movement speed of tillage working body $V_w$, m/s (km/h) | Coefficient of terradynamic resistance $K_t$ | $R_{ud}$, kN/m² (kg/cm²) |
|-----------------------------|--------------------------------------------------------|---------------------------------------------|--------------------------|
| Typical tillage working body | 2.15 (7.74) | 0.194 | 62.78 (0.6278) |
|                            | 2.72 (9.80) | 0.159 | 82.54 (0.8254) |
|                            | 3.16 (11.4) | 0.130 | 90.84 (0.9084) |
| Dynamic tillage working body | 2.15 (7.74) | 0.160 | 42.24 (0.4224) |
|                            | 2.72 (9.80) | 0.126 | 53.01 (0.5301) |
|                            | 3.16 (11.4) | 0.097 | 55.37 (0.5537) |

Active frontal area of the tillage working body at a depth of 12 cm:
- typical: $F_{ro} = 137.96$ cm² or 0.013796 m².
- dynamic: $F_{ro} = 193.05$ cm² or 0.019305 m².

Figure 3 shows the graphical dependences of the coefficient of terradynamic resistance of tillage working bodies on the speed of their movement at a fixed tillage depth h=12 cm.
Figure 3. Dependences of the coefficient of terradynamic resistance of tillage working bodies: 1 – typical; 2 – dynamic with an energy-storage transmitting device.

It was found that with an increase in the speed of movement of the typical working body (Figure 1b) from 2.15 to 3.16 m/s, the coefficient of terradynamic resistance decreases from 0.194 to 0.130. Within these limits of the change in the speed of movement of the dynamic tillage working body, the coefficient $K_t$ decreases from 0.160 to 0.097.

As experimental data show, the values of the coefficient of the $K_t$ dynamic tillage working body are 17.53-25.40% less than that of the typical working body. This suggests that in terms of the degree of self-adjustment, the typical working body is inferior to the dynamic working body.

The regularities of changes in the coefficient of $K_t$ tillage working bodies from the speed of their movement, which are described by empirical dependencies, are revealed:

- typical tillage working body:
  \[ K_t = -0.00446V_w^2 - 0.03968V_w + 0.29993; \]  
  \[ K_t = -0.00620V_w^2 - 0.02946V_w + 0.25200. \]  

Empirical dependences (4) and (5) are valid in the velocity range $V_w = 2.15 - 3.16$ m/s.

Figure 4 shows the graphical dependences of the resistivity per unit of the active frontal area of dynamic and typical tillage working bodies on the speed of their movement at a fixed tillage depth $h = 12$ cm.
The regularities of changes in the resistivity per unit of the active frontal area of tillage working bodies are revealed, which are described by the following empirical dependencies:

- typical tillage working body:
  \[ R_{ud}^T = -15.64656V_w^2 + 110.86544V_w - 103.25444; \]  \[ (6) \]
  \[ R_{ud}^T = -13.39713V_w^2 + 84.13876V_w - 76.73010. \]  \[ (7) \]

Empirical dependences (6) and (7) are valid in the velocity range \( V_w = 2.15 - 3.16 \) m/s.

Analysis of experimental data (Table 1 and Figure 4) shows that with an increase in the speed of \( V_w \) movement of tillage working bodies, there is an increase in the resistivity \( R_{ud}^T \) per unit of the active frontal area of dynamic and typical tillage working bodies.

When the speed increases \( V_w \) from 2.15 to 3.16 m/s the resistivity \( R_{ud}^T \) of typical tillage working body increases from 62.78 kN/m² (or 0.6278 kg/cm²) to 90.84 kN/m² (0.9084 kg/cm²), and the resistivity \( R_{ud}^D \) of the dynamic tillage working body increases from 42.24 kN/m² (0.4224 kg/cm²) to 55.37 kN/m² (0.5537 kg/cm²). Experimental data indicate that the resistivity of the \( R_{ud}^D \) dynamic tillage working body is 32.72-39.05% less than that of the typical working body.

The values \( R_{ud}^D \) show that the dynamic tillage working body is structurally more perfect than the typical working body.

During the operation of the dynamic tillage working body at high speeds, as the results of experiments have shown, the inertia force and kinetic energy are formed by a high-frequency dynamic impact on the tillable soil layer.

As a result, the traction resistance is reduced by an average of 20% compared to typical working bodies.

Based on the formula (3) the number of degrees of freedom for the typical tillage working body \( m_{df} = 1 \), and dynamic one \( m_{df} = 3 \).

Indicators of tillage quality: the depth and degree of soil loosening, the degree of destruction of weeds and the levelling of the field after tillage also characterize the degree of perfection of the working bodies and their self-adjustment to soil conditions.
As an example, let's consider the patterns of changes in tillage depth and the degree of soil crumbling.

Figure 5 shows the graphical dependences of changes in tillage depth $h_s$ on the speed of movement of the studied tillage working bodies.

The regularities of changes in tillage depth of tillage working bodies from the speed of their movement, which are described by the following empirical dependencies, are established:

- dynamic tillage working body:
  \[ h_s = 0.23963V_w^2 - 1.88629V_w + 15.18784; \]  
  \[ (9) \]

- typical tillage working body:
  \[ h_s = -0.12435V_w^2 + 0.02666V_w + 12.69751. \]  
  \[ (10) \]

Experimental data show that with an increase in the speed of movement of tillage working bodies, the tillage depth tends to decrease, which is typical for all tillage working bodies and machines.

With increasing speed $V_w$ from 2.15 to 3.16 m/s, the tillage depth by the dynamic working body (curve 1, Figure 5) decreased from 12.24 cm to 11.62 cm, that is, by 0.62 cm, which fits within the permissible limits of changing this parameter set by agrotechnical requirements.

Within the specified limits of the change in the speed of movement of the typical working body, the tillage depth decreased from 12.18 cm to 11.54 (curve 2, Figure 5) cm, that is, by 0.64 cm, which also does not exceed the tolerance for changing the tillage depth.

Considering the above, it can be concluded that typical and dynamic tillage working bodies ensure the stability of the tillage depth within the permissible limits specified by agrotechnical requirements.

Figure 6 shows graphical dependences of the degree of soil crumbling by $K_o$ tillage working bodies on the speed of their movement.
Figure 6. Dependences of the degree of soil crumbling on the speed of movement of tillage working bodies: 1 - dynamic; 2 - typical.

The regularities of changes in the degree of soil crumbling by tillage working bodies from the speed of their movement are established, which are described by the following empirical dependencies:

- dynamic tillage working body:

\[ K_o = -2.94898V_w^2 + 21.20363V_w + 59.74384; \]  \hspace{1cm} (11)

- typical tillage working body:

\[ K_o = 4.52414V_w^2 - 18.87465V_w + 102.96768. \]  \hspace{1cm} (12)

Empirical dependences (11) and (12) are valid in the range of speeds of movement of tillage working bodies \( V_w = 2.15 \text{ to } 3.16 \text{ m/s} \).

When the speed changes \( V_w \) from 2.15 to 3.16 m/s, the degree of soil crumbling by the dynamic tillage working body increases from 91.7 to 97.3%. At given speeds, the degree of crumbling by the typical working body increases from 83.3 to 88.5%.

The use of the dynamic tillage working body in comparison with a typical working body provides an increase in the degree of soil crumbling by 8.4-8.8%.

In conclusion, it can be noted that the dynamic tillage working body, in comparison with the typical working body, has many degrees of freedom, relatively lower values of resistivity per unit of active frontal area and the coefficient of terradynamic resistance, ensures high quality of tillage.

The properties of dynamism and a high degree of self-adjustment allow the dynamic working body to function effectively at increased speeds, which is the basis for increasing productivity and reducing the energy intensity of tillage.

4. Conclusion
A brief analysis of studies on the assessment of the influence of soil characteristics on traction resistance and performance indicators of working bodies, substantiation of the relevance of the research direction is given.

The criteria for assessing the self-adaptability of tillage working bodies to soil conditions are substantiated.

Graphical dependences are constructed and patterns of changes in the indicators of self-adjustment of tillage working bodies from the speed of their movement are revealed.
It has been experimentally established that the dynamic tillage working body with the energy-storage transmitting device developed in the IAEP branch of the FSBSI FSAC VIM is more efficient and adapted to changing soil conditions in comparison with the typical tillage working body.

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