Regularities of deformation of the bending of elastic elements and the parameters of vibrations of a dynamic tillage operating part

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Abstract. Revealing the regularities of bending deformation of elastic elements and vibration parameters of dynamic tillage operating parts is an urgent task, as it ensures the development of new innovative energy-efficient operating parts. The aim of the study is to identify the patterns of deformation of elastic elements and oscillations of the wing of a dynamic tillage part of the operating part. The object of research is a dynamic arrow-shaped tillage operating part with a working width of 330 mm for surface tillage to a depth of 14 cm. The subject of research is the regularities of the bending deformation of elastic elements and the vibration parameters of dynamic tillage operating parts. The research was carried out using methods of mathematical modeling based on the study of physical laws that occur during soil cultivation; experimental studies on energy assessment of tillage operating part, analysis and generalization of experimental data. The scientific novelty of the work is represented by empirical dependencies for determining the value of the deflection of an elastic element, displacement of the extreme point of the wing and the amplitude of oscillations of the extreme point of the wing of a dynamic tillage operating part. The graphical and empirical dependences of the deflection value of the elastic element, the movement of the extreme point of the wing and the amplitude of its oscillations from the bending moment, the speed of movement and the load of the dynamic tillage operating part are given. It was found that within the range of bending moment variation from 36.2 to 95.35 N∙m, the deflection of the elastic element ranges from 5.5 to 15.8 mm. At the same time, within the limits of the change in the speed of movement of the dynamic tillage worker from 1.94 to 3.61 m/s, the average value of the movement of the wing extreme point increases from 11.55 mm to 14.75 mm. The relationship of the parameters considered above on the bending moment, load and speed of movement of a dynamic tillage operating part is described by empirical dependencies with the coefficient of determination $R^2 = 0.67 - 0.85$. The error of the sample mean $S_y$ of the investigated parameters of the dynamic operating part varied within 0.039 – 0.136.

1. Introduction

Urgent problem. Scientists are developing various methods to ensure the effectiveness of soil cultivation technology and related technical means. As an example, we can cite studies [1-2], which are aimed at the use of pulsating compressed air to improve the quality of soil cultivation.

Also, transformable operating parts have been developed for moldboard-free tillage based on the principles of transformation, carried out by block-modular construction and completing them with various operating parts using a scientifically grounded combination of replaceable elements [3].
It has been established that tillage machines, which have in their design links in the fastening of the operating parts, under certain conditions can generate operating continuous oscillations of the operating parts due to the peculiarities of the process of cutting the soil layer [4].

Experimental data obtained by the authors of [5] indicate that the higher the percentage of clay in the soil, the higher the possibilities of sustained oscillations of the operating parts that generate it. It was found that on soils with a sand content of more than 63%, the generation of the operating part should be carried out forcibly, due to an additional vibration generator [5].

We have developed and created experimental samples of new dynamic tillage operating parts [6-8], which provide an increase in the quality and energy efficiency of soil cultivation in comparison with typical operating parts.

Dynamic tillage operating parts mean operating parts with automatic change of some structural dimensions, such as frontal projection area, cutting and crumbling angles within certain limits depending on the value of soil hardness and density. The variability of design parameters is ensured by the use of elastic elements in the design of dynamic operating parts.

The results of theoretical and experimental studies [9-15] show that dynamic tillage operating parts act as:

- vibration damper (damper), providing a rapid decrease in the amplitude of load fluctuations to permissible limits;
- mechanical damper for external load fluctuations of the tillage machine.

With the use of dynamic tillage implements in tillage machines, opportunities arise:

- instantaneous automatic reduction of the frontal projection area, cutting angle within the specified limits and an increase in the specific pressure on the (hard) dense soil layer. This allows you to instantly respond to the dynamic pressure of the soil, partially stabilize vibrations and reduce traction resistance and the measure of its dissipation;
- to increase the degree of soil loosening due to high-frequency vibrations of individual elements of the operating parts when they work at high speeds;
- work at higher speed modes of operation, which will provide an increase in the productivity and energy efficiency of tillage implements;
- develop tillage machines that provide high energy efficiency of the soil cultivation process in comparison with domestic and foreign analogues;
- improve the energy efficiency of soil cultivation technology.

To further improve the design of dynamic soil-cultivating operating parts conditions, an urgent task has arisen - to establish the regularities of the bending deformation of flat elastic elements and the vibration parameters of their wing.

2. Materials and methods
During the research, theoretical modeling methods were used, based on the study of the regularities that occur in the process of loading an elastic element of a dynamic tillage operating part; systems approach; generalization and analysis of experimental data.

The purpose of the research was to obtain experimental data that allow to reveal the regularities of the bending deformation of elastic elements of a dynamic tillage operating part from load and bending moment.

Experimental samples of dynamic tillage operating parts were made (Figure 1).
The flat elastic element of the dynamic tillage element can be considered as a cantilever beam with a rectangular section. Dimensions of the investigated elastic element:

- length - 400 mm;
- width - 60 mm;
- thickness - 4 mm;
- material - St65G.

The deformation of the elastic element of a dynamic tillage operating part can be considered as a straight bend (Figure 2).

**Figure 2** - Scheme for determining the bending moment and the amount of deflection of the elastic element of a dynamic tillage operating part.

Theoretically, the value of the maximum deflection can be determined by the well-known formula:

\[
    h_{\text{max}} = \frac{PL}{3EI} = \frac{Ml}{3EI}
\]

where \( P \) – is the force acting on the elastic element;
\( l \) – distance to the point of application of force from the fixed end of the elastic element (Figure 2);
\( E \) – modulus of elasticity of a material of an elastic element, which characterizes the ability of a material to elastically deform when a force is applied to it;
\( I \) – moment of inertia of the section of an elastic element relative to the main central axis perpendicular to the plane of the bending moment \( M_l \).
During the experiments, the distance \( l \) to the points A, B and C (Figure 2) of the application of force from the fixed end of the elastic element were taken: 123 mm, 223 mm and 324 mm.

A load was applied to the set points 98,1; 196,2 and 294,3 H in triplicate. According to experimental data, the average values of the bending moment and the amount of bending from it were determined.

In the process of experimental studies, the value of the movement of the extreme point of the wing L1 from the speed of movement \( V_p \) of the dynamic tillage operating part was also determined.

A fragment of the recording of the movement of the extreme point of the wing L1 from time \( t \) is shown in Figure 3.

![Figure 3](image1.jpg)

**Figure 3.** Fragment of the recording of the movement of the wing extreme point L1 from time \( t \) in the information-measuring complex IP 264.

Experimental studies of the innovative dynamic tillage operating part (Figure 4) were carried out in the fields of the experimental base "Krasnaya Slavyanka".

![Figure 4](image2.jpg)

**Figure 4.** Research of the work of dynamic tillage operating part with the help of the measuring and information complex IIK-IAEP at the experimental base "Krasnaya Slavyanka".

Experimental studies of a dynamic tillage operating part were carried out under the following conditions:

- type of soil - sod-medium podzolic. Soil - medium loamy (light loamy) on moraine loam;
- relief, hail - 1-2;
• ridge surface of the field, cm - 3-4;
• soil hardness before processing in a layer of 5-20 cm - MPa 0.85-1.0.

3. Results and discussion
In Figure 5-7 show graphical dependences of the deflection value of the elastic element of the dynamic tillage operating part on the bending moment at points A, B and C (Figure 2).

![Figure 5](image)

**Figure 5.** Dependence of the value of the deflection $h$ of the elastic element of the dynamic tillage operating part on the bending moment $M_i$ at point A (Figure 2) at $l=123$ mm.

The empirical dependence describing the regularity of the change in the value of the deflection $h$ of the elastic element of the dynamic tillage operating part from the bending moment $M_i$ at point A (Figure 5) looks as follows:

$$h = -0.001035M_i^2 + 0.195029M_i - 0.203151.$$  \hspace{1cm} (2)

Empirical dependence (2) is valid in the range of variation of the bending moment $M_i = 0 - 36.2$ H · m.

![Figure 6](image)

**Figure 6.** Dependence of the value of the deflection $h$ of the elastic element of the dynamic tillage operating part on the bending moment $M_i$ at point B (Figure 2) at $l = 223$ mm.
An empirical dependence has been established (Figure 6), which describes the regularity of the change in the deflection $h$ of the elastic element of a dynamic tillage operating part from the bending moment $M_l$ at point B:

$$h = -0.002165M_l^2 + 0.373417M_l + 4.783835. \tag{3}$$

Empirical dependence (3) is valid in the range of variation of the bending moment $M_l = 0 - 65.63 \, N \cdot m$.

Figure 7. Dependence of the value of the deflection $h$ of the elastic element of the dynamic tillage operating part on the bending moment $M_l$ at point C (Figure 2) at $l=324 \, mm$.

Empirical dependence describing the regularity of the change in the value of the deflection $h$ of the elastic element of the dynamic tillage operating part (Figure 7) from the bending moment $M_l$ at point C:

$$h = 0.000050M_l^2 + 0.138340M_l + 2.15286. \tag{4}$$

Empirical dependence (4) is valid in the range of variation of the bending moment $M_l = 0 - 95.35 \, N \cdot m$.

Table 1 shows the values of the maximum deflection $h$ of the elastic element of the dynamic tillage operating part at the points of application of the bending moment $M_l$.

| $M_l$, N\(\cdot\)m | Force point | $l$, mm | $h$, mm | Calculation formula |
|---------------------|-------------|---------|--------|---------------------|
| 36.2                | A           | 123     | 5.5    | $h = 0.000257M_l^2 + 0.140331M_l + 0.083299$ |
| 65.63               | B           | 223     | 10.4   | $h = 0.000022l_l^2 + 0.0413134l_l + 0.082353 \ (0 \leq M_l \leq 96 \, H \cdot m; \ 0 \leq l \leq 324 \, mm)$ |
| 95.35               | C           | 324     | 15.8   |                     |

Table 1. Values and empirical formulas for calculating the maximum deflection $h$ of the elastic element of a dynamic tillage operating part at the points of application of the bending moment (maximum load $P=294.3$ H).

In Figure 8 shows a graphical dependence of the deflection $h$ of the elastic element of a dynamic tillage working tool on the parameter $l$. 
Figure 8. Dependence of the value of the deflection $h$ of the elastic element of the dynamic tillage operating part on the parameter $l$ at a load $P=294.3$ N.

The values of the average value of the displacement of the wing extreme point $L$, the amplitude $A$ of its oscillations are directly proportional to the value of the deflection $h$ of the elastic element of the dynamic tillage operating part.

Experimental data made it possible to establish patterns of change in the movement of the extreme point of the wing $L$, the amplitude $A$ of its oscillations from the speed of movement of a dynamic tillage organ and the load on it.

In Figure 9 shows the dependence of the average value of the movement of the extreme point of the wing $L_1$ on the speed of movement $V_p$ of a dynamic tillage operating part.

![Graph](image)

**Figure 9.** Dependence of the average value of the movement of the extreme point of the wing $L_1$ on the speed of movement $V_p$ of the dynamic tillage operating part.

An empirical dependence of the average value of the movement of the extreme point of the wing (Figure 9) on the speed of movement of the dynamic tillage operating part, which looks as follows:

$$L_1 = 0.54836V_p^2 - 1.12654V_p + 11.66766.$$  \hspace{1cm} (5)

Empirical dependence (5) is valid in the range of speed of movement of the dynamic operating part $V_p = 1.94 - 3.61$ m/s.

It has been experimentally established that a change in the speed of movement of a dynamic tillage working tool significantly affects the movement of the extreme point of the wing $L_1$ of a dynamic tillage working tool.
Within the range of change in the speed of movement $V_p$ of a dynamic tillage worker $V_p = 1.94 - 3.61$ m/s, the average value of the movement $L_1$ of the extreme point of the wing increases from 11.55 mm to 14.75 mm.

In Figure 10 shows the dependence of the average value $L_1$ on the load $R_\alpha$ on the dynamic tillage operating part.

The regularity of the change in the average value of $L_1$ from the load $R_\alpha$ (on a dynamic tillage operating part at a speed of 2.78 m/s) is described by the formula:

$$L_1 = -0.05870R_\alpha^2 + 1.68910R_\alpha + 9.73293. \quad (6)$$

Expression (6) is valid in the range of load variation $R_\alpha = 1.12 - 3.36$ kN.

With an increase in the load from 1.12 to 3.36 kN on a dynamic operating part, an increase in the average value of $L_1$ is observed (Figure 10).

A close relationship was also established between the amplitude of oscillations $A$ of the wing of a dynamic tillage operating part with its speed and load modes (Figure 11 – 12).

The empirical dependence for determining the amplitude of wing oscillations on the speed of movement $V_p$ of a dynamic tillage operating part (at $V_p = 1.94 - 3.61$):

$$A = 5.73161V_p^2 - 28.08386V_p + 50.26448. \quad (7)$$
Figure 12. Dependence of the amplitude $A$ of wing oscillations on the load $R_a$ on the dynamic tillage operating part.

An empirical dependence of the wing oscillation amplitude on the load on the dynamic tillage operating part (at $R_a = 1.12 \text{ to } 3.36 \text{ kN}$):

$$A = 2.67477R_a^2 - 9.20067R_a + 24.27727. \quad (8)$$

Experimental data show that with an increase in the speed of movement of a dynamic tillage working tool from 1.94 to 2.8 m/s and an increase in the load on it from 1.12 to 1.85 kN, a slight decrease in the amplitude of wing oscillations is observed, on average by only 1 mm. Further, with an increase in the displacement speed from 2.80 m/s and the load from 2 kN, a sharp increase in the amplitude of oscillations is observed. This is due to the fact that the work of a dynamic tillage operating part at high speed and load modes contributes to the occurrence of high-frequency oscillations with a greater amplitude, which have a positive effect on the quality of soil loosening.

The established regularities of bending deformation of flat elastic elements of a dynamic tillage operating part from the load and the speed of its movement make it possible to optimize the distance to the point of application of the force and bending moment from the fixed end of the elastic element, depending on the conditions of its functioning. When calculating, it is necessary to take into account the modulus of elasticity of the material of the elastic element, which characterizes the ability of the material to elastically deform when a force is applied to it, as well as the moment of inertia of the section of the elastic element relative to the main central axis.

The relationship of the parameters considered above on the bending moment, load and speed of movement of a dynamic tillage operating part is described by empirical dependencies with the coefficient of determination $R^2=0.67-0.85$.

The error of the sample mean $S_y$ of the investigated parameters of the dynamic operating part varied within $0.039 \text{ to } 0.136$.

4. Conclusions
The graphical and empirical dependences of the deflection value of the elastic element of the dynamic tillage operating part on the bending moment at various points of its application have been established. Also, the regularities of the change in the amplitude of oscillations of the extreme point of the wing, and the movement of the extreme point of the wing from the speed and load on the dynamic tillage operating part were established.

The established patterns make it possible to optimize the distance to the point of application of the force and bending moment, from the fixed end of the elastic element of the dynamic tillage working tool, depending on the conditions of its functioning.
References

[1] Ibrahim A, Bentaher H, Hbaieb M, Maalej A, Mouazen A 2015 Study the effect of tool geometry and operational conditions on mouldboard plough forces and energy requirement: Part 1. Finite element simulation. Computers and Electronics in Agriculture Vol 117 pp 258-267

[2] Izmailov A, Liskin I, Lobachevskii Ya, Sidorov S, Khoroshenkov V, Mironova A, Luzhnova E 2017 Simulation of soil-cutting blade wear in an artificial abrasive environment based on the similarity theory. Russian Agricultural Sciences Vol 43 N1 71-74

[3] Pakhomenko G 2019 Tractors and agricultural machinery Vol 4 28-36

[4] Mudariso S, Gabitov I, Lobachevsky Y, Mazitov N, Rakhimov R, Khamaletdinov R, Rakhimov I, Farkhutdinov I, Mukhamedtinov A, Gareev R 2019 Modeling the technological process of tillage. Soil & tillage research. Vol 190 pp 70-77

[5] Ani O, Uzoejinwa B, Ezeama A, Onwualu A, Ugwu S, Ohagwu C 2018 Overview of soil-machine interaction studies in soil bins. Soil Tillage Res Vol 175 pp 13-27

[6] Armin A, Fotouhi R, Szyszkowski W 2017 Experimental and finite element analysis for mechanics of soil-tool interaction. Int. J Mech. Mechatr. Eng. Vol 11 (2), pp 433-439

[7] Bentaher H, Ibrahim A, Hamza E, Hbaieb M, Kantchev G, Maalej A, Arnold W 2013 Finite element simulation of moldboard-soil interaction. Soil Tillage Res Vol 134, pp 11-16

[8] Sun J, Wang Y, Ma Y, Tong J, Zhang Z 2018 DEM simulation of bionic subsoilers (tillage depth& 40 cm) with drag reduction and lower soil disturbance characteristics Adv. Eng. Softw Vol 119, pp 30-37

[9] Ucgul M, Saunders C, Fielke J 2017 Discrete element modelling of tillage forces and soil movement of a one-third scale mouldboard plough Biosyst. Eng., Vol 155, pp. 44-54

[10] Ibrahim A, Bentaher H, Maalej A 2014 Soil-blade orientation effect on tillage forces determined by 3D finite element models. Spanish J. Agric. Res Vol 12 (4), 941-951

[11] Lobachevsky Ya, Kolmogortsev V, Starovoytov S, Khramovskikh K 2016 Analysis of traction resistance of the elements of a cylindroid plow body. Agricultural machines and technology Vol 2 P 11

[12] Lin Z, Shuang-Shuang P, Xi C, Tien-Chien J 2016 Combined finite element and multi-body dynamics analysis of effects of hydraulic cylinder movement on ploughshare of Horizontally Reversible Plough Soil and Tillage Research Vol 11

[13] Mattetti M, Massimiliano V, Giovanni M, Morelli F 2016 Influence of the speed on soil-pressure over a plough. Biosystems Engineering. 04

[14] Sidorov S, Khoroshenkov V, Lobachevskii Y, Akhmedova T 2017 Improving wear resistance of agricultural machine components by applying hard-alloy thick-layer coatings using plasma surfacing. Metallurgist Vol 60 N11-12 pp 1290-1294

[15] Lobachevskii Y, Aulov V, Ivanov V 2019 Method for preparing an efficient master alloy for steel boriding Metallurgist Vol 62 N 9-10 pp 986-993