

# The analyses of physical and mechanical properties in the process of soil interaction with working elements of the cultivator of vibrating principle action

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**Abstract.** The characteristics of the natural-climatic zone of the Omsk region are given and an analysis of the physical and mechanical properties of soils is carried out. A technical solution for cultivating the soil using the working parts of vibrating cultivator has been proposed. In the process of this research, the dependences of the trajectory movement of the vibrating-type lancet paw and its blades ends when interacting with the cultivated soil were established, and calculations of traction resistance were performed. The use of vibrating working body of the cultivator reduces traction resistance by 5%, which saves fuel, increases the degree of weed cutting by 10%, and decrease the degree of soil sticking by 15%. The effectiveness of using cultivator with vibration-action working parts helps to increase crop yields and reduce the cost of resulting products.

## 1 Introduction

Omsk region is located in the western part of the Siberian Federal district and geographically occupies three natural zones: forest, forest-steppe and steppe. About 50 percent of the territory is occupied by forest-steppes. Each natural zone is characterized by their hydroclimatic and biogenic resources due to latitudinal distribution of heat and moisture, and soil types:

- Forest zone (about 600 thousand hectares) is the most swampy, lasting for a year waterlogged, groundwater lies at a depth of 1-3 meters. Podzolic, swamp and meadow soils, which have a low supply of humus (up to 3%), nitrogen and phosphorus, acidic, low-power are prevailed.
- Forest-steppe zone (51%) in its soil cover has meadow-black, chernozem-meadow and meadow soils, as well as solonets complexes. Average humus content is within 4... 5%. For agricultural needs 3 million 744 thousand hectares of land have been developed in the zone, of which about 55% is used for arable land.
- The steppe zone occupies about 8.6% of the region, but it is agriculturally most developed and used in crop production. Plowing the soil in some farms reaches 95%. In

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land fund of the steppe zone common and southern chernozems prevail and often carbonate and solonchic. Quantity of humus - from 4 to 9%.

## 2 Materials and methods

Main agricultural crop production is located in the forest-steppe and steppe zones, as this is favored by the climate.

The climate of the steppe zone is compared with the forest-steppe zone by duration of growing and frost-free periods, long average annual and average monthly temperatures, great dryness. Therefore, the lands of the steppe zone suffer from a lack of moisture: on average, 250-300 mm of precipitations fall per year here, 1.5-2 times less than in the central regions of Russia.

Winter is severe in the steppe zone, frosts up to -35... - 40 degrees, and thin uneven snow cover of 25... 30 cm does not cover the soil well. Snow comes down in a short time - 10... 12 days. Strong winds dry up the soil, increase evaporation, and often cause dust storms. Rains during the spring period are rare [1]. Late spring frosts are common here. In summer period the temperature rises up to + 30... + 35 degrees. In the first half of summer a dry wind is a common phenomenon [2].

N.A. Kachinsky, P.U. Bakhtin (1969) and other researchers developed soil classifications by hardness, which are presented in Table 1. Since hardness depends on the shape of the tip and humidity during measurement, classification takes these parameters into account [3].

**Table 1.** Classification of soils by air-dry hardness.

Grade of soil hardness	hardness, kgs/sm <sup>2</sup>			
	Plunger – cone, cross-sectional area 1 sm <sup>2</sup>			Plunger – cylinder, cross-sectional area 2 mm <sup>2</sup>
	According to Kachinsky	According to Vysotsky	According to Golubev	According to Goryachkin
Fused	> 100	> 80	> 90	> 70
Quite hard	100-50	80-40	90-45	70-35
Hard	50-30	40-25	45-27	35-20
Less hard	30-20	25-15	27-18	20-15
Less loose	20-10	15-8	19-9	15-7
Loose	< 10	< 8	< 9	< 7

There are also several particular classifications of hardness constructed on the analysis of local material. One of this classification of hardness composition is given in Table 2 [4].

**Table 2.** Composition indicators of the arable layer of southern carbonate chernozems of Crimea (P.S. Smorodin etc 1969).

Soil structure	Density of structure, g/sm <sup>3</sup>	Hardness, kgs/sm <sup>2</sup>	Porosity, %	Water permeability, mm/hour		Field moisture capacity, mm
				During the first hour	During the sixth hours	
Loose	1.07	13.8	58.4	34.0	142.0	75.5
Compacted	1.15	15.5	55.9	38.4	146.4	77.9
Thick	1.20	18.2	54.8	36.4	133.4	80.8
Very thick	1.31	28.3	49.9	12.0	66.4	93.1

Causes of soil degradation can be characterized by following factors:

- Over-compaction of the soil can be identified as one of the factors due to the use of energy-intensive tractors of large mass as part of machine-tractor units.
- Use of large mass combines with large capacity hopper.
- Refusal to regular ploughing and use of "No-Till" technology also resulted in compaction of soil horizon.

To determine the traction resistance of the cultivator working element, we will use the formula from agricultural mechanics, which was proposed by V.P. Goryachkin [5]:

$$R_n = R_1 + R_2 + R_3, \quad (1)$$

Where  $R_1$  is the constant resistance independent of plough operation mode,  $R_1 = f \cdot G$ , where  $f$  is coefficient of resistance to plough pulling in open furrow (similar to coefficient of friction);  $G$  - weight of implement;  $R_2$  are the resistances caused by deformation (destruction) of soil layers, therefore they are proportional to the cross-sectional area of the deformed layers,  $R_2 = k \cdot S \cdot n$ , where  $k$  is the specific resistance of the soil,  $S$  is the cross-sectional area of the soil layer;  $n$  - number of simultaneously treated soil layers (number of working elements);  $R_3$  are the resistances associated with "manpower" (kinetic energy) to the soil slices thrown aside. These resistances are proportional to the cross-sectional area of the slices and the square of the plough speed,  $R_3 = \varepsilon \cdot S \cdot n \cdot V_2$ , where  $\varepsilon$  is the speed resistance coefficient dependent on the soil properties and the geometric shape of the working surfaces of the plough bottoms;  $V_2$  - plough speed.

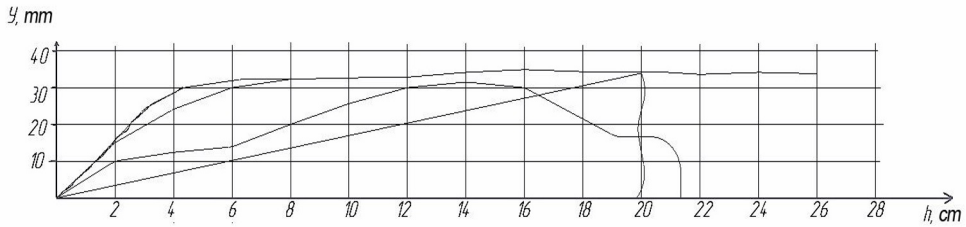
At present time it is necessary to strive for global trends in reducing the energy intensity of technological operations such as tillage. As the most energy-intensive process of tillage is the plowing, carried out by moldboard plows. Surface tillage carried out by wide-coverage cultivators is more efficient operation compared to common tillage. Thus, the use of wide-coverage cultivators allows to reduce costs by 10-15% compared to common tillage. However, it is necessary to strive to further reduce the cost of performing an energy-intensive process. Therefore, the team of scientific and pedagogical employees of Agroengineering Department of Technical Service in the Agro-Industrial Complex faculty of Omsk GAU proposes to use a vibratory arrow-shaped foot, which will further reduce the traction resistance of cultivated machine-tractor units by 7-10%.

## 2.1 Proposed technical solution

The working element of the cultivator operates as follows. When the working element of the cultivator moves along the working area, its working elements are buried to the specified depth. The bit cuts the soil layer, lifts the soil up and loosens. The remainder of the soil slice is loosened and cut with foot blades. Since the soil density in different areas of the field is not uniform, the foot blades will make independent horizontal oscillations due to the damping element located between the rack and the cheek of the blade. When an obstacle hits one of the blades, it will deflect backwards, trying to pass the obstacle until the stiffness of the damping element is fully used. Collectively, all of these mechanisms make it possible to significantly reduce traction resistance of cultivator working element and the machine-tractor unit as a whole [6].

In order to determine the optimal design parameters of the arrow-shaped foot of vibratory type cultivator, it is necessary to consider the interaction of the foot blades with the soil and establish a relationship between such parameters as soil hardness and stiffness of the elastic element, the movement trajectory of the arrow-shaped foot elements in the soil and indicators of amplitude and frequency of vibrations.

In accordance with the measurements of soil hardness using "Revyakin" system hardness meter (plunger - cylinder, section area 2 mm<sup>2</sup>, force scale k = 1.25 kgs/mm), the following data were obtained in Cherlak district of the Omsk region (Figure 1).



**Fig. 1.** Soil hardness index in Cherlak district of the Omsk region.

### 3 Results and Discussion

The average soil hardness value is 25 kgs/cm<sup>2</sup>, its structural composition changes from sandy to light loamy. The measurements carried out in the same conditions in Lyubinsky district of the Omsk region (training-experimental fields of the Omsky SAU) - the average soil hardness value was 30 kgs/cm<sup>2</sup>, structural composition changes from light loamy to loamy. In some places there are solonetz embeddings [7].

According to the Newton's Second Law interaction of the soil slice with arrow-shaped foot it can be written in the form:

$$S \cdot q = k \cdot \Delta x \quad (2)$$

Where S is the cross-sectional area of the soil layer cut by arrow-shaped foot which can be expressed in term of surface area of arrow-shaped foot ( $S_n$ ) and angles of its setting to the horizon ( $\alpha$  to the horizon,  $\gamma$  solution of arrow-shaped foot):  $S = S_n \cdot \sin \alpha \cdot \sin \gamma$

$\Delta x$  – deformation of the elastic element, maximum value according to the construction  $\Delta x_{max} = 5$  mm; k – stiffness of the elastic element.

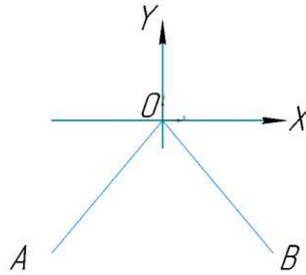
Expressing the value of stiffness of the elastic element and substituting values into the formula:

$$k < \frac{S_n \sin \alpha \cdot \sin \gamma \cdot q}{\Delta x_{max}} \quad (3)$$

We will obtain a value of  $k \leq 15$  kN/m.

If the stiffness of elastic element is up to 15 kN/m, the blades of the arrow-shaped foot will reciprocate rotationally relative to the attachment point (point O, Figure 2). When the blade of the arrow-shaped foot is deflected by a certain angle of  $\Delta \phi$ , a change in the traction resistance of the arrow-shaped foot in the 140,18-149,72N range will be observed. Compared to a standard arrow-shaped foot, the traction resistance is less 7% [8].

To determine the trajectory of the arrow-shaped foot, we will use the xOy coordinate system, shown in Figure 2.



**Fig. 2.** Coordinate system xOy, located in the base of the cultivator foot rack.

The segments AO and BO (Figure 2) in the xOy coordinate system denote the left and right blades of the arrow-shaped foot, respectively. The center of the coordinate system (point O) will move at a speed equal to the movement speed of the machine-tractor unit. As the unit speed movement, we assume a value equal to 9 km/h, which meets the agrotechnical requirements when performing surface tillage - cultivation [9].

The motion path of point O can be defined by a system of equations

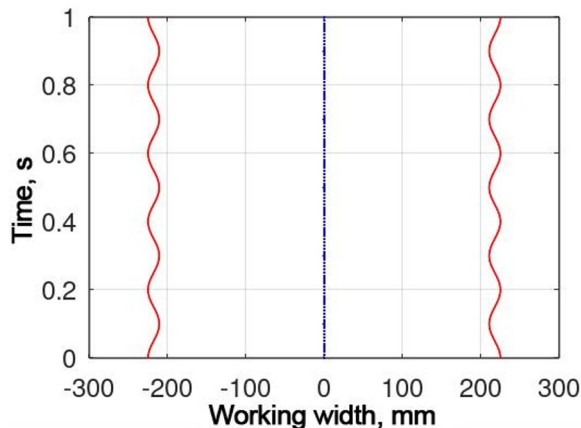
$$\begin{cases} x = 0 \\ y = t \end{cases} \quad (4)$$

The motion of points A and B, which oscillate relative to point O by a value of  $\pm 3^\circ$ , can also be represented by the equations:

$$A(t) = -\frac{\cos^2(\omega t)}{14,34} - 350\sin^2(40^\circ) + \frac{\sin^2(\omega t)}{14,34^{-1}} \quad (5)$$

$$B(t) = \frac{\cos^2(\omega t)}{14,34} + 350\sin^2(40^\circ) - \frac{\sin^2(\omega t)}{14,34^{-1}} \quad (6)$$

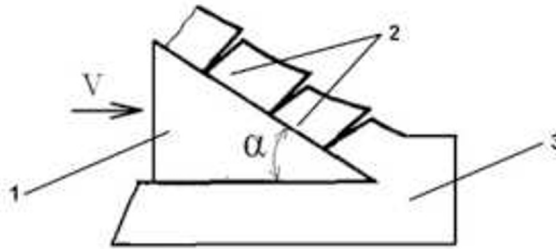
By substituting values in formulas (0.4) and (0.5), we obtain a graph of the motion path of points A and B of the ends of the arrow-shaped foot, respectively (Figure 3).



**Fig. 3.** Motion path of the arrow-shaped foot of the vibratory type and its blade ends.

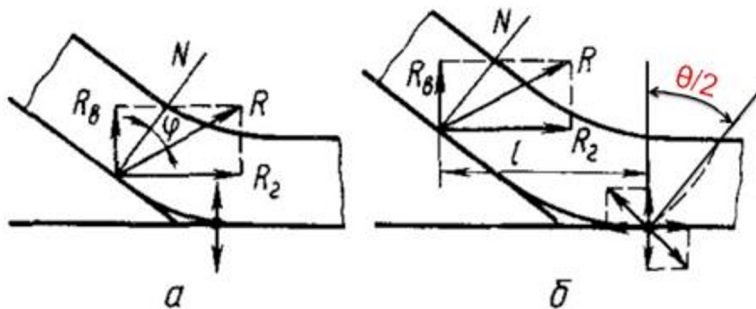
It can be seen from Figure 3 that working width of the arrow-shaped foot varies from a maximum value of 550 mm (449.96) to a leg minimum value of 420mm (421.27). The deviation of the working width on one side of the arrow-shaped foot is 15 mm, which does not contradict the agrotechnical requirements for the technological operation of cultivation, in this case arrow-shaped foot are installed with overlap up to 40 mm on the side [10].

The frequency of oscillation of the arrow-shaped foot blades is in the range of  $5 \div 10$  hertz and depends on soil hardness at a given time  $dT/dt$  near the arrow-shaped foot blade. When the arrow-shaped foot interacts with the treated soil, spalling of the soil is formed (Figure 4).



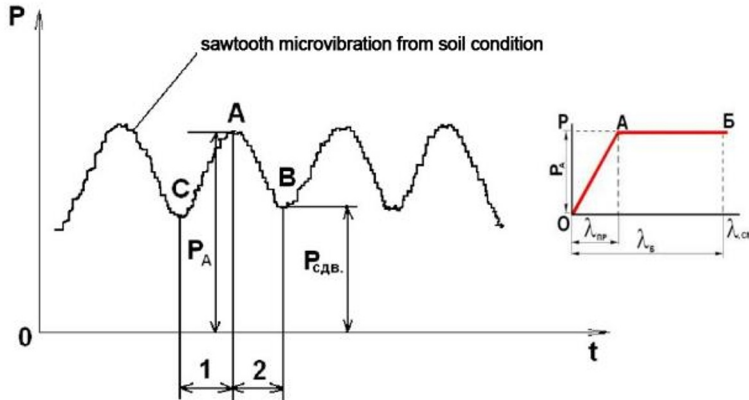
**Fig. 4.** Formation deformation by wedge: 1 - wedge; 2 - soil aggregates; 3 - treated soil layer.

Soil splitting depends on the physical and technological properties of the soil and the angle  $\alpha$  installation of the wedge working face. Two main effects of the wedge on the soil layer are identified (Figure 5): in the first case, a leading crack is formed; in the second - the separation of the block at oblique fracture, with the value of the soil splitting angle  $\theta = 40 \dots 50^\circ$ .



**Fig. 5.** Diagrams of the wedge impact on the soil layer: a - formation of advanced crack; b - separation of the block in case of oblique fracture.

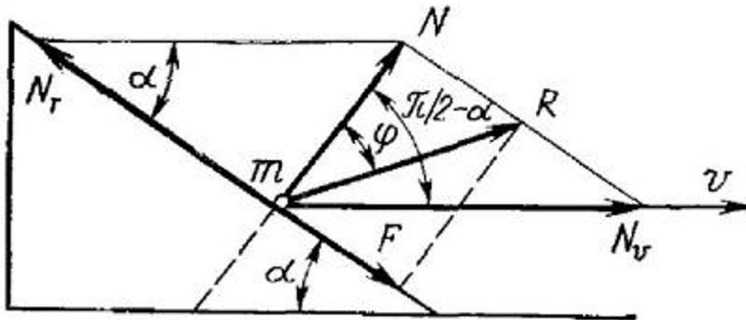
More detailed study of the wedge effect on the soil layer revealed that changes in soil resistance to wedge movement are cyclic (Figure 6).



**Fig. 6.** Cyclic nature of soil resistance to wedge movement: 1 - first phase (compaction, bending); 2 - second phase (splitting, breakaway).

Therefore, when using cultivator foot of vibratory type, we obtain resonant vibrations, which makes it possible the splitting of the soil layer with less energy consumption.

Considering the wedge operation, two modes can also be distinguished: 1 - when, the soil slides along the working face of the wedge (analogues can be: shares, cultivator leg); 2 - the soil is unloaded in front of the working face of the wedge (analogues: bulldozer blade, grader blade). The diagram of the action of forces on the soil particle from the side of the wedge is shown in Figure 7.



**Fig. 7.** Forces acting on soil particle during wedge-soil interaction:  $N_T > F_{\max}$  – stable sliding;  $N_T = N \operatorname{tg}(\pi/2 - \alpha)$ ;  $F_{\max} = N \operatorname{tg} \varphi$ .

Therefore, the sliding condition ensuring the continuous interaction of the working face of the wedge with the soil will be as follows:

$$N \operatorname{tg}(\pi/2 - \alpha) > N \operatorname{tg} \varphi$$

or  $\alpha < \pi/2 - \varphi$  – mode 1  
 $\alpha > \pi/2 - \varphi$  – mode 2

## 4 Conclusion

Experimental studies have shown that the use of the proposed vibratory cultivator working element allows reducing traction resistance by 5% by using a damping element between the checks of the foot blades and fixing the foot in the lower part of rack by bolting. Proposed vibratory cultivator working element increases degree of weed cutting by 10% due to

movable versatile foot blades with vertical cheeks. The working element of the cultivator reduces the degree of soil sticking to the front part of the working element of the cultivator by 15%, due to the usage of trapezoidal form bit in the front part.

The obtained economic indicators show the sufficient economic effectiveness of using the cultivator for overall tillage. Reduction of labour input and cost of mechanized operations, saving fuel of lubricants, as well as annual economic effect are obtained due to high-quality work of the developed cultivator for overall tillage of soil. Higher quality of tillage ensures higher yield of crops and reduction of produced products cost.

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