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JUSTIFICATION OF RATIONAL OPERATING PARAMETERS OF VIBRATION DISC-WORKING ENGINES OF SEEDING UNITS TO IMPROVE ENERGY-TECHNOLOGICAL INDICATORS

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The article addresses the interaction of disc vibration working elements of a seed drill with soil to reduce traction resistance and energy consumption in soil processing. Regularities characterizing the impact of vibrations on the soil are identified, and a mechanical-mathematical model of soil cutting by the vibrational disc-working element of a seed drill is developed. Mathematical dependencies for determining the parameters of vibro-impact interaction of the cutting edge of the disc-working element with the soil are obtained. The efficiency conditions of the vibro-cutting process, in terms of reducing traction resistance and energy consumption, are established. A methodology for selecting rational parameters for vibro-cutting soil in the design and operation of the disc-working element of seeding equipment is developed. Experimental results of a prototype vibrational working equipment are presented, confirming theoretical findings and demonstrating the effectiveness and feasibility of vibrational soil cutting by the disc-working element for reducing traction resistance and energy costs. The research, the results of which are presented in this article, is funded by the Committee on Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (grant AP14869252 "Development of the universal sowing complex with increased productivity for the agro-industrial production of the Republic of Kazakhstan").

Keywords: sowing, seed drill, coulter, cutting disc, disk tillage tool, vibrating tillage tools, vibration, traction resistance, energy intensity

1 INTRODUCTION

Direct seeding technology is employed to enhance the efficiency of agricultural crop production [1, 2]. Seeders used for direct seeding, such as Salford 520 (Canada), Bereginya AP-402 (Russia), CPH-2000F (USA), SD7200 (Kazakhstan), John Deere 1590 (USA), Crucianelli Pionera 2717, and others (Figure 1), must cut through plant residues, minimally disturb the soil, and ensure precise seeding at the specified depth. The opener assembly is the most crucial, complex, and heavily loaded component of the seeder. Currently, disc openers are widely used for direct seeding. Additionally, a disc blade on an independent suspension is often installed in front of each opener to cut through the furrow, break up the compacted upper layer, shred plant residues, etc. [3, 4]. Currently, the development of disc opener seeders is trending towards increasing working widths and seeding speeds [5-10], inevitably leading to increased resistance forces and energy consumption. Therefore, one of the most pressing challenges in the development of high-performance disc opener seeders is the reduction of cutting resistance forces and energy consumption based on the application of combined soil cultivation tools with active working elements and the rational selection of their design and operational parameters [12-14].

1 - opener; 2 - parallelogram lever mechanism; 3 - roller; 4-disc knife

Fig. 1. Seeder with cutting discs and disc coulters

The most promising direction for reducing energy indicators in soil processing involves synthesizing soil cultivation tools with devices that generate additional disturbing forces and fields, such as pulse impacts in the form of vibrational oscillations that alter the interaction between the working tools and the soil [12-17].

The effectiveness of applying additional vibration to soil cultivation tools is associated with three main aspects: creating a cumulative stress field of higher intensity; transitioning the soil into a pseudo-liquid state and acoustical softening; reducing the coefficient of friction and soil forces on the working tools. To enhance the vibrational effect, loading pulses must alternate with complete relaxation of compressive stresses, achieved by periodically interrupting the contact between the working tool and the soil.

Many researchers have established the positive effect of reducing resistance through the use of vibrating working elements in soil cultivation tools [12-17]. However, the results obtained do not indicate the completion of research in this direction.

Firstly, based on information from published sources [17-18], vibrational cutting has been applied to plows, cultivators, and other tools, but not to disc opener seeders. Moreover, the movement speeds did not exceed 1.5 m/s, and vibrational cutting modes involved oscillations at audible frequencies (50…100 Hz or less). All researchers noted that power savings were more significant at lower speeds, and increasing speed with constant frequency and amplitude of vibrations led to increased traction resistance.

Secondly, some authors note [13, 17] that the reduction in cutting forces during vibrational cutting occurs when the ratio of cutting speed V to vibration speed aω (where a, ω - amplitude and frequency of tool oscillations) holds $\frac{V}{a \cdot \omega} < 1$.

However, calculations show that under such inequality, the reduction in cutting forces could be achieved at relatively high cutting speeds, small amplitude values, and sound frequencies of oscillations. In practice, the positive effect of vibrational cutting, on the contrary, is observed only at low speeds of the base machine (1…1.5 m/s or less) and high values of frequency or amplitude of oscillations. This suggests that the inequality $\frac{V}{a \cdot \omega} < 1$ is incorrect and requires correction to appropriately select the operating modes of vibrating working elements.

Therefore, the process of vibrational cutting of soil by disc working elements at high speeds of seeding units requires corresponding research and justification. The search for rational modes of vibrational impact of working elements on the environment to increase productivity and reduce energy consumption is relevant and significant.

This work represents one of the stages of the authors' research in this field and attempts to bring some clarity to the understanding of the mechanics of vibrational cutting of soil by disc working elements.

The goal of the work is to increase the efficiency of soil cutting by applying vibrational disc working elements of seeding equipment, determining the operational parameters of their work, developing a methodology for engineering calculation, and selecting the parameters of vibrational working equipment.

Thus, the main idea of the new type of seeding equipment is the imposition of additional vibro-impact oscillations with relatively low energy of a single impact in the direction coinciding with the main movement on the disc tool, which has the main working movement with some constant speed. Such an impact on the processed medium significantly differs from traditional static cutting and, with the correct selection of vibration parameters, can reduce resistance forces compared to static cutting.

The structural diagram of the machine with additional vibrational impact on the soil is shown in Figure 2 and includes a base machine with running gear and an internal combustion engine, disc working equipment, and a mechanism for generating force impulses (vibrations).

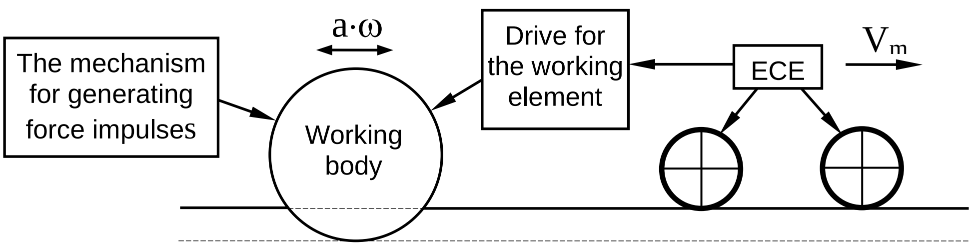


Fig. 2. Structural diagram of a machine with impulse impact on the soil

The main parameters of vibrational equipment for soil cutting are the frequency ω in (s-1) and the amplitude a in meters (m) of tool oscillations, as well as the speed (V_m) in meters per second (m/s) of the translational movement of the base machine.

However, clear recommendations on selecting parameters for the process of vibrational soil cutting with disc working elements are currently absent. By appropriately choosing and justifying the parameters of forced vibrations (frequency and amplitude) of the disc working element for a given value of the base machine's movement speed, determining the influence of the translational movement speed, amplitude, and frequency of oscillations on the parameters of impulse force impact, rational operating modes can be achieved. This can lead to a reduction in cutting resistance forces and energy consumption for soil processing, ultimately increasing processing speed.

An important question that has yet to receive a definitive answer is the relationship between the speed of the unit and the vibrational speed.

2 THEORETICAL STUDIES

The selection of amplitude and frequency values for vibrations, taking into account the translational speed of the base machine, is only possible through the development of reliable mathematical calculation methods.

In the process of vibrational cutting, the cutting edge of the disc tool performs harmonic oscillations with a frequency ω (1/s) and an amplitude a (m) (for an eccentric vibrational drive, a=2e, where e is the eccentricity) in the direction of the base machine movement at a constant speed V_m (Fig. 3, Fig. 4).

The motion process of the cutting-edge x(t) for the vibrational cutting mode in the direction of the base machine movement can be represented according to the scheme in Fig. 3 and Fig. 4 as a sum of two movements: the movement of the base machine and the additional oscillations of the working tool. In this case, the motion law of the working tool (the current value of the disc cutting edge coordinate) can be expressed as a function of the current time t:

$$x(t) = x_m(t) + x_{po}(t) = e \cdot (1 - \cos \omega t) + V_m \cdot t = \frac{1}{2} \cdot a \cdot (1 - \cos \omega t) + V_m \cdot t \tag{1}$$

It is necessary to relate the movement of the working tool (disc) to the period of its oscillations T (T=2π/ω), obtaining a generalized regularity for the displacement of the working tool for various vibrational drives.

Suppose that the movement of the working tool has a simplified sawtooth character in accordance with the duration of the oscillation period T and occurs with an amplitude of oscillations a.

The diagram of the vibrational cutting process with a disc-working tool with intermittent contact with the soil is shown in Fig. 3. The trajectory of the cutting-edge movement is presented in Fig. 4.

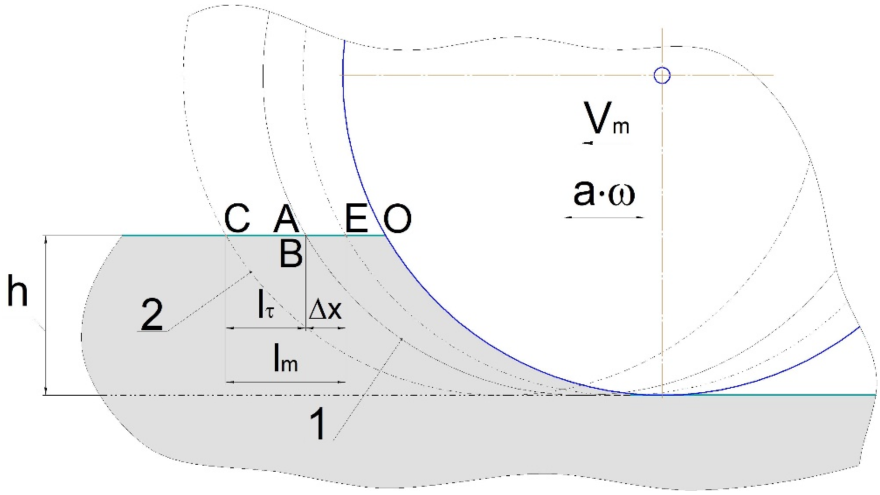


Fig. 3. Diagram of the vibrational cutting process with horizontal oscillations of the tool

A working tool (disk) is introduced into the soil at the starting point O and moves in the direction of the base machine. At point A, the displacement of the cutting edge reaches its maximum value, and soil deformation occurs on the compression area 1. After stopping at point A, during the reverse movement, the cutting edge exits contact with the soil over a distance Δx from point A to point E. At point E, when the cutting edge is maximally out of contact with the soil, the cutting-edge stops, and its next movement in the direction of the machine begins. At point B, the cutting edge enters into new contact with the soil and moves to point C, where its movement again reaches the maximum value, causing a new soil deformation on compression area 2. In the process of vibratory cutting, the cutting edge periodically comes into contact with the soil and then exits. The condition for the dynamic action of the cutting tool on the medium is the time $t_4 > 0$, or $\Delta x > 0$. The interaction of the cutting edge with the soil lasts for the time t5. The distance traveled by the cutting edge in contact with the soil is denoted as l_τ. On the segments OA and BC, the cutting force impulse P0 is applied. The depth h is determined by the required furrow depth for seeding.

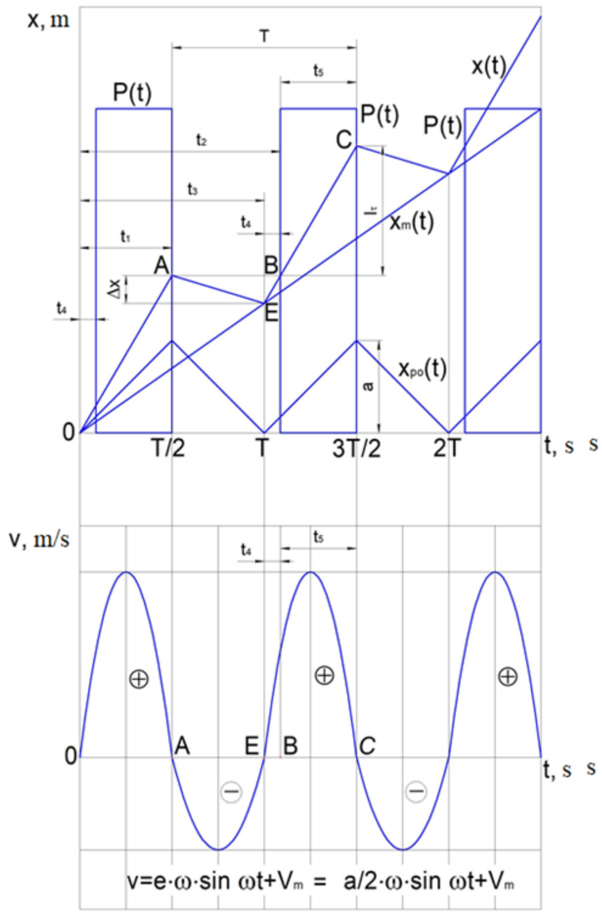


Fig. 4. Mechanism of vibrational cutting (trajectory of the cutting-edge movement, velocity of the cutting edge, cutting force impulses)

The maximum coordinate x(t) of the tool movement is reached at point A, where the speed of movement of the cutting edge is zero. The total speed of the cutting edge (during the movement of the base machine and vibrational movements) is described by the formula:

$$\dot{x}(t) = e \cdot \omega \cdot \sin \omega t + V_m \tag{2}$$

The moment of time t_1, at which the cutting edge of the disk reaches point A, stops, and begins the reverse movement while separating from the soil, can be described from Figure 4 $t_1 = \frac{T}{2}$:

The speed of the cutting edge at point A, from expression (2):

$$\dot{x}(t)_A = e \cdot \omega \cdot \sin \omega t_1 + V_m = V_m$$

The coordinate of point A from expression (1):

$$x_A = e \cdot (1 - \cos\, \omega t_1) + V_m \cdot t_1 = a + V_m \cdot t_1 = a + V_m \cdot \frac{T}{2} = a + V_m \cdot \frac{\pi}{\omega}$$

The time t_3 corresponds to the displacement of the cutting edge from the beginning of its movement (point O) to the maximum exit from the cutting zone (point E), and from Figure 4, it is determined by the expression $t_3 = T = \frac{2\pi}{\omega}$:

The coordinate of point E:

$$x_E = e \cdot (1 - \cos\, \omega t_3) + V_m \cdot t_3 = V_m \cdot T = V_m \cdot \frac{2\pi}{\omega}$$

The magnitude *Δx* of the maximum exit of the disk cutting edge from the contact zone with the soil during the working tool (disk) movement from point A to point E can be found from the expression: $\Delta x = x(t_1) - x(t_3)$, where $x(t_1) = x_A$ and $x(t_3) = x_E$:

$$\Delta x = x(t_1) - x(t_3) = x_A - x_E = (a + V_m \cdot \frac{T}{2}) - V_m \cdot T = a - 0{,}5 \cdot V_m \cdot T \tag{3}$$

According to the mechanism of impact vibrational cutting, the value Δx should have a positive value. If $\Delta x \leq 0$, then during the process of vibrational cutting, the cutting edge does not exit the contact zone, meaning the destruction mechanism is similar to static cutting.

The maximum speed of the movement of the base chassis V_m can be found from expression (3), assuming the condition $\Delta x \to 0$:

$$V_m = \frac{2 \cdot a}{T} = \frac{a \cdot \omega}{\pi} = 0{,}318 \cdot a \cdot \omega \text{, m/s.} \quad (4)$$

To determine the influence of the movement speed of the base chassis, calculations were performed using expression (3), and dependencies $\Delta x=f(V_m)$ and $\Delta x=f(V_m/(a \cdot \omega))$ were obtained for the amplitudes of oscillations of the cutting edge a=1 mm, a=5 mm (see Figure 5) and a=3 mm, a=5 mm, a=10 mm (see Figure 6).

With an increase in the translational speed of the base machine (V_m), the value Δx of the cutting tool exiting contact with the medium decreases, especially for smaller values of the amplitude of oscillations *a*. The working process of vibrational cutting, under certain values of speed, period, and amplitude of oscillations, may transform into a mode of static cutting.

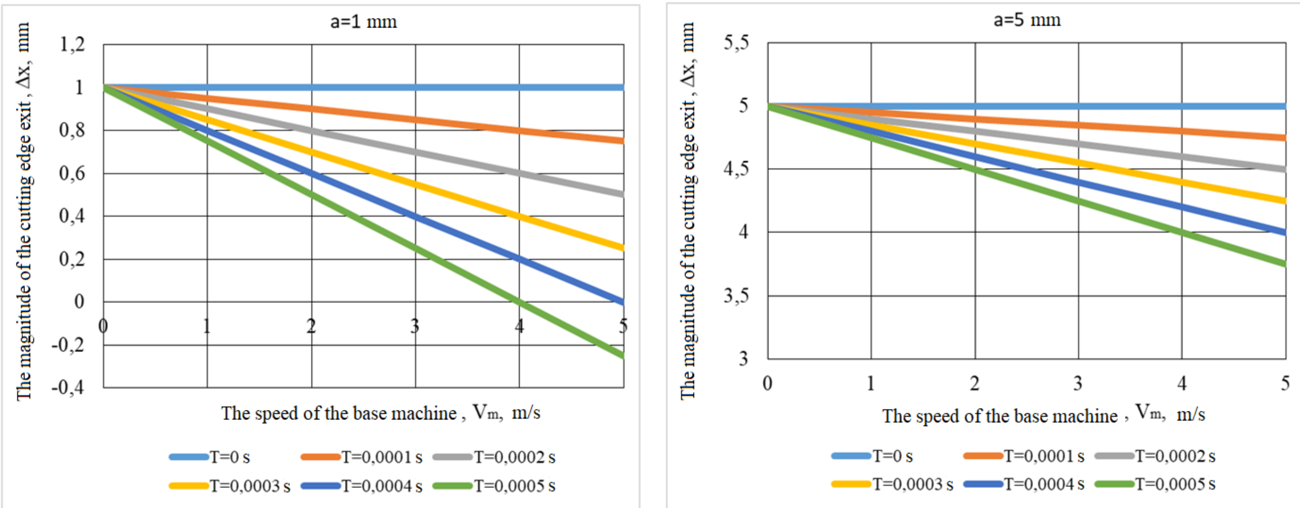


Fig. 5. Influence of the movement speed of the base chassis V_m on the magnitude Δx

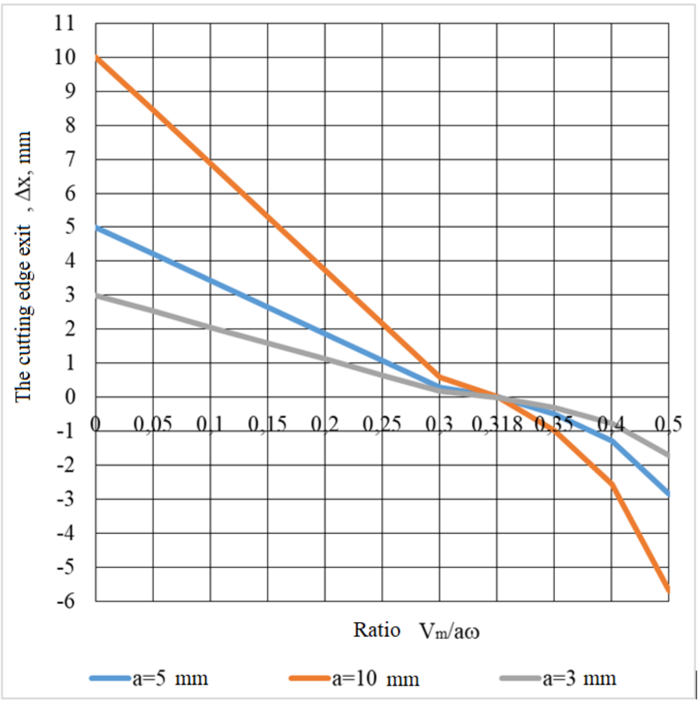


Fig. 6. Dependency Δx from $V_m/(a \cdot \omega)$

The disruption of the working medium is the result of the impulsive force impact of the working tool during the time t_5 of interaction with the working medium (see Figure 4). It is essential to establish the relationship and the influence of vibration parameters on the cutting force.

The function of the impulsive cutting force, characteristic of vibrational cutting, can be expanded into a Fourier series [19-20]:

$$F(t)=\frac{t_5}{T}\cdot F_0+\frac{2}{\pi}\cdot F_0\cdot\sum_{n=1}^{\infty}\frac{1}{n}\cdot\sin\left(n\frac{\tau}{T}\pi\right)\cdot\cos(n\omega t) \qquad (5)$$

where n - the number of the term (harmonic) in the Fourier series expansion of the function;

T - period of oscillations

t_5 - time of impulsive action of force;

ω - angular frequency of oscillations of the cutting edge, rad/s;

F_0 - force of static cutting.

From equation (5), it follows that with a decrease in the time t_5 of the impulse force action, the average value of the cutting force *F(t)* decreases. In other words, the force of vibrational cutting significantly depends on the time t_5 of the interaction of the working tool with the medium (the time of action of the force impulse *F*), which, according to Figure 4, can be determined as: $t_5=\frac{T}{2}-t_4=t_1-t_4$

Then, the average cutting force will be:

$$F_{cp}=\frac{\frac{T}{2}-t_4}{T}\cdot F_0=(0{,}5-\frac{t_4}{T})\cdot F_0 \qquad (6)$$

From equation (6), it can be seen that to reduce the cutting force, it is necessary to strive for an increase in the time t_4, during which the tool comes into contact with the soil after the start of movement in the direction of the base machine. Moreover, the time t_4 is generally more significant for reducing cutting force than the time t_5.

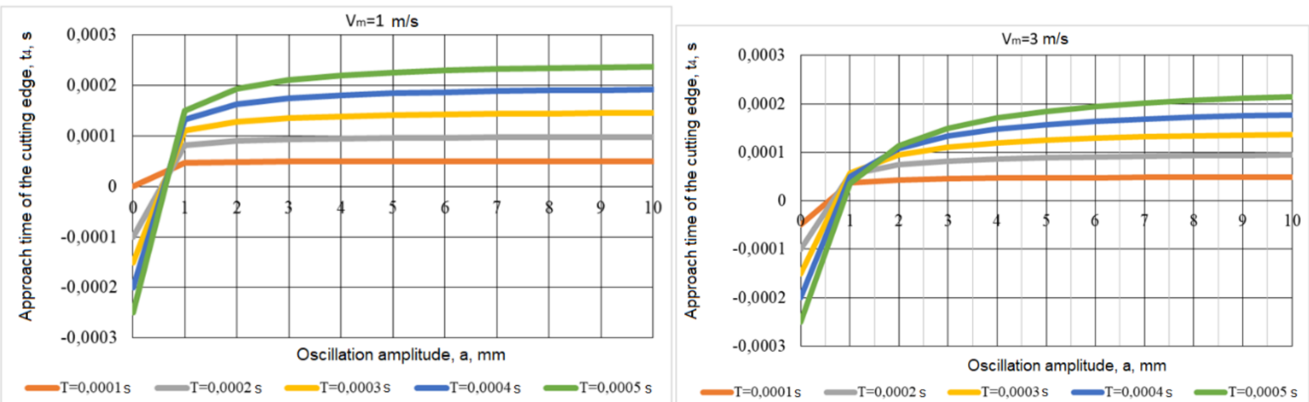
The factors influencing the value of time t_4 are considered. By equating the coordinates of points A and B, expressed through the total speed of the tool, which is the sum of the speed of the base machine V_m and the average vibration speed of the tool v, i.e., $V_m+v=V_m+\frac{2a}{T}$, and the time of its movement, including the time t4:

$$x_A=\frac{T}{2}\cdot(V_m+\frac{2a}{T});\qquad x_B=V_m\cdot T+t_4\cdot(V_m+\frac{2a}{T}),$$

upon transformation, the time is obtained:

$$t_4=\frac{a-0{,}5\cdot V_m\cdot T}{V_m+\frac{2a}{T}}=\frac{\pi}{\omega}\cdot\frac{a\cdot\omega-\pi\cdot V_m}{a\cdot\omega+\pi\cdot V_m}=\frac{\pi}{\omega}\cdot\frac{1-\pi\cdot\frac{V_m}{a\cdot\omega}}{1+\pi\cdot\frac{V_m}{a\cdot\omega}} \qquad (7)$$

For different speeds of the base machine V_m =1 m/s,3 m/s,5 m/s, graphs (Figure 7) were constructed to show the influence of the amplitude of oscillations on the time t_4, taking into account the period T of oscillations. As seen from the graphs, for oscillation periods T=0.0001 s; 0.0002 s; 0.0003 s; 0.0004 s; 0.0005 s with the minimum amplitudes a are as follows: for V_m =1 m/s amplitude a=0.5...0.6 mm, for V_m =3 m/s amplitude a=0.55 mm; 0.6 mm; 0.75 mm; 0.8 mm; 0.85 mm, for V_m =5 m/s amplitude a=0.65 mm; 0.75 mm; 0.85 mm; 1 mm and 1.3 mm.



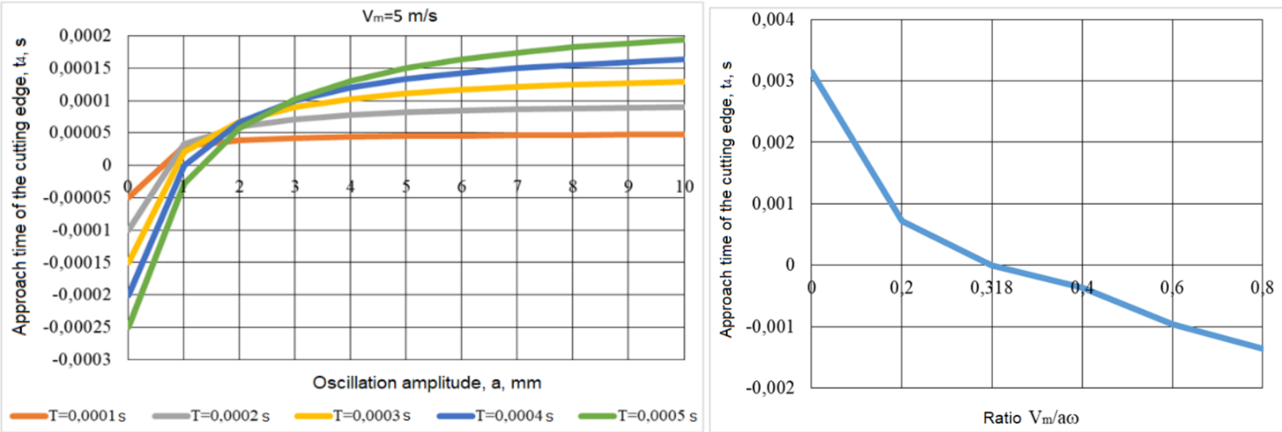


Fig. 7. Influence of oscillation amplitude and parameter $\frac{V_m}{a \cdot \omega}$ on time t_4

Time t_4 increases slowly with increasing oscillation amplitude. Obviously, time t_4 cannot take negative values ($t_4 \geq 0$), since in this case the tool does not leave contact with the soil and vibration cutting mode is not provided. This requirement is met if, according to equation (7), $a \cdot \omega > \pi \cdot V_m$. Then the speed of the base machine has a limitation $V_m < \frac{a \cdot \omega}{\pi} = 0{,}318 \cdot a \cdot \omega$, which is consistent with formula (4). In this case, it is obvious that the parameter is dimensionless $0 < \frac{V_m}{a \cdot \omega} \leq 0{,}318$ (at t_4=0).

In order to clarify the influence of the speed of movement of the base chassis on the time t_4 for the vibration amplitude a = 1 mm; 5 mm, graphs $t_4 = f(V_m)$ was constructed (Fig. 8).

It follows from the graphs that with increasing speed of the base chassis, time t_4 decreases, and more intensely for the vibration cutting process with a lower oscillation frequency.

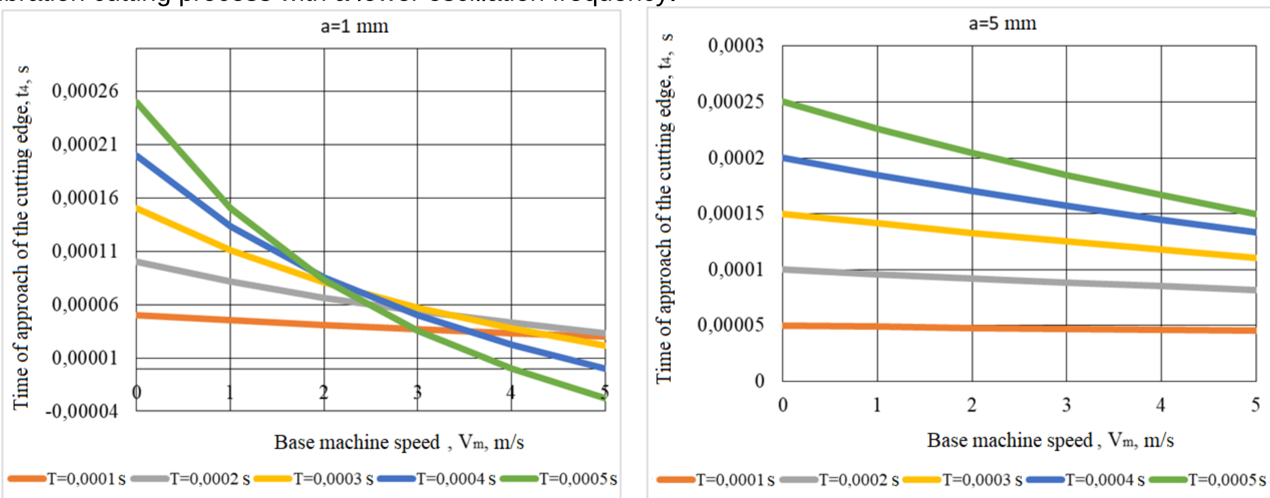


Fig. 8. Influence of the base chassis speed V_m on time t_4

The time t_5 of interaction of the working body with the soil:

$$t_5 = \frac{T}{2} - t_4 = \frac{\pi}{\omega} \cdot \left(1 - \frac{a \cdot \omega - \pi \cdot V_m}{a \cdot \omega + \pi \cdot V_m}\right) = \frac{\pi}{\omega} \cdot \left(1 - \frac{1 - \pi \cdot \frac{V_m}{a \cdot \omega}}{1 + \pi \cdot \frac{V_m}{a \cdot \omega}}\right) \quad (8)$$

Obviously, the time $t_5 \geq 0$ (the maximum value of time $t_5 = \frac{\pi}{\omega}$ occurs when $\frac{V_m}{a \cdot \omega} = 0{,}318$). Reducing the dimensionless parameter $\frac{V_m}{a \cdot \omega}$ shortens the time t_5 of interaction between the working tool and the medium, and, as can be assumed from equation (5), increases the cutting force.

At the same time, the limitation of the dimensionless parameter $0 < \frac{V_m}{a \cdot \omega} \le 0{,}318$ clearly indicates that at high speeds V_m, vibrational cutting can be effective only at very high values of the oscillation frequency.

The time t_2 from the start of the movement of the cutting edge of the disk (point O) to its re-entry into the soil (point B) can be determined from Figure 4:

$$t_2 = T + t_4 = T + \frac{\pi}{\omega} \cdot \frac{1 - \pi \cdot \frac{V_m}{a \cdot \omega}}{1 + \pi \cdot \frac{V_m}{a \cdot \omega}} = \frac{\pi}{\omega} \cdot \left(2 + \frac{1 - \pi \cdot \frac{V_m}{a \cdot \omega}}{1 + \pi \cdot \frac{V_m}{a \cdot \omega}}\right)$$

After determining the time t_2, it is possible to determine V_2 - the initial penetration velocity of the cutting edge of the working equipment into the soil (point B, Figure 3, Figure 4), characterizing the kinetic energy of the tool impact on the soil:

$$V_2 = e \cdot \omega \cdot \sin \omega t_2 + V_m = \frac{a}{2} \cdot \omega \cdot \sin\left(\pi \cdot \left(2 + \frac{1 - \pi \cdot \frac{V_m}{a \cdot \omega}}{1 + \pi \cdot \frac{V_m}{a \cdot \omega}}\right)\right) + V_m$$

It is evident that the penetration velocity V_2 of the working tool into the soil decreases with the increase in the dimensionless parameter $\frac{V_m}{a \cdot \omega}$. When $\frac{V_m}{a \cdot \omega} = 0{,}318$ approaches $V_2 = V_m$ (Figure 9), meaning vibrational cutting ceases, and the process becomes similar to simple static cutting.

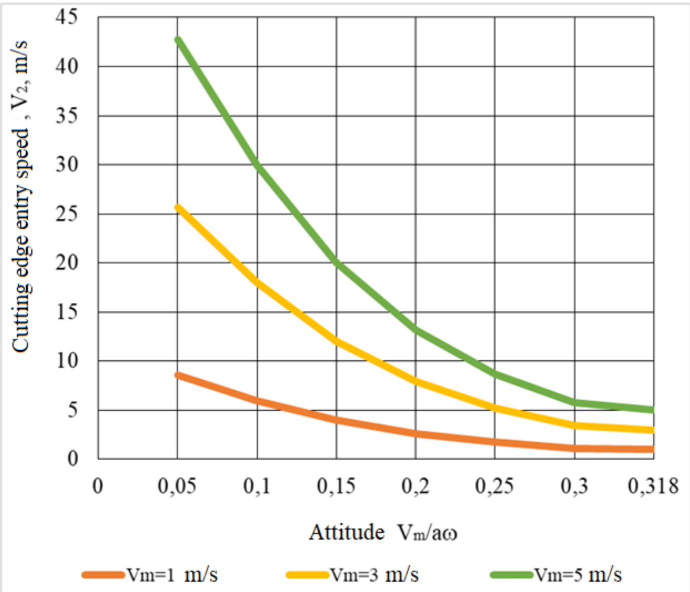


Fig. 9. Influence of the ratio on the penetration velocity of the cutting edge

It is necessary to divide the time t_4 and t_5 (expressions (7) and (8)) by the period T and obtain the dimensionless parameters of time t_4/T and t_5/T , which can be conveniently evaluated as a function of the dimensionless parameter of the interaction speed of the working tool with the medium $\frac{V_m}{a \cdot \omega}$:

$$\frac{t_4}{T} = \frac{1}{2} \cdot \frac{1 - \pi \cdot \frac{V_m}{a \cdot \omega}}{1 + \pi \cdot \frac{V_m}{a \cdot \omega}}; \quad \frac{t_5}{T} = \frac{1}{2} \cdot \left(1 - \frac{1 - \pi \cdot \frac{V_m}{a \cdot \omega}}{1 + \pi \cdot \frac{V_m}{a \cdot \omega}}\right) \qquad (9)$$

In this case, the graphs of dependencies $t_4 = f\left(\frac{V_m}{a \cdot \omega}\right)$ and $t_5 = f\left(\frac{V_m}{a \cdot \omega}\right)$ (Figure 10) remain unchanged with variations in parameters such as V_m, a, and ω.

From the graphs in Figure 10, it can be observed that an increase in the dimensionless parameter $\frac{V_m}{a\cdot\omega}$ leads to a decrease in t_4/T and an increase in t_5/T. The maximum limiting values are $t_5/T=0,5$ at $\frac{V_m}{a\cdot\omega}=0,318$ and $t_4/T=0,5$ at $\frac{V_m}{a\cdot\omega}=0$.

The proportion of periods t_4/T and t_5/T represents an important parameter for the study and verification of vibrational cutting. It is evident that for the maximum manifestation of the vibrational cutting effect and the reduction of cutting resistance, the condition must be met: $\frac{t_4}{T}\to 0,5$ and $\frac{t_5}{T}\to 0$ (or $t5\to 0$, $t4\to 0,5T$), while $t5\neq 0$ ($t4\neq 0,5T$).

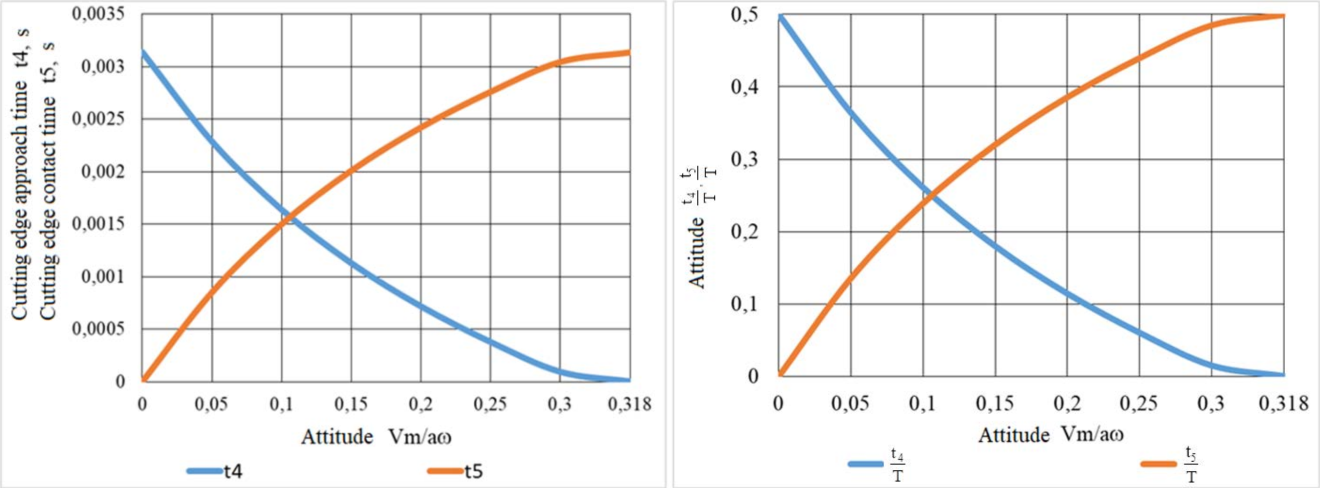


Fig. 10. Influence of the parameter $\frac{V_m}{a\cdot\omega}$ on the time t_4 and t_5 and on the ratios $\frac{t_4}{T}$ and $\frac{t_5}{T}$

Thus, reducing the translational speed of the base machine V_m or increasing the vibrational speed $a\cdot\omega$ can provide a significant reduction in soil cutting forces.

It is known [1, 11] that effective soil cutting is possible only under the condition of a sufficient depth l_τ (Figure 3) of penetration of the cutting edge into the soil, where the depth of penetration ensures the creation of the necessary stress-strain state. This is achieved when the displacement l_τ of the cutting edge in the medium exceeds the value of the plastic deformation of the soil. The condition for soil deformation is $l_m>l_\tau$, $\Delta x>0$, where l_τ is the distance traveled by the cutting edge in contact with the soil.

The displacement of the cutting edge in the soil can be found:

$$l_\tau = V_m\cdot t_5 + v\cdot t_5 = (V_m + \frac{a\cdot\omega}{\pi})\cdot t_5$$

where $v=\frac{2\cdot a}{T}=\frac{a\cdot\omega}{\pi}$ - the average vibrational velocity of the cutting-edge movement.

The distance traveled by the cutting edge in time *T*:

$$l_m = 2\cdot\Delta x + l_\tau = V_m\cdot T = V_m\cdot\frac{2\pi}{\omega}=\frac{V_m}{\omega}\cdot 2\pi\cdot\frac{a}{a}=2\pi\cdot a\cdot\frac{V_m}{\omega\cdot a}$$

In boundary conditions, when $\Delta x\to 0$, $l_m\to l_\tau$ find the displacement l_τ taking into account the dimensionless velocity $\frac{V_m}{a\cdot\omega}$

$$l_\tau = V_m\cdot T = 2\pi\cdot a\cdot\frac{V_m}{\omega\cdot a}=2\pi\cdot a\cdot(0...0,318) \quad (10)$$

3 METHODOLOGY FOR DETERMINING THE PARAMETERS OF VIBRATIONAL CUTTING

To choose rational parameters for the vibrational cutting process, the criterion of the minimum possible values of the time t_5/T is used, at which the cutting force reaches its minimum value. Additionally, the condition of achieving the necessary depth l_τ of the tool blade penetration, sufficient for soil deformation is considered.

To select the amplitude of oscillations, the dependence is used (8.1) $\frac{t_5}{T} = f(\frac{V_m}{a \cdot \omega})$, as well as the dependence (10) $l_\tau = f(\frac{V_m}{a \cdot \omega})$. During vibration, the amplitude *a* of the working tool oscillations must exceed the limit of elastic deformation of the soil. To choose the parameters of the vibrational cutting process, the value of $\frac{t_5}{T}$ is set, from the range 0 to 0.5, which corresponds to one of the values of the dimensionless velocity $\frac{V_m}{a \cdot \omega}$ from the range 0…0,318. For example, based on the condition of ensuring vibrational cutting $t_4 \geq t_5$, assume $t_4 = t_5$, then $\frac{t_5}{T} = 0{,}25$. From the graph $\frac{t_5}{T} = f(\frac{V_m}{a \cdot \omega})$, the corresponding value of the dimensionless velocity parameter $\tau = \frac{V_m}{a \cdot \omega} = 0{,}11$ is found. In addition, the required value of l_τ, the penetration depth of the cutting edge into the soil is used. For average speeds of seeders V_m=8…10 km/h (2-3 m/s), l_τ=10 mm, the amplitude of oscillations from expression (10) is determined:

$$a \geq \frac{l_\tau}{2\pi} \cdot \frac{\omega \cdot a}{V_m} = \frac{l_\tau}{2\pi \cdot (0...0{,}318)} = \frac{0{,}01}{2\pi \cdot 0{,}11} = 0{,}014$$

m = 14 mm.

The amplitude of oscillations of a disc instrument *a* is determined by the dimensionless speed $\frac{V_m}{a \cdot \omega}$ and the minimum required penetration depth of the cutting edge, l_τ, which ensures soil deformation, are known. Knowing the amplitude and assuming the value of the speed V_m of the movement of the base chassis, the expression (4) can be used to determine the required frequency of oscillations *ω*.

For $\frac{V_m}{a \cdot \omega} = 0{,}11$, speed V_m=3 m/s, a=0,014 m, frequency of oscillations:

$$\omega = \frac{V_m}{a} \cdot (\frac{a \cdot \omega}{V_m}) = \frac{V_m}{(0...0{,}318) \cdot a} = \frac{3}{0{,}11 \cdot 0{,}014} = 1948 \text{ s}^{-1}$$ = 18600 oscillations per minute.

Additionally, according to this methodology, having the value of amplitude a and specifying the circular frequency of oscillations ω, it is possible to determine the speed V_m of the base chassis movement. Alternatively, by knowing the speed V_m of the movement of the base chassis and the corresponding frequency of oscillations ω, one can determine the required amplitude. It is also possible to calculate the frequency of longitudinal oscillations of the working tool needed for periodically achieving a negative speed of its absolute displacement.

The proposed methodology allows obtaining rational parameters for the working equipment during the design stage, ensuring a stable mode of vibro-cutting with a disc-working organ.

4 EXPERIMENTAL STUDIES

The aim of conducting experimental research is to validate the theoretical principles, conditions for achieving rational parameters, and modes of operation of the disc vibrational working organ.

In the course of experimental studies, a natural disc-working organ was used, additionally equipped with an inertial vibratory exciter and installed on a specially designed research stand (see Figure 11).

The studies were conducted with the vibrator turned off and then turned on (correspondingly, static and vibrational cutting). The cutting depth was 40 mm and 80 mm. The frequency of oscillations varied from 10 Hz to 50 Hz, and the amplitude ranged from 1 to 5 mm. The experiments were repeated three times.

The stand (Figure 11) consists of a soil trough 1, a traction trolley 2 on which the natural disc working organ 3 is suspended, a traction winch 4 with a multi-channel frequency speed regulator 5. The winch cable is connected to the traction trolley through an electronic dynamometer 6. An inertial generator of vibrations (vibrator) 7 is attached to the frame of the disc working organ, allowing for changes in amplitude and frequency of oscillations within various ranges, also connected to the frequency speed regulator. The frequency of the working organ oscillations is set by the frequency regulator, and the amplitude is adjusted by changing the mass of unbalances and the angle of their installation. The amplitude of oscillations is measured by an electronic vibrometer 8 (VT-27 or Baltech 1470), the sensor 9 of which is connected to the working organ.

Fig. 11. Experimental stand for studying vibrational disc working organs of seeders

A multifactorial experiment was conducted on the research stand. The variable factors included the speed of movement, frequency of oscillations, and amplitude of the working organ's vibrations, with the output parameter being the traction resistance (pull force). Additionally, the deviation of cutting depth from the mean value was determined.

According to the plan of experimental research, the measurement of the traction resistance of the disc working organ was carried out during static and vibrational cutting at two speeds of the working organ's movement. The results of the experiments were processed and presented in the form of graphs.

In the first series of experiments, the change in the cutting force was investigated concerning the direction of vibrations of the disc working organ. The research was conducted at a frequency of 50 Hz, amplitude *a*=4 mm, and a main movement speed ranging from 0.2 m/s for circular oscillations, oscillations directed normal to the direction of the main movement of the setup (vertical), and oscillations coinciding with the direction of the main movement of the setup (horizontal). The results are presented in Figure 12. It was found that when the additional vibrations of the cutting tool are directed along the direction of soil cutting at low cutting speeds, the traction force decreases by 30% compared to other types of vibrations, which almost do not reduce the cutting force compared to static cutting. Moreover, with circular and vertical oscillations, the stability of cutting depth significantly deteriorates, i.e., the depth of the furrow created by the working organ varies widely, exceeding the permissible deviation limits.

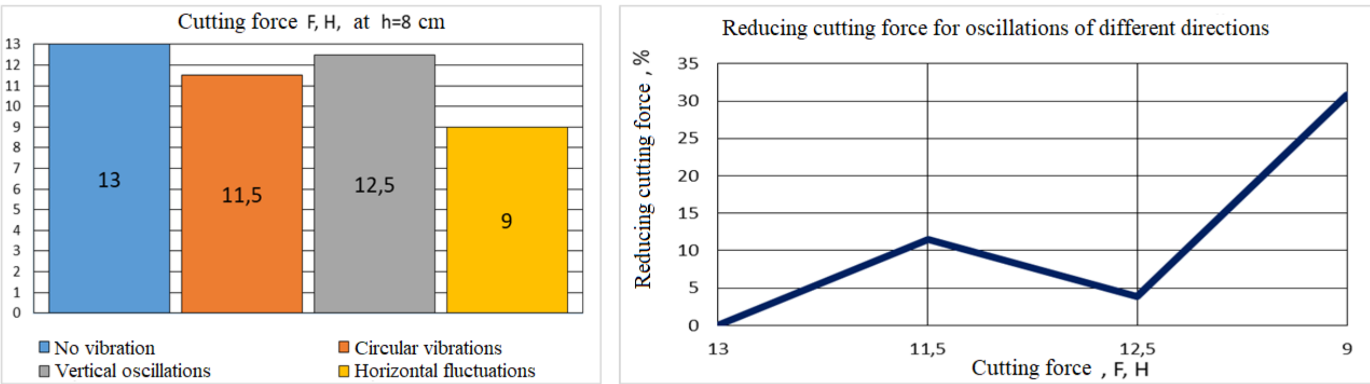


Fig. 12. Influence of the direction of vibrations on the magnitude of cutting force

In the second series of experiments, the variation in the cutting force was investigated concerning the values of the relative dimensionless characteristic $\frac{V_m}{a \cdot \omega}$. The research was conducted for cutting depths of 40 mm and 80 mm.

Initially, the validity of the theoretically obtained dimensionless ratio $\frac{V_m}{a \cdot \omega} \leq 0{,}318$ was determined, and its

comparison with the commonly accepted condition $\frac{V_m}{a \cdot \omega} \leq 1$, for which experiments were conducted to determine the cutting force without vibration (static cutting), with $\frac{V_m}{a \cdot \omega} = 0{,}5$, and $\frac{V_m}{a \cdot \omega} = 0{,}16$ for the movement speed of the working organ V_m=0.2 m/s.
The results are presented in Figure 13.

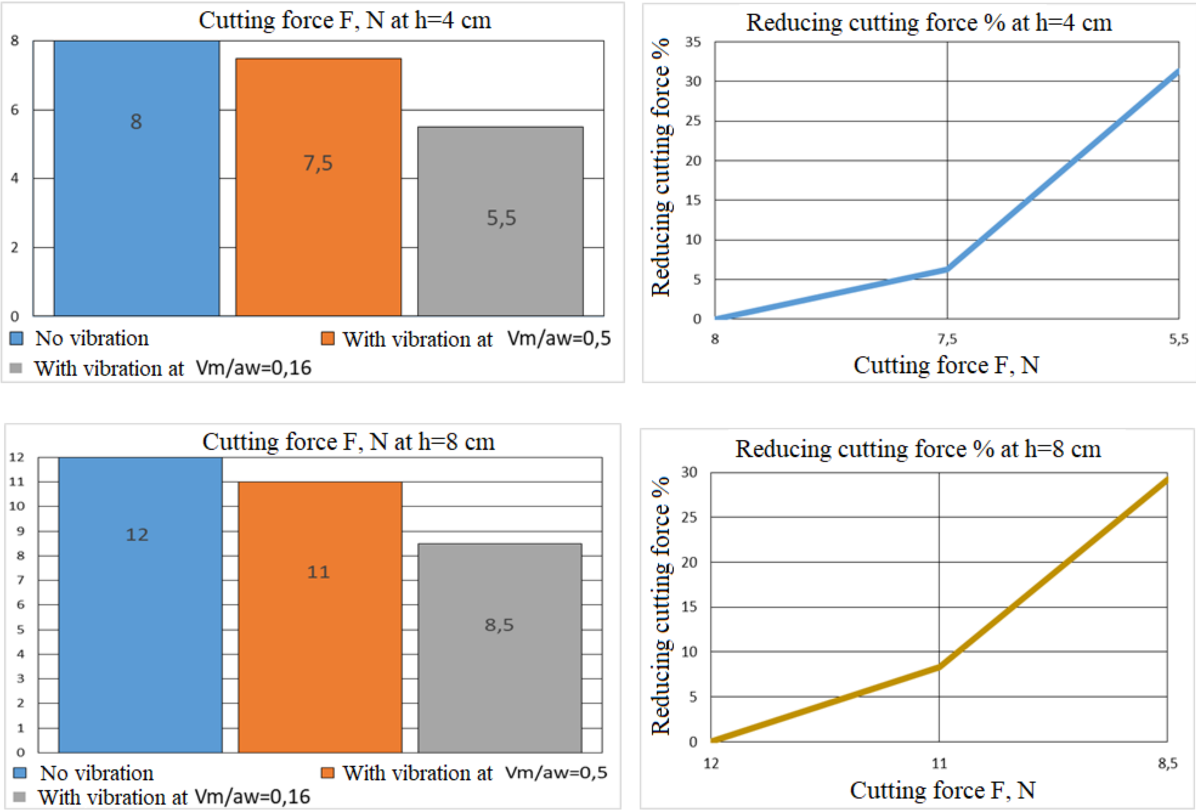
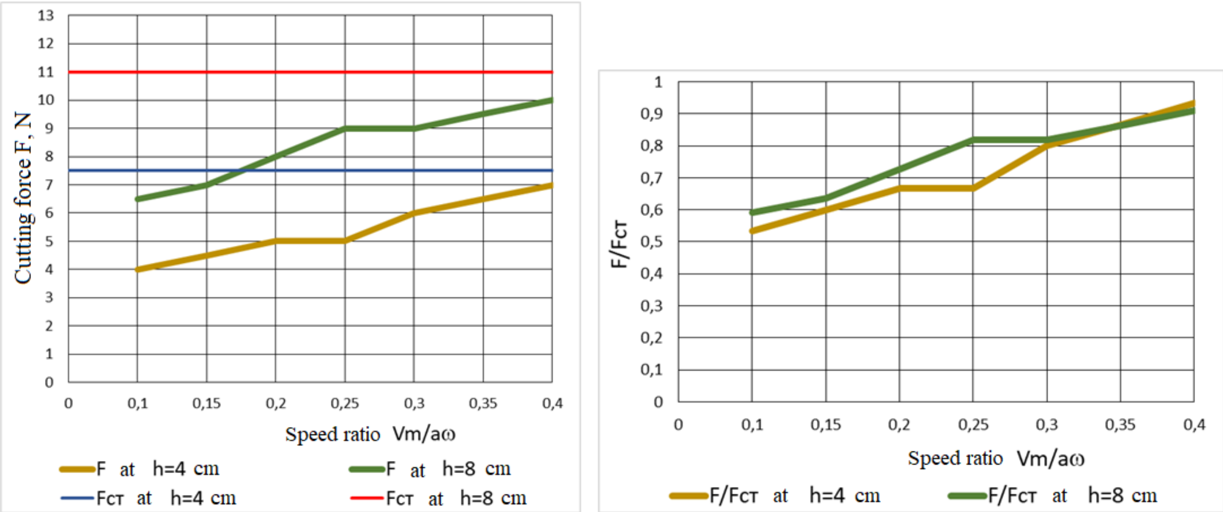


Fig. 13. Cutting force as a function of the parameter $\frac{V_m}{a \cdot \omega}$

The graphs show that vibro-cutting at $\frac{V_m}{a \cdot \omega} = 0{,}5$ practically does not reduce the cutting force, although some effect, apparently due to pseudo-liquidation of the soil, is present. In contrast, vibro-cutting at $\frac{V_m}{a \cdot \omega} = 0{,}16$ reduces the cutting force compared to static cutting by 31% at a cutting depth of 4 cm and by 29% at a cutting depth of 8 cm. This indicates the validity of the theoretically obtained boundaries for the dimensionless ratio $0 < \frac{V_m}{a \cdot \omega} \leq 0{,}318$.

Further experiments were conducted to determine the cutting force for various values of the dimensionless ratio $\frac{V_m}{a \cdot \omega}$ within the established range of 0…0.318 at a movement speed of the working organ V_m=0.1 m/s.

The results are presented in Figure 14.



F_{CT} - static soil cutting force; F - cutting force with a vibrating cutting tool; V_m - translational speed; a,ω - amplitude and frequency of oscillations.

Fig. 14. Dependence of cutting force on vibro-cutting parameters $V_m/(a\cdot\omega)$

Analyzing the graphical dependencies of the traction resistance of the vibrational working organ (Figure 14) as a function of the dimensionless parameter $\frac{V_m}{a\cdot\omega}$, it can be asserted that experimental studies confirm the effectiveness of vibrational impact on the soil cutting process with a disc working organ and its significant influence on the cutting force throughout the range of working parameter variations. It is established that with an increase in the dimensionless ratio $\frac{V_m}{a\cdot\omega}$, the soil cutting process deteriorates, and the cutting force increases. At higher values of $\frac{V_m}{a\cdot\omega} > 0{,}318$, the cutting force approaches the value of static cutting with increased resistance forces, confirming the theoretical justification of the vibrational cutting process parameters.

Experiments have shown that increasing the amplitude, especially the frequency of oscillations, while maintaining translational speed, leads to a reduction in cutting force when decreasing the values of the dimensionless ratio $\frac{V_m}{a\cdot\omega} < 0{,}318$. When reducing the translational speed of the working organs from 0.2 to 0.1 m/s, vibrational effects become more pronounced due to increased intensity of vibration energy impact on the soil mass. The deviation of the average cutting depth from the specified value for all experiments remained within the limits of regulatory requirements.

Thus, based on the results of experimental studies, it can be concluded that the obtained theoretical principles fairly well reflect real working processes in vibrational soil cutting. The use of vibration in the working organ reduces its traction resistance.

5 CONCLUSIONS

For high-speed and high-productivity disc seeders, reducing cutting resistance forces and the energy consumption of soil processing is crucial. This can be effectively achieved by applying vibrational oscillations to the working organs, combined with selecting a rational mode for their vibrational impact on the environment.

As a result of theoretical studies, a mechanical-mathematical model of the vibrational soil cutting process with a disc working organ has been developed. The dimensionless parameter $\frac{V_m}{a\cdot\omega} = 0...0{,}318$ has been identified, determining the boundary between static and vibrational cutting of the disc-working organ, along with the condition limiting the translational speed of the base machine $V_m < 0{,}318\cdot a\cdot\omega$. To manifest the vibro-cutting effect and reduce resistances, it is necessary for $\frac{V_m}{a\cdot\omega} < 0{,}318$ to be less than a certain value. The reduction in cutting forces is attributed to the decrease in the interaction time t_5 of the cutting edge with the soil, an increase in the exit time t_4 of the tool from contact with the soil, and the fulfillment of conditions for dimensionless ratios $\frac{t_4}{T}\to 0{,}5$ and $\frac{t_5}{T}\to 0$. This results in the cutting edge exiting the contact zone with the soil Δx>0.

The proposed method for selecting vibro-cutting parameters, based on the developed mechanical-mathematical model, allows a more reasoned approach to designing working equipment and determining rational parameters that ensure a stable mode of vibro-cutting with a disc working organ.

Experimental studies have confirmed the effectiveness of vibrational impact on the soil cutting process with a disc working organ and the reduction in cutting force. The results demonstrate that the obtained theoretical principles fairly well reflect real working processes during vibrational soil cutting. When oscillations are directed in line with the translational speed of the base machine and the ratio $\frac{V_m}{a \cdot \omega} < 0{,}318$ is within a certain range, vibro-cutting allows for a reduction in the traction resistance of the disc working organ by up to 30%. Correspondingly, energy costs can also be reduced.

To decrease traction resistance and energy consumption, and to increase the speed and productivity of seeding units, their modernization is necessary through the provision of additional vibration to the disc working organs.

6 ACKNOWLEDGMENT

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