Theoretical substantiation of the parameters of the mechanism of autoresonant vibroimpact interaction of cultivator claws with soil

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Abstract. It is proposed to introduce a mechanism with moving masses separated by elastic elements of different rigidity into the design scheme of the cultivator working body to ensure the self-oscillating resonant interaction of the cultivator claw with the soil. The frequencies of the main oscillations of the system with moving masses, corresponding to the range of oscillation frequencies of the cultivator claw in the soil, are determined using the oscillation theory. The oscillation frequency of the cultivator paw was determined experimentally in the soil channel. By calculation, using the obtained equations, the values of the moving masses and the rigidity of the elastic elements of the mechanism of self-oscillating vibro-impact interaction with the soil of the cultivator are found.

1. Problem in general form
When cultivating the soil, the cultivator share with an elastic stance makes an oscillatory motion, with a varying frequency, under the influence of variable soil resistance in periodic phases of compression and chipping of soil blocks [1, 2]. To reduce the resistance of the cultivator claw, it is necessary to provide a self-oscillating process when moving it in the soil [3-5]. In this process, the frequency of natural oscillations of the cultivator claw must coincide with the frequency of the disturbing action of the force, leading to a self-oscillating process [6].

2. Analysis of recent achievements and publications
Studies of domestic and foreign scientists have shown a positive effect from the use of soil-cultivating vibrating working bodies to reduce traction resistance and improve quality indicators [7-11]. The use of vibrating tillage implements increases soil resistance to erosion [12-16]. Therefore, this direction is relevant in the environmental context.

3. The formulation of the goals and objectives of the work
In order to ensure the emergence of self-oscillating resonant interaction of the cultivator claw with the soil, it is proposed to introduce a mechanism with movable masses separated by elastic elements of different rigidity into the design of the cultivator working body (Fig. 1). In this case, cylindrical or semi-spherical rigid impact bulges are installed on the end parts of the intermediate masses, which allow vibroimpact interaction of the masses with the maximum amplitude of oscillations at the
moments of their impact.

The proposed scheme of the cultivator working body contains (Fig. 1) a claw 1, an elastic rack 2, a rack bracket 3, a bottom elastic element 4, a bottom movable mass 5, an upper elastic element 6, an upper movable mass 7, impact bulges 8 on movable masses and a cylindrical vertical axis 9 for installing moving masses with intermediate elastic elements.

To find the range of vibration frequencies corresponding to the vibration frequencies of the cultivator claw during soil cultivation, let us determine the frequencies of the main vibrations of the system with moving masses \( m_1 \) and \( m_2 \) shown in Fig. 1. Since the masses of elastic elements are insignificant in comparison with the masses of the claw and strut, they can be neglected.

In the proposed in Fig. 1 the scheme of the cultivator working body, we take the vertical displacements \( y_1 \) and \( y_2 \) of the masses \( m_1 \) and \( m_2 \) from the equilibrium position as generalized coordinates. Let us consider the distribution of energies in this system of a cultivator working body with movable masses on elastic elements.

![Figure 1. Scheme of a cultivator working body with a mechanism of self-oscillating vibroimpact interaction with the soil: 1 - claw; 2 - elastic rack; 3 - bracket; 4 - bottom elastic element; 5 - bottom movable mass; 6 - upper elastic element; 7 - upper movable mass; 8 - impact bulges; 9 - cylindrical vertical axis; F - force of resistance to advancement of the claw in the soil.](image)

4. Presentation of the basic material investigations

The expression for determining the kinetic energy \( K \) of this system will have the following form:

\[
K = 0.5(m_1 y_1^2 + m_2 y_2^2),
\]

where \( m_1 \) and \( m_2 \) – respectively, the bottom and upper moving masses;

\( y_1 \) and \( y_2 \) – respectively, vertical displacements of the bottom and upper masses.

The potential energy of such a system can be defined as a system of potential energies of deformed elastic elements and potential energies of moving masses in a gravity field according to the following expression:

\[
\hat{I} = \hat{I}_1 + \hat{I}_2,
\]

where \( \hat{I}_1 \) – potential energy of deformed bottom and upper elastic elements;

\( \hat{I}_2 \) – potential energy of the bottom and upper moving masses.
Taking into account the rigidity coefficients of the bottom and upper elastic elements and the displacement of the moving masses, the equations for determining the potential energy $I_1$ of the deformed elastic elements of this system will take the following form:

$$I_1 = 0.5\lambda_1(l_1 + y_1)^2 - 0.5\lambda_1l_1^2 + 0.5\lambda_2(l_2 + y_2 - y_1)^2 - 0.5\lambda_2l_2,$$

(3)

where $\lambda_1$ and $\lambda_2$ – rigidity coefficients of the bottom and upper elastic elements, respectively; $l_1$ and $l_2$ – static deflections, respectively, of the bottom and upper elastic elements.

The potential energy of the bottom and upper moving masses in the gravity field (Fig. 1) is determined by the expression:

$$I_2 = -m_1gy_1 - m_2gy_2,$$

(4)

where $m_1$ and $m_2$ – respectively, the values of the bottom and upper moving masses; $g$ – acceleration of gravity; $y_1$ and $y_2$ – respectively, vertical displacements of the bottom and upper moving masses.

Taking into account expressions (3) and (4), we obtain a formula for determining the potential energy in this system in the following form:

$$I = 0.5\lambda_1(l_1 + y_1)^2 - 0.5\lambda_1l_1^2 + 0.5\lambda_2(l_2 + y_2 - y_1)^2 - 0.5\lambda_2l_2 - m_1gy_1 - m_2gy_2$$

(5)

Under the condition of equilibrium of the system under consideration in the cultivator working body (Fig. 1), we transform this expression to the following form:

$$\frac{dI}{dy_1} = \lambda_1l_1 - \lambda_2l_2 - m_1g = 0,$$

(6)

$$\frac{dI}{dy_2} = \lambda_2l_2 - m_2g = 0.$$

(7)

Based on these transformations, we finally obtain the formula for determining the potential energy of the proposed system in the following form:

$$I_1 = 0.5[(\lambda_1\lambda_2)y_2 - 2\lambda_2y_1y_2 + \lambda_2y_2^2].$$

(8)

Using the obtained expressions for the kinetic $K$ and potential $I$ energies, we determine the values of the coefficients of rigidity $\lambda$ and inertia $\mu$ in the following form:

$$\lambda_{11} = \lambda_1 + \lambda_2; \quad \lambda_{12} = -\lambda_2; \quad \lambda_{22} = \lambda_2;$$

$$\mu_{11} = m_1; \quad \mu_{12} = 0; \quad \mu_{22} = m_2.$$

The frequency equation for this system [3] has the following form:

$$(\lambda_{11} - \mu_{11}k^2)(\lambda_{22} - \mu_{22}k^2) - (\lambda_{12} - \mu_{12}k^2)^2 = 0.$$  

(9)

After substituting the rigidity and inertia coefficients into the frequency equation (9), we obtain an expression in the form:

$$(\lambda_1 + \lambda_2 - m_1k^2)(\lambda_2 - m_2k^2) - \lambda_2^2 = 0.$$  

(10)

Transforming equation (10), we obtain:

$$k^4 = \left[\frac{\lambda_2m_1 + (\lambda_1 + \lambda_2)m_2}{m_1m_2}\right]k^2 + \frac{\lambda_1\lambda_2}{m_1m_2} = 0.$$  

(11)

Then the formulas for calculating the frequencies of the main vibrations of the bottom and upper moving masses on elastic elements as part of the cultivator working body will have the following form:

for bottom moving mass:
\[ k_1 = \sqrt{\frac{\lambda_2 m_1 + (\lambda_1 + \lambda_2) m_2}{2m_1 m_2}} - \sqrt{\left(\frac{\lambda_2 m_1 + (\lambda_1 + \lambda_2) m_2}{2m_1 m_2}\right)^2 - \frac{\lambda_1 \lambda_2}{m_1 m_2}}; \]  
\hspace{2cm} (12)

for upper moving mass:

\[ k_2 = \sqrt{\frac{\lambda_2 m_1 + (\lambda_1 + \lambda_2) m_2}{2m_1 m_2}} + \sqrt{\left(\frac{\lambda_2 m_1 + (\lambda_1 + \lambda_2) m_2}{2m_1 m_2}\right)^2 - \frac{\lambda_1 \lambda_2}{m_1 m_2}}. \]  
\hspace{2cm} (13)

For the emergence and maintenance of autoresonant interaction of the cultivator claw with the soil with the possibility of impact of the bottom and upper moving masses, the frequencies of their main oscillations should be determined from the condition that the oscillation frequency of the cultivator claws during tillage \( k_c \) should be in the range of frequencies of the main oscillations of the bottom \( k_1 \) and upper \( k_2 \) moving masses. This condition is met by selecting the values of the bottom \( m_1 \) and upper \( m_2 \) moving masses and rigidities of the bottom \( \lambda_1 \) and upper \( \lambda_2 \) elastic elements:

\[ k_1 \leq k_c \leq k_2 \]  
\hspace{2cm} (14)

where \( k_c \) – oscillation frequency of the cultivator claw during tillage.

The minimum and maximum soil shearing forces are determined by the formulas [5]:

\[ R_{ck \min} = \frac{2S}{\pi^2 v_{\max}}; \]  
\hspace{2cm} (15)

\[ R_{ck \max} = \frac{2S}{\pi^2 v_{\min}}; \]  
\hspace{2cm} (16)

\[ R_{ck cp} = \frac{R_{ck \min} + R_{ck \max}}{2}; \]  
\hspace{2cm} (17)

where \( v_{\min}, v_{\max} \) – deformation index of soil, respectively, minimum and maximum; \( S \) – claw working surface area.

The rigidity of the bottom and upper elements is determined by the following formulas:

\[ \lambda_1 = \frac{R_{ck \min}}{(i-1)x_1} = \frac{R_{ck \min}}{(2-1)m_1 v_1^2} = \frac{2R^2_{ck \min}}{m_1 v_1^2}; \]  
\hspace{2cm} (18)

where \( x_1 \) – deformation of the bottom elastic element, determined by the expression:

\[ x_1 = \frac{m_1 v_1^2}{2R_{ck \min}}; \]  
\hspace{2cm} (19)

where \( v_1 \) – bottom mass \( m_1 \) movie speed;  
\( i \) – the number of masses in the mechanism, in this case \( i=2 \),

\[ \lambda_2 = \frac{R_{ck \max}}{(i-1)x_2} = \frac{R_{ck \max}}{(2-1)m_2 v_2^2} = \frac{2R^2_{ck \max}}{m_2 v_2^2}; \]  
\hspace{2cm} (20)

where \( x_2 \) – deformation of the upper elastic element, determined by the expression:

\[ x_2 = \frac{m_2 v_2^2}{2R_{ck \max}}; \]  
\hspace{2cm} (21)

\( v_2 \) – upper mass \( m_2 \) movie speed.

If the elastic element is made in the form of a spring, then the number of turns of the bottom and upper springs is determined by the following formulas:

\[ n_1 = \frac{Gd^4}{8D^3\lambda_1}; \]  
\hspace{2cm} (22)

where \( G \) – spring element material shear modulus;  
\( d \) – bar diameter;
\( D \) – average spring diameter,

\[
\frac{6d^4}{8D^3\lambda_2} = 23.
\]

Having determined the rigidity of the bottom and upper elastic elements according to the formulas (18) and (20), taking into account the minimum and maximum values of the deformation index of the soil, processed by the cultivating working body according to the formulas (12) and (13), the values of the bottom and upper moving masses are determined, ensuring the operation of the cultivator claws in autoresonant vibro-impact mode.

With one movable mass \( m_1 \), on the vertical axis of the C-shaped rack, resting on an elastic element with rigidity \( \lambda_1 \), under the action of a periodic disturbing force \( \bar{P} \), the kinetic energy of such a system (Fig. 2) with one degree of freedom is determined by the expression:

\[
K = 0.5m_1\dot{y}_1^2;
\]

where \( \dot{y}_1^2 \) – moving mass \( m_1 \) speed.

\[\begin{figure}
\textbf{Figure 2.} Scheme of a cultivator working body with a vibro-impact mechanism with soil with one degree of freedom: 1 – claw; 2 – elastic rack; 3 – rack bracket; 4 – elastic element; 5 – movable mass; 6 – impact bulges; 7 – vertical cylindrical axis; \( \bar{P} \) – the force of resistance to the advancement of the claw in the soil; \( P \) – periodic disturbing force.
\end{figure}\]

The potential energy of this system with one degree of freedom is determined by the following expression:

\[
J = 0.5\lambda_1 y_1^2;
\]

The differential equation of moving of this system has the following form:

\[
m_1\ddot{y}_1 + \lambda_1 y_1 = \bar{P}.
\]

After transforming this equation, we get an expression (27) in the form:

\[
\ddot{y}_1 + \frac{\lambda_1}{m_1} y_1 = \bar{P}.
\]

As a result of solving this equation (28), we obtain an expression for determining the frequency of oscillations in a system with a moving mass \( m_1 \) on an elastic element with rigidity \( \lambda_1 \) as part of a
A cultivator working body in the following form:

\[ k = \frac{\lambda_1}{m_1} \]  

(28)

Experiments carried out in the soil canal of the research laboratory of bionic agroengineering (Fig. 3) showed that when a cultivator working body containing a lancet claw on a C-shaped elastic rack moves in the soil at depths from 0.08 m to 0.16 m at speeds from 1 to 2 m/s, the frequency range of its oscillations is \( k_C = 0.70-1.63 \) Hz.

By calculation using formulas (12), (13) using the Mathcad 2001 Professional software, the values of the moving masses and the rigidity of the elastic elements of the mechanism of self-oscillating vibroimpact interaction with the soil of the cultivator working body are found, under which the condition (14): \( m_1=2.8\text{kg}, m_2=2.1\text{kg}, \lambda_1=100\text{N/m}, \lambda_2 = 150 \text{N/m} \).

For a cultivator working body with a vibroimpact mechanism with soil with one movable mass (see Fig. 2), the vibration frequency in a system with a movable mass \( m_1 = 2.8 \) kg on an elastic element with rigidity \( \lambda_1 = 100 \text{ N/m} \) will be \( k = 0.95 \text{ Hz} \), which fits into the range vibration frequencies of the cultivator working body in the soil.

5. Conclusion

Thus, the found values of the values of the moving masses and rigidity of elastic elements are suitable both for the mechanism of self-oscillatory vibro-impact interaction with the soil of a cultivator working body with two moving masses, and with one moving mass.

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