МЕХАНІКО-ТЕХНОЛОГІЧНІ ПРОЦЕСИ, ВИКОНАВЧІ ОРГАНИ ТА МАШИНИ ДЛЯ РОСЛИННИЦТВА

UDC 631-356.02

DEVELOPMENT OF MAIN PROVISIONS OF THE THEORY OF IMPACT INTERACTION OF A VIBRATING DIGGING WORKING TOOL WITH BEET ROOT

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Annotation

The problem. When digging sugar beet root out of the soil by using a vibration digging working tools, there occur impact contacts of the working tools and sugar beet roots placed in the soil. Such phenomena is formed mainly in conditions of dry and solid soil. The consequence of this is a significant impact contact tails breaks, chips or damage of the side surfaces of roots, which leads ultimately to a non-return losses on sugar mass.

The purpose. Therefore there is a need to develop the basic provisions of the refined theory of impact interaction of a vibrating digging working tool with the body of the sugar beet root fixed in the soil, and on the basis of the results obtained to justify rational kinematic and structural parameters of advanced vibration digging working tool.

Methods of investigation. Within the research there was used the methods of higher mathematics, theoretical mechanics, programming and numerical calculations on the PC.

Results. 1. We have developed a refined theory of impact interaction of digging of the working body of the sugar beet harvester with the body of sugar beet root during vibratory digging of sugar beet roots from the dry and solid soil.

2. On the basis of obtained equations and their numerical solution by PC programme it was possible to define the kinematic and structural parameters of vibration digging working tool that will ensure the conditions not to damage or break the tails of the sugar beet roots during their digging out from the dry and solid soil.

3. We have investigated the so-called symmetric impact of the digging working body and the body of sugar beet root.

Conclusions. There was developed a refined theory of the impact interaction of the digging working tool with the sugar beet root, fixed in the soil. Based on a obtained equation of the impact interaction, which acts in two points, there was determined an impact impulse and maximal impact force, which occur at a specified impact interaction. There was obtained an analytical expression for determining the permissible vibration frequency of the vibrating digging working tool on the basis of the conditions not to damage the beet roots with regard of its design parameters and the forward speed of the sugar beet harvester. It allows to define the desired frequency when digging sugar beet roots from the soil.

Key words: sugar beet root, harvest, vibrations, digging working tool, impact impulse, vibration frequency, the equation of the impact interaction, design parameters.

Introduction

Currently, for the harvesting of sugar beet roots there are widely used vibration digging working tools, which are installed on sugar beet digging harvesters, produced in many countries around the world. Such method of the digging of the sugar beet root from the soil has several advantages compared with other methods, particularly in a dry and solid soil. Namely, when a vibrating digging is used there is achieved the most complete cleaning of the side surfaces of the sugar beet roots from adhering soil, as well as minimal damage of the sugar beet roots. In addition, due to the vibratory destruction of the soil surrounding the roots, there can be observed the intensive decreasing of the specific resistance of the forward movement of digging tools that finally results in lower energy requirements for the implementation of this technological process. Therefore, namely this technological process of harvesting of the sugar beet roots requires a more deep analytical research and further development in order to create more effective working tools for sugar beet digging. In relation to sugar beet harvesters as a main requirement can be considered the quality of the sugar beet roots from the soil without damage of the roots (cliffs on the root tails, slices, chips and heavy damage to the side surfaces) and losses (in the soil, in the form of broken and remaining there or tails on the their surface). It is obvious that the probability of the damage of the sugar beet roots and their losses exists, in the greatest extent, during the direct interaction of the digging working tools with the sugar beet roots located (actually fixed) in the soil. This is especially true for vibrating digging working tools, working in dry soil conditions during sugar beet harvest. Therefore there is a need for theoretical study of the interaction impact of the vibrating digging working tool and sugar beet root fixed in the soil and on the basis of the results obtained to determine the kinematic and design parameters of the improved working body that ensures the process of sugar beet roots digging from the soil without damage.

Therefore, there is analysed the initial impact contact interaction of the digging working tool and body of the sugar beet root and subsequent of its removing from the soil. Such approach can be considered as a most accurate and complex task in the area of mechanization of the sugar beet harvest.

Analysis of the latest research and publications

Currently, there exist a number of publications presenting new results of theoretical and experimental investigation concerning the digging process of the sugar beet roots from the soil. So, fundamental theoretical investigations of the vibration process of digging of sugar beet roots from the soil are given in [1-7].

However, the analytical study of the impact interaction between the vibration digging working tool and sugar beet root, fixed in the soil root, there is not considered. Only in publications [8, 9] there are presented some experimental data obtained in the study of the interaction of a pendulum impact with the head of sugar beet root.

Published earlier theoretical studies of the impact interaction of vibrating digging working tool and sugar beet root in the symmetric and asymmetric of its capture are not sufficient to accurately reflect the full extent of the actual process, which occurs in such impact interaction [10, 11]. Therefore there is a need for a more comprehensive and inclusive investigation of the technological process. It means that it is necessary to develop basic fundamentals of the revised theory of symmetric impact of vibrating digging working tool and sugar beet root.

Aim of the research

To develop the basic provisions of the revised theory of the impact interaction of vibration digging working tool with the body of the sugar beet root fixed in the soil, and on the basis of the results obtained to justify rational kinematic and design parameters of improved vibration digging working tools.

In general, the obtained results of analytical studies should be used for further improvement of the technological process of digging of sugar beet roots from the soil, based on the conditions not to damage the roots.

Methods used in research

For creating a refined theory of symmetric impact of the vibration digging working tool and sugar beet root there were used the methods of higher mathematics, theoretical mechanics, in particular, the theory of vibrations and impact theory. Theoretical studies were carried out on the basis of the general theory of vibration digging of the sugar beet roots, presented in [2-7, 15, 17]. Obtained final equations are solved numerically on a PC with the using of own software.

Results of the research

In a first step we consider the physical process of impact interaction of a vibrating digging working tool with a sugar beet root during its extraction from the soil. It was found that during the forward movement and approaching of the vibrating digging working tool to the sugar beet root, as a result of vibrating of the digging shares in longitudinal vertical plane, the crushed soil particles located between shares and sugar beet root actually are not accumulated.

Therefore, the first contact of the digging shares with the side surface of sugar beet root is direct or, in extreme cases, through a sufficiently thin layer of the soil. Thus, during an approach of the vibrating shares of digging working tool occurs an impact, that can be characterized by an impact pulse of considerable value.

Since impact pulse has a finite value, and it acts in a very short period of time, the impact force will has a significant value, which will greatly exceed all other forces, which will act at that moment on a sugar beet root.

Taking into account the fact that sugar beet root is still sufficiently fixed in a soil, there is a risk of its breaking or destruction during impact (what very often happens during harvest, especially when soil is very solid and hard, having decreased soil moisture content). Let us first consider in more details some of the common position of impact interaction of tools of mechanical systems. It should be noted that in the study of impact interactions, there is often believed that the duration of the impact is equal (or close) to zero and, therefore, it is considered that the velocities of the tools that collide, are changed instantly to some finite value.

The positions of the bodies are not changed, so the presence in the mechanical system of elastic bonds does not affect the duration of the impact. This is because the deformations of said links, during the impact, do not appear, and therefore does not occur the reaction of these links.

If there are in mechanical systems some viscous components, then during the impact, there appear responses of the relationships, however, these reactions are of finite size (since the velocity also have finite values), and therefore their pulses during the impact are equal to zero [12].

Typically, the further (after impact) the movement will be carried out in different ways, depending on the presence or absence of a viscous or elastic ties. Since, during the collision of the vibrating digging working tool on the sugar beet root in its lower part there is not loosened soil (root of the sugar beet in its lower part is actually fixed in the layer of soil). During this impact this soil plays the role of elastic or viscous buffer (depending on the soil composition and soil moisture in the soil layer).

Thus, it is clear that the harder and drier the soil is, the above statements are correct and completely adequate to the real process of impact of the digging working tool at its contact with the sugar beet root located in the soil.

And, since during the impact interaction occurs the breaking of the tail of the sugar beet root or demaging and it is the most likely, which is always the case during the real harvest, especially when the root is in the solid and dry soil. Such case of fixing of the sugar beet root in the soil should be investigated analytically.

To solve this problem, in a first step it is very necessary to develop a force scheme of the impact interaction of a vibrating digging working tool with the body of sugar beet root. It is very important to know what happens during collision of the digging working tool with the sugar beet root.

For this, we present the vibratory digging working tool in the form of two wedges (share-type digging working tool for digging of sugar the sugar beet roots consists namely of two digging planes – shares) $A_1B_1C_1$ and $A_2B_2C_2$, and each of them has in the space the slopes at an angle α, β, γ and which are set with respect to each other in such a a way that they form a working channel, the back of which narrows (Fig. 1). These wedges oscillate in a longitudinal-vertical plane, and the direction of translational movement of vibrating digging working tool is presented by the arrow. We suppose that the sugar beet root is completely in the soil. However, in the moment of impact interaction, the soil surrounding the root has a varying degree of connection with the sugar beet root. Thus, the front ends of the digging shares (even before their plane will be in contact with the body of root) are loosening the top layer of soil from the two sides around the root. The thickness of the soil layer is determined by the depth of digging of the vibrating working tool in the soil.

Therefore, at a given depth, the connection of the sugar beet root with the soil will be more attenuated. Below a depth of digging of the working tool in the soil this relationship of the soil with the sugar beet root is unbroken and, therefore, more durable. Separation zone of said different layers of the soil on the Fig. 1 is presented by a conventional line.

We consider that the impact interaction of the sugar beet root, which is approximated by a cone-shaped body, with the surfaces of the two wedges $A_1B_1C_1$ и $A_2B_2C_2$, has symmetrical form, at the points K_1 and K_2. Moreover, the impact contact may occur, directly or through a sufficiently thin layer of soil between the surface of the wedge and sugar beet root.

For an analytical description of the impact process it is necessary to select the system of coordinate axes. We associate with vibrating digging working body the Cartesian coordinate system *Oxyz*, the center *O*, which is located in the middle of the working tool of the narrowed channel of the working tool, the axis *Ox* coincides with the direction of its forward movement, the axis *Oz* direction is up, and the axis *Oy* is directed to the right side of the working tool.

We will show the forces that arise from the interaction of the vibrating digging working tool with the body of the sugar beet root (Fig. 1).

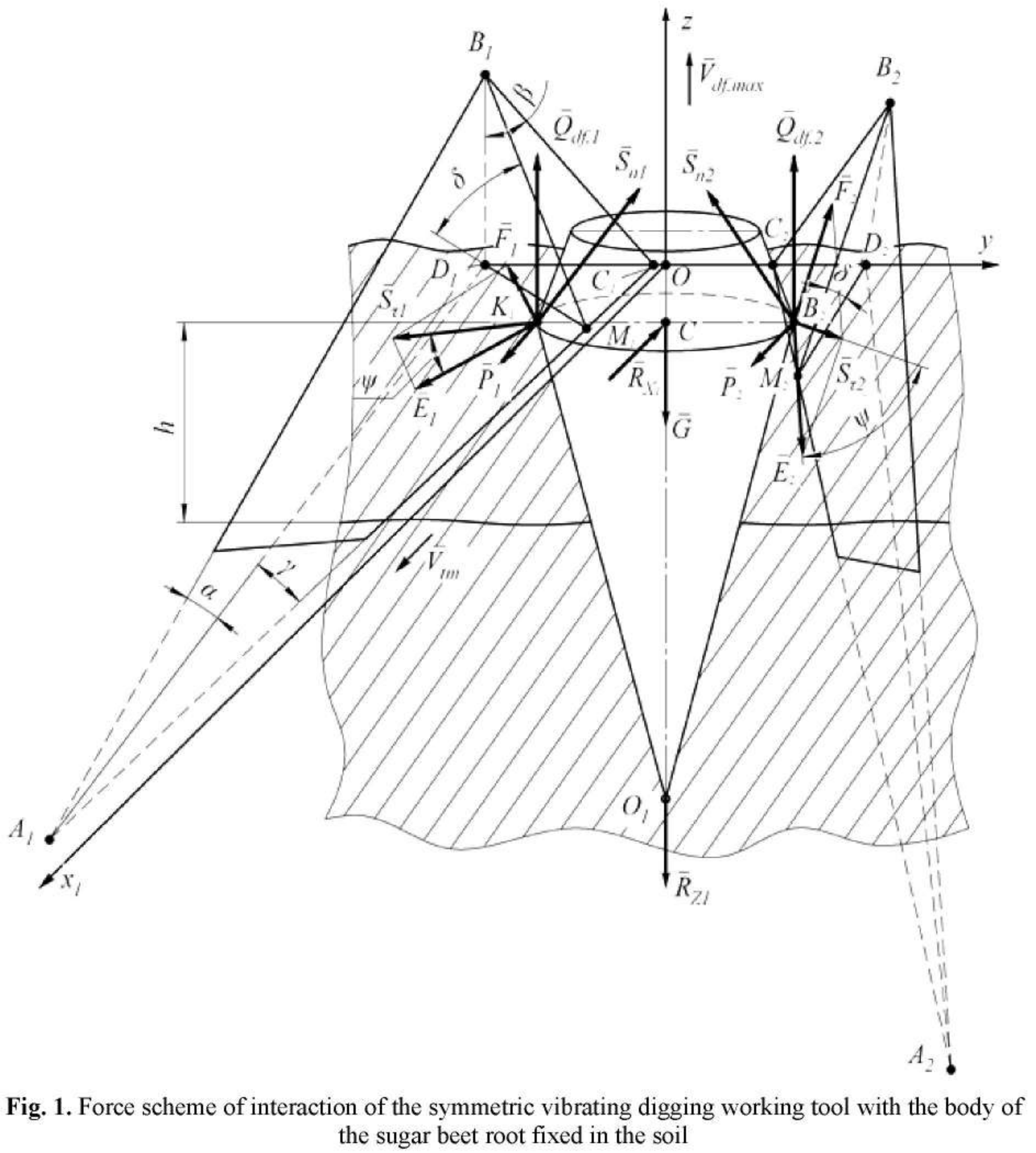

Fig. 1. Force scheme of interaction of the symmetric vibrating digging working tool with the body of the sugar beet root fixed in the soil

From vibrating digging working tool on the sugar beet root fixed in the soil, there is transmitted the vertical disturbing force $\bar{Q}_{df.}$, which is created by digging shares, and which varies according to the harmonic law. In the analytical form the law of variation of the given disturbing force may have the following form:

$$Q_{df.} = H \sin \omega t, \quad (1)$$

where H – the amplitude of the disturbing force; ω – frequency of the disturbing force.

Since the disturbing force is applied to the body of the sugar beet root from both sides, therefore on the force scheme (Fig. 1) it is represented by two components $\bar{Q}_{df.1}$ and $\bar{Q}_{df.2}$, which are attached at points K_1 and K_2 at a distance h from the surface of a unloosened soil in which the sugar beet roots are fastened by their lower part (below the depth of the digging working tool).

Due to the fact that in this case there is a symmetric interaction of vibrating digging working tool with sugar beet root, the capture of sugar beet root by digging shares is performed equally on both sides (at the points K_1 and K_2), and will take place the following ratio:

$$Q_{df.1} = Q_{df.2} = 0,5H \sin \omega t . \quad (2)$$

Taking into account that vibrating digging working tool moves progressively in direction of the axis *Ox*, therefore in the direction of the *Ox* axis there are also active driving forces $\overline{P}_1$ and $\overline{P}_2$, which are also attached to the points K_1 and K_2.

In addition, in points of contact K_1 and K_2, there are frictional forces $\overline{F}_{K1}$ и $\overline{F}_{K2}$ acting to oppose of the slipping of sugar beet root on the working surfaces of the wedges $A_1B_1C_1$ and $A_2B_2C_2$ of the digging working tool. In the center of gravity of the sugar beet root (point *C*) there is acting the weight force of the sugar beet root G_k.

Forces causing the connection of the sugar beet root with the soil in the direction of *Ox* andи *Oz* axes are denoted by $\overline{R}_x$ and $\overline{R}_z$ and, respectively. And finally, during the impact on the sugar beet root crop from the side of the vibrating digging working tool there are acting impact pulses $\overline{S}_{n1}$ and $\overline{S}_{n2}$, which are also applied at the points K_1 and K_2, and in the symmetric interaction takes place also the ratio: $S_{n1} = S_{n2}$. These shock pulses $\overline{S}_{n1}$ and $\overline{S}_{n2}$ are directed along the normals to the surfaces of shares, e.t. in normal direction to the planes $A_1B_1C_1$ andи $A_2B_2C_2$ respectively.

Furthermore, the tangential impact pulses $S_{\tau1}$ and $S_{\tau2}$ ($S_{\tau1} = S_{\tau2}$) act on the wedge surfaces. According to the Rous hypothesis, the relationship between the quantities of the tangent and normal impact pulses is formulated similarly to Coulomb law of friction, and namely [13]:

$$S_\tau \le f\, S_n , \quad (3)$$

where f – dynamic coefficient which characterizes the properties of the surfaces of bodies that collide (in general, this ratio can be different from the coefficient of friction in the case of the relative un-separated slippage of the bodies). The inequality sign refers to the case when the tangential momentum is so small that there is no slippage of the bodies. And only in the case of slippage of the bodies in this relation should be taken an equal sign.

We factorize (decompose) the tangential impact pulses $\overline{S}_{\tau1}$ and $\overline{S}_{\tau2}$ on components $\overline{F}_1$ and $\overline{F}_2$, perpendicular to the lines A_1C_1 and A_2C_2 respectively, and components $\overline{E}_1$ and $\overline{E}_2$, which are parallel to lines A_1C_1 and A_2C_2, also respectively (Fig. 1).

Thus, we obtain an expression for the tangential impact pulses:

$$\overline{S}_{\tau i} = \overline{F}_i + \overline{E}_i , \; i = 1, 2 . \quad (4)$$

Further, it is obvious that the angle ψ between the component $\overline{E}_i$ and the vector $\overline{S}_{\tau i}$ ($i = 1, 2$), in a first approximation depends on the ratio $V_{d f.\max} \cdot V_t^{-1}$. Also, presented vectors $\overline{S}_{\tau1}$ and $\overline{S}_{\tau2}$ allowed subsequently to find their projections on the axis *Ox* и *Oy*.

Since the vibrating digging working tool simultaneously moves forward in the direction of the *Ox* axis and oscillates in the direction of the *Oz* axis, it is quite obvious that the impact pulses $\overline{S}_{n1}$ and $\overline{S}_{n2}$ can always be decomposed into components along the axes *Ox* и *Oz*. It is also quite obvious that the shock pulse component along the *Ox* axis during impact contact for any root will be the same as the speed of translational motion of the digging working tool is constant.

The component of the impact pulse on *Oz* axis can have different value depending on the speed of oscillation of the vibrating digging working tool in the vertical plane. Furthermore, since the sugar beet root has a conical shape, then during motion of the vibratory digging working tool in downward direction, the vertical component of the impact pulse will actually absent. In this case, the impact pulse will occur only during the forward speed of the digging working body.

Let us examine in more detail the vibration motion of the vibrating working tool. We assume here that vibrating working tool first moves up from its lower position "$-a$" to its top position "a" (where a – the amplitude of the working tool vibrations), and then, on the contrary, moves down from its top position "a" to lower position "$-a$". Thus, the vibrations of the vibrations of the vibrating digging working tool should be carried out according to the following harmonic law:

$$z_k = -a\cos\omega t\,, \qquad (5)$$

where z_k – working body deviation from the horizontal axis about which the oscillations are carried out; ω – the frequency of oscillation of the working tool.

Then, the linear velocity $V_{df.}$ of the vibrational motion of the vibrating digging working tool at any time *t* is equal to:

$$V_{df.} = a\omega\sin\omega t\,, \qquad (6)$$

and maximal value of the given velocity is equal to:

$$V_{d\,f.\max} = a\omega\,. \qquad (7)$$

Thus, it is necessary to examine analytically such case of the impact interaction, when impact impulse will have a maximum value. This is exactly the case when at the moment of collision of the vibrating digging working tool on the sugar beet root, both its shares will be moving up to a maximum speed $V_{d\,f.\max}$.

Since all the forces, that are shown on Fig. 1, have a finite value, in the moment of impact, the impulses from all of these forces must be equal to zero. Only impact impulses S_{n1} and S_{n2} have a non-zero value, it is obvious that $S_{n1} = S_{n2}$ (the impact is symmetrical).

For next investigation we accept the theory related to changes of the motion during an impact [14]:

$$m\left(\overline{U} - \overline{V}\right) = \overline{S}_{n1} + \overline{S}_{n2} + \overline{S}_{\tau 1} + \overline{S}_{\tau 2}\,, \qquad (8)$$

where $\overline{V}$ – velocity of the digging working tool before an impact; $\overline{U}$ – velocity of the digging working tool after an impact; m – weight of the working tool related to the point of impact.

In such case:

$$\overline{V} = \overline{V}_{t.m.} + \overline{V}_{d\,f.\max}\,, \qquad (9)$$

where $\overline{V}_{t.m.}$ – forward velocity of the motion of the working tool; $\overline{V}_{d\,f.\max}$ – maximal oscilation velocity of the working tool.

Vector translational speed $\overline{V}_{t.m.}$ of the digging working tool is directed along the *Ox* axis and the velocity vector of the vibrational motion of the working tool $\overline{V}_{d\,f.\max}$ – according to the the *Oz* axis upwards. Taking into account (3), the vector equation (8) will be as follows:

$$m\left(\overline{U} - \overline{V}\right) = \overline{S}_{n1} + \overline{S}_{n2} + f\overline{S}_{n1} + f\overline{S}_{n2}\,. \qquad (10)$$

We write the vector equation (10) in the projections on the axes of the Cartesian coordinate system *Oxyz*.

As the impact, in this case, is in fact symmetrical about a plane *xOz*, the vector equation (10) is reduced to a system of two equations – in projections onto the axis *Ox* and *Oz*.

We define the necessary projection of the vectors that go into the equation (10).

It is obvious that:

$$V_x = V_{t.m.}\,. \qquad (11)$$

Since the vectors $\overline{S}_{n1}$ и $\overline{S}_{n2}$ are directed along the normal to the surface of the wedges, according to [15], we obtain:

$$S_{n1x} = S_{n2x} = \frac{S_{n1} tg\gamma}{\sqrt{tg^2\gamma + 1 + tg^2\beta}}\,. \qquad (12)$$

As it can be seen from Fig. 1, projections of the vectors $\overline{E}_1$, $\overline{E}_2$ and $\overline{F}_1$, $\overline{F}_2$ on the Ox axis will be equal to:

$$E_{1x} = E_{2x} = E_1\cos\gamma = S_{\tau 1}\cos\psi\cos\gamma\,, \qquad (13)$$

$$F_{1x} = F_{2x} = F_1\cos\delta\sin\gamma = S_{\tau 1}\sin\psi\cos\delta\sin\gamma\,. \qquad (14)$$

It is obvious also, that:

$$V_z = V_{d\,f.\max}\,. \qquad (15)$$

According to [15] we have:

$$S_{n1z} = S_{n2z} = \frac{S_{n1} tg\beta}{\sqrt{tg^2\gamma + 1 + tg^2\beta}}\,. \qquad (16)$$

Besides,

$$E_{1z} = E_{2z} = 0\,, \qquad (17)$$

$$F_{1z} = F_{2z} = F_1\sin\delta = S_{\tau 1}\sin\psi\sin\delta\,. \qquad (18)$$

With respect to equations (11) – (18), vector equation (10) is leading to the following system of equations:

$$\left.\begin{aligned} m\left(U_x - V_{t.m.}\right) &= \frac{2S_{n1}tg\gamma}{\sqrt{tg^2\gamma+1+tg^2\beta}} + 2fS_{n1}\cos\psi\cos\gamma - 2fS_{n1}\sin\psi\cos\delta\sin\gamma, \\ m\left(U_z - V_{d\,f.\max}\right) &= \frac{2S_{n1}tg\beta}{\sqrt{tg^2\gamma+1+tg^2\beta}} + 2fS_{n1}\sin\psi\sin\delta. \end{aligned}\right\} \quad (19)$$

Thus, we have obtained a system of two equations with three unknowns S_{n1}, U_x and U_z. To solve the problem, it is necessary to have the third equation which can be obtained by using Newton's hypothesis about the collision of two bodies [14].

Thus, the relationship between the speed of the working tool after the impact and before the impact can be expressed by using of the coefficient of restitution ε, namely:

$$U_n = -\varepsilon V_n, \quad (20)$$

where U_n – projection of the velocity of the working tool after the impact on the surface of the wedge; V_n – projection of the velocity of the working tool before the impact on the surface of the wedge.

As:

$$\bar{U} = \bar{U}_x + \bar{U}_z, \quad \bar{V} = \bar{V}_{t.m.} + \bar{V}_{d\,f.\max},$$

when taking into the account [15], we obtain:

$$U_n = \frac{U_x tg\gamma + U_z tg\beta}{\sqrt{tg^2\gamma+1+tg^2\beta}}, \quad (21)$$

$$V_n = \frac{V_{t.m.}\cdot tg\gamma + V_{d\,f.\max}\cdot tg\beta}{\sqrt{tg^2\gamma+1+tg^2\beta}}. \quad (22)$$

By using of equaitions (21) and (22) in (20), we obtain the required third equation:

$$U_x tg\gamma + U_z tg\beta = -\varepsilon\left(V_{t.m.}\cdot tg\gamma + V_{d\,f.\max}\cdot tg\beta\right). \quad (23)$$

Thus, we finally have a system of three equations of the following form:

$$\left.\begin{aligned} m\left(U_x - V_{t.m.}\right) &= \frac{2S_{n1}tg\gamma}{\sqrt{tg^2\gamma+1+tg\beta}} + 2fS_{n1}\cos\psi\cos\gamma - 2fS_{n1}\sin\psi\cos\delta\sin\gamma, \\ m\left(U_z - V_{d\,f.\max}\right) &= \frac{2S_{n1}tg\beta}{\sqrt{tg^2\gamma+1+tg^2\beta}} + 2fS_{n1}\sin\psi\sin\delta, \\ U_x tg\gamma + U_z tg\beta &= -\varepsilon\left(V_{t.m.}\cdot tg\gamma + V_{d\,f.\max}\cdot tg\beta\right). \end{aligned}\right\}. \quad (24)$$

We write the system of equations (24) in a form suitable for solution by Cramer method:

$$\left.\begin{aligned} & mU_x + 0\cdot U_z - \left(\frac{2tg\gamma}{\sqrt{tg^2\gamma+1+tg^2\beta}} + 2f\cos\psi\cos\gamma - 2f\sin\psi\cos\delta\sin\gamma\right)S_{n1} = mV_{t.m.}, \\ & 0\cdot U_x + mU_z - \left(\frac{2tg\beta}{\sqrt{tg^2\gamma+1+tg^2\beta}} + 2f\sin\psi\sin\delta\right)S_{n1} = mV_{d\,f.\max}, \\ & tg\gamma U_x + tg\beta U_z + 0\cdot S_{n1} = -\varepsilon\left(V_{t.m.}\cdot tg\gamma + V_{d\,f.\max}\cdot tg\beta\right). \end{aligned}\right\} \quad (25)$$

We can write the main determinant of the system of equations (25) and calculate its value. We obtain:

$$\Delta = \begin{vmatrix} m & 0 & -\left(\dfrac{2tg\gamma}{\sqrt{tg^2\gamma+1+tg^2\beta}}+2f\cos\psi\cos\gamma-2f\sin\psi\cos\delta\sin\gamma\right) \\ 0 & m & -\left(\dfrac{2tg\beta}{\sqrt{tg^2\gamma+1+tg^2\beta}}+2f\sin\psi\sin\delta\right) \\ tg\gamma & tg\beta & 0 \end{vmatrix} =$$

$$= m\left(\frac{2tg\beta}{\sqrt{tg^2\gamma+1+tg^2\beta}}+2f\sin\psi\sin\delta\right)tg\beta + \tag{26}$$

$$+m\left(\frac{2tg\gamma}{\sqrt{tg^2\gamma+1+tg^2\beta}}+2f\cos\psi\cos\gamma-2f\sin\psi\cos\delta\sin\gamma\right)tg\gamma.$$

We write the determinant for a finding of the unknown S_{n1} and calculate its value. It will be equal to:

$$\Delta_{Sn1} = \begin{vmatrix} m & 0 & mV_{t.m.} \\ 0 & m & mV_{d\,f.\max} \\ tg\gamma & tg\beta & -\varepsilon\left(V_{t.m.}\cdot tg\gamma+V_{d\,f.\max}\cdot tg\beta\right) \end{vmatrix} =$$

$$= -\left[m^2\varepsilon\left(V_{t.m.}\cdot tg\gamma+V_{d\,f.\max}\cdot tg\beta\right)+m^2tg\beta V_{d\,f.\max}\right]-m^2V_{t.m.}\cdot tg\gamma. \tag{27}$$

I such case, according to Cramer method:

$$S_{n1} = \frac{\Delta_{S\,n1}}{\Delta}. \tag{28}$$

After substituing (26) and (27) into equation (28) and after some transformations we obtain:

$$S_{n1} = -\frac{m(1+\varepsilon)\ \left(V_{t.m.}tg\gamma+V_{d\,f.\max}tg\beta\right)\times}{2tg^2\beta+2f\sin\psi\sin\delta\ tg\beta\sqrt{tg^2\gamma+1+tg^2\beta}+2tg^2\gamma+}\times$$

$$\times\frac{\times\sqrt{tg^2\gamma+1+tg^2\beta}}{+\left(2f\cos\psi\cos\gamma-2f\sin\psi\cos\delta\sin\gamma\right)\ tg\gamma\sqrt{tg^2\gamma+1+tg^2\beta}}. \tag{29}$$

Thus, there was defined the normal component of the defined impact pulse, that occurs during the impact interaction of one of digging wedges of the vibrating working tool with the sugar beet root, fixed in soil. Expression (29) describes the functional dependence of the normal component S_{n1} of a impact pulse on the structural and kinematic parameters of vibrating digging working tool of the sugar beet harvest machine.

The sign "–" in the expression (29) means that the impuls pulse S_{n1} acts from the on the side of sugar beet root on the working tool. Impact pulse that acts from the side of the working tool on the root, has a positive sign and the same magnitude.

If we denote the total impact impulse, which acts from the side of the digging working tool on the sugar beet root (simultaneously from both digging planes) as a $\overline{S}$, that is:

$$\overline{S} = \overline{S}_{n1} + \overline{S}_{n2} + \overline{S}_{\tau1} + \overline{S}_{\tau2}, \tag{30}$$

then, as can be seen from equations (19), that its projection on the Ox axis and Oz respectively, will be equal to:

$$S_x = \frac{2S_{n1} tg\gamma}{\sqrt{tg^2\gamma + 1 + tg^2\beta}} + 2fS_{n1}\cos\psi\cos\gamma - 2fS_{n1}\sin\psi\cos\delta\sin\gamma\,, \tag{31}$$

$$S_z = \frac{2S_{n1} tg\beta}{\sqrt{tg^2\gamma + 1 + tg^2\beta}} + 2fS_{n1}\sin\psi\sin\delta\,, \tag{32}$$

where S_{n1} is determined according to equation (29), and definitely with the positive sign.

Thus, on the basis of expressions (31), (32) and (29) we can determine the total impact pulse which acts on the sugar beet root from the side of vibrating digging working tool:

$$S = \sqrt{S_x^{\ 2} + S_z^{\ 2}}\,. \tag{33}$$

It is obvious that vector $\overline{S}$ lies in the plane xOz, and in the same plane are located also its projections S_x and S_z.

However, the greatest value represents the magnitude of the impact force, rather than the impact impulse, as most indicators of physical and mechanical properties of sugar beet roots are connected with the forces which act on the sugar beet root from the side of the digging working tool.

As a rule, the unknown is a law of change of the impact force, but anyway we know that this force can be increased in a very short period of time $t_{b.}$ from zero value to a maximum value and then decreases again to zero value. Obviously, the maximum impact force is approximately twice as large, compared to its average value is the time interval $t_{b.}$ [14].

Because the:

$$S = F_{b.av.} \cdot t_{b.}\,,$$

where S – impact impulse, $F_{b.av.}$ – average value of the impact force, $t_{b.}$ – time duration of the impact, and then:

$$F_{b.av.} = \frac{S}{t_{b.}}\,.$$

So,

$$F_{b.} = 2F_{b.av} = \frac{2S}{t_{b.}}\,, \tag{34}$$

where $F_{b.}$ – maximal value of the impact force.

Taking into account the equations (31), (32) and (34), we can write the projection of the force $F_{b.}$ respectively on the axis Ox and Oz:

$$F_{b.x} = \left(\frac{4tg\gamma}{\sqrt{tg^2\gamma + 1 + tg^2\beta}} + 4f\cos\psi\cos\gamma - 4f\sin\psi\cos\delta\sin\gamma \right)\frac{S_{n1}}{t_{b.}}\,, \tag{35}$$

$$F_{b.z} = \left(\frac{4tg\beta}{\sqrt{tg^2\gamma + 1 + tg^2\beta}} + 4f\sin\psi\sin\delta \right)\frac{S_{n1}}{t_{b.}}\,, \tag{36}$$

where the value of S_{n1} is determined according to equation (29), taken with the positive sign.

The duration of the impact $t_{b.}$ can be determined only experimentally. According to [9] $t_{b.} \approx 0,6 \cdot 10^{-2}$ sec.

Thus, there was developed the basic provisions of the theory of impact interaction of a vibrating digging working tool with body of sugar beet roots, which acts in two points. In the future, it is necessary to carry out numerical modeling on the PC in order to determine of the conditions not to damage the beet roots, depending on the parameters of vibrating digging process.

Conclusions

1. There was developed a refined theory of the impact interaction of the digging working tool with the sugar beet root, fixed in the soil.

2. Based on a obtained equation of the impact interaction, which acts in two points, there was determined an impact impulse and maximal impact force, which occur at a specified impact interaction.

3. There was obtained an analytical expression for determining the permissible vibration frequency of the vibrating digging working tool on the basis of the conditions not to damage the beet roots with regard of its design parameters and the forward speed of the sugar beet harvester. It allows to define the desired frequency when digging sugar beet roots from the soil.

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