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SIMULATION OF THE SUGAR BEET ROOT CROPS VIBRATION AT DIGGING

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Summary. A new mathematical model is developed which describes the process of beet root crop direct extraction from soil, realized under act of vertical disturbing force and traction effort, which are transmitted to the root crop from a vibration digger. Some sets of differential equations, whose solution has enabled to determine the law of the root crop movement during its direct vibration extraction are received.

Key words: sugar beet, root crop, vibration digger, elastic medium, differential equations of movement, oscillation, amplitude, frequency.

INTRODUCTION

Use of sugar beet root crops vibration at digging from soil has a number of essential advantages in comparison with other ways. It is characterized by less damage of root, lowering of crop losses at harvesting, more intensive cleaning of root crops from the stuck soil, smaller blocking up of a digger working channel by soil and by plant residues. Therefore, this technological process requires detailed analytical research, further development, and manufacturing application of advanced vibration diggers.

PROBLEM STATEMENT

Theoretical studies of technological process of sugar beet root crops vibration at digging from soil enable to justify scientifically constructive and kinematic parameters of vibration diggers. Such investigations are necessary first of all for the theoretical analysis of vibration digging up end-effectors operation in adverse conditions, on heavy and hard soils where reliability of beet-harvesting machines operation essentially decreases. In turn, a deep theoretical analysis of any technological process is possible only at presence of adequate mathematical models which describe the given process.

ANALYSIS OF RESEARCHES AND PUBLICATIONS

Thorough theoretical and experimental studies of sugar beet root vibration extraction are richly described in [Vasylenko et al. 1970, Pogorelyy et al. 1983, Bulgakov et al. 2003, 2004, 2005, 2006].

Thus, in [Bulgakov et al. 2006] the process of a root crop extraction from soil is considered in the most general case – at asymmetrical capture of a root crop by vibration digger. This process is described by means of kinematic and dynamic equations of Euler. The set of differential equations received in [Bulgakov et al. 2006] describes spatial oscillatory process of the root crop fixed in the soil, as in the elastic medium, with one fixing point.

In present work the process of a root crop vibration extraction from soil is considered at symmetric capture of a root crop by both shares of vibrating digger.

At such capture of a root crop by digging up shares the process of further full extraction of a root crop from soil is possible. Therefore, let's examine the process of a root crop direct extraction from soil at its symmetric capture by vibration digger.

RESEARCH OBJECTIVE

To develop mathematical model of a sugar beet root crop direct extraction from soil, realized under act of vertical disturbing force which is transmitted to root crop from vibrating digger, and traction effort which arises owing to translation movement of digger.

RESEARCH RESULTS

At first let's make the necessary formalization of the technological process under consideration. Despite the fact, that the process of sugar beet root crop extraction from soil will take place in a short time interval (thus forward speed of root diggers can amount to 2 *m/s*), all the process can be divided into separate, interconnected sequential operations. As it was noted above, the extraction is possible only at symmetric capture of a root crop by the digger, and simultaneously with translation oscillations of a root crop, its angular oscillations occur at some angle around a conditional fixing point.

At the first stage of extraction, and especially at the first oscillations, restoring force at angular oscillations and its moment concerning a conditional fixing point will be maximal. That is why the angle of inclination of a root crop will be sufficiently small and full (or partial) restoration of its vertical position owing to forward movement of the digger will be possible. Nevertheless, owing to action of root crop forward oscillations together with the surrounding soil, the compactness of the soil will decrease, and restoring force at angular oscillations will decrease, too. So, with each following oscillation the angle of inclination of the root crop will increase, and at restoration to the previous position – will decrease. The root crop will be loosened around the conditional fixing point with gradual increase of its inclination angle forward on a digger course. It will lead to the break of root crop connections with loose soil in the direction of digger's movement, beginning from the top part of the root crop conic surface, gradually approaching to its conditional fixing point. So, from what was stated above it follows, that the destruction of root crop connections with soil occurs simultaneously in two directions – along the forward digger's movement and in the direction perpendicularly to specified (along the full depth of the root crop arrangement in soil). Thus the forces of root crop connections with soil and elastic forces of soil will gradually decrease to such minimal magnitude when oscillatory processes pass into the processes of root crop continuous moving upwards and forward – along the translational digger movement, and also continuous root crop rotation around the center of its mass at some angle down to full root crop extraction from soil. Elastic forces of soil will pass in forces of resistance of loose soil at a root crop movement in a digger working channel. After that the stage of the sugar beet root crop direct extraction out from soil is begun.

For development of mathematical model first of all we shall make the equivalent scheme of a root crop interaction with working surfaces of vibration digger at root crop direct extraction (Fig.). Let's present a vibration digger in the form of two coupled digging up surfaces (wedges) $A_1B_1C_1$ and $A_2B_2C_2$, each of which has some slope in a space under angles α, β, γ and which thus are located one to one, so that the working channel is formed, and its back part is narrowed. The pointed wedges realize oscillation movements in longitudinal-vertical plane (the mechanism of shares drive into oscillation movement is not shown), with corresponding amplitude and frequency. A direction of vibration digger forward movement is shown by an arrow. Projections of points B_1 and B_2 to an axis O_1y_1 are designated by points D_1 and D_2, accordingly.

Let's assume, that the root crop interacts with surfaces of wedges $A_1B_1C_1$ and $A_2B_2C_2$ in the corresponding points. It is approximated by solid matter of the cone-shaped form, and the capture of the root crop by digger occurs symmetrically from its both sides.

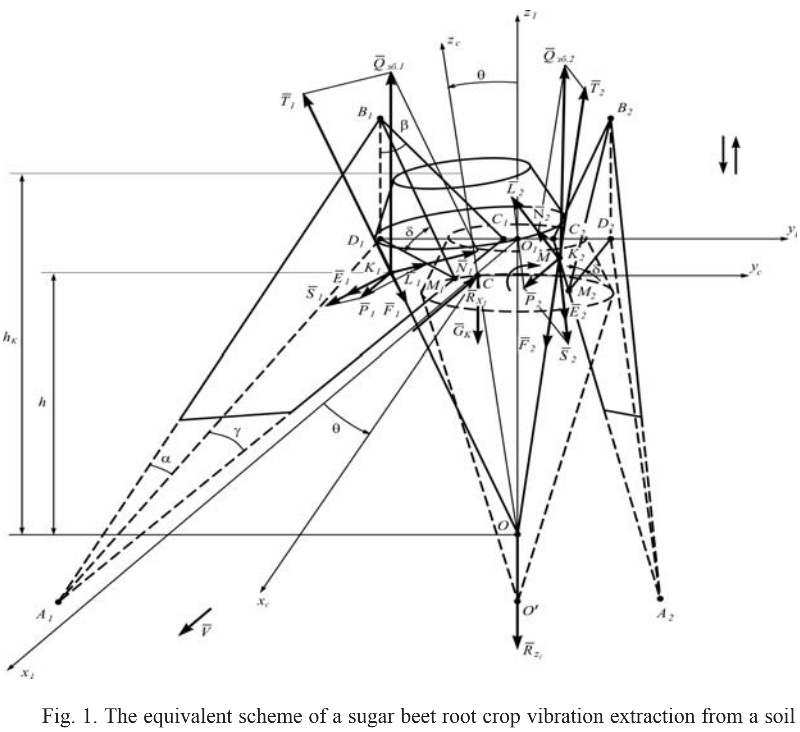

Fig. 1. The equivalent scheme of a sugar beet root crop vibration extraction from a soil

Let's assume further, that the working surface of the wedge $A_1B_1C_1$ realizes direct contact to a root crop in a point K_1, and the surface $A_2B_2C_2$ – in a point K_2. Lines lead through points K_1 and K_2 of a root crop contact and points B_1 and B_2 form at section with the sides of wedges A_1C_1 and A_2C_2 corresponding points M_1 and M_2. Thus, δ is dihedral angle ($\angle B_1M_1D_1$) between the bottom basis $A_1D_1C_1$ and the working surface of the wedge $A_1B_1C_1$ or accordingly a dihedral angle ($\angle B_2M_2D_2$) between the bottom basis $A_2D_2C_2$ and a working surface of a wedge $A_2B_2C_2$.

Let's show forces which arise owing to interaction of the root crop with vibration digger.

From vibration digger the vertical disturbing force $\bar{Q}_{tr}$ operates which changes under the harmonious law of the form:

$$Q_{tr} = H \sin \omega t, \tag{1}$$

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

This force plays a basic role during loosening soil in the digger working channel zone and the root crop extraction. Specified disturbing force $\bar{Q}_{tr}$ is applied to a root crop from its two sides and on the scheme it is presented by two compounds $\bar{Q}_{tr.1}$ and $\bar{Q}_{tr.2}$. These forces are applied accordingly in points K_1 and K_2 on distance h from conditional fixing point O and they cause the root crop oscillations in longitudinal-vertical planes which destroy connections of the root crop with soil and create for the root crop required conditions of extraction from soil.

As a capture of the root crop is symmetric it is obvious, that there will be the following correlation:

$$Q_{tr.1} = Q_{tr.2} = \frac{1}{2} H \sin \omega t. \tag{2}$$

Let's decompose the given forces into normal $\overline{N}_1$ and $\overline{N}_2$ and tangents compounds $\overline{T}_1$ and $\overline{T}_2$, as it is shown in the figure. As vibration digger moves forward in the direction of an axis O_1x_1 according to a root crop which is fixed in a soil and during the moment of capture of a root crop by the digger in the direction of an axis O_1x_1 motive forces $\overline{P}_1$ and $\overline{P}_2$ operate as well. Let's decompose the forces $\overline{P}_1$ and $\overline{P}_2$ in two compounds: normal $\overline{L}_1$ and $\overline{L}_2$ and tangents $\overline{S}_1$ and $\overline{S}_2$ to surfaces $A_1B_1C_1$ and $A_2B_2C_2$, accordingly.

Besides, in points of contact K_1 and K_2 forces of friction $\overline{F}_{K1}$ and $\overline{F}_{K2}$ act accordingly which counteract to a root crop sliding on a working surface of wedges $A_1B_1C_1$ and $A_2B_2C_2$ during its capture by vibration digger. Vectors of these forces are directed opposite to a vector of relative speed of a root crop sliding on a surface of wedges.

A root crop sliding on a surface of wedges can occur in a direction of forces $\overline{T}_1$, $\overline{T}_2$ action (parallel lines B_1M_1 and B_2M_2) and in the direction, opposite to the action of forces $\overline{S}_1$, $\overline{S}_2$, due to motion resistance force of soil.

The vector of relative speed of root crop sliding on a surface of wedges can be decomposed into the compounds in the directions specified above. So, force of friction $\overline{F}_{K1}$ can also be decomposed in two compounds: $\overline{F}_1$ in a direction, opposite to vector $\overline{T}_1$, and $\overline{E}_1$ – in a direction of the vector $\overline{S}_1$.

Similarly, force of friction $\overline{F}_{K2}$ can also be decomposed in two compounds: $\overline{F}_2$ – in the direction opposite to vector $\overline{T}_2$, and $\overline{E}_2$ – in the direction of the vector $\overline{S}_2$.

It is obvious, that $F_1 = F_2$, $E_1 = E_2$.

In the center of a root crop mass (point C) force of the root crop mass operates $\overline{G}_k$. Forces of resistance of loose soil at the root crop movement in a working channel of digger in the direction of axes O_1x_1 and O_1z_1 are designated through $\overline{R}_{x1}$ and $\overline{R}_{z1}$, accordingly.

At direct root crop extraction from soil the rotation of the root crop around its center of mass (point C) will be carried out under the action of pair of resistance forces of the loosened soil. We shall designate the moment of this pair of forces as M.

At direct root crop extraction it is possible to consider forces of resistance of the loosened soil dependent on the speed of root crop movement in the loosened soil or as a first approximation – simply constants. Therefore for simplification of mathematical model we shall consider the forces $\overline{R}_{x1}$, $\overline{R}_{z1}$ and the moment of pair M as constants.

Let's make at first the differential equations of movement of the center of a root crop mass (point C), i.e. forward movement of a root crop along axes O_1x_1 and O_1z_1. Considering the above-given scheme of forces, the differential equation of movement of the root crop mass centre in the vector form at its direct extraction will be of the form:

$$m_k\overline{a} = \overline{N}_1 + \overline{N}_2 + \overline{L}_1 + \overline{L}_2 + \overline{F}_1 + \overline{F}_2 + \overline{E}_1 + \overline{E}_2 + \overline{G}_k + \overline{R}_{z1} + \overline{R}_{x1}, \qquad (□)$$

where: $\overline{a}$ – acceleration of movement of the root crop mass center.

As the process of extraction specified above occurs at symmetric capture of a root crop by digger, so the root crop movement along a working channel of the digger occurs actually in longitudinal-vertical planes (planes $x_1O_1z_1$). That is why the vector equation (□) is reduced toset of two equations in pro□ections to axes Ox_1 and Oz_1.

After the definition of values of all forces which enter into the vector equation (□),and their pro□ections to axes Ox_1 and Oz_1 we shall receive two following sets of differential equations:

$$\left.\begin{aligned}
\ddot{x}_1 = &\frac{1}{m_k}\left[\frac{\cos\delta\, tg\gamma}{\sqrt{tg^2\gamma+1+tg^2\beta}} + f\cos^2\delta\,\sin\left(\gamma+\frac{\alpha_{K1\max}}{2}\right)\sin\gamma + \right.\\
&\left. + f\cos\delta\cos\left(\gamma+\frac{\alpha_{K1\max}}{2}\right)\cos\gamma\right]H\sin\omega t + \frac{2}{m_k}\times\\
&\times\left[\frac{\sin\gamma\, tg\gamma}{\sqrt{tg^2\gamma+1+tg^2\beta}} + f\sin^2\gamma\,\sin\left(\gamma+\frac{\alpha_{K1\max}}{2}\right)\cos\delta + \right.\\
&\left. + f\sin\gamma\,\cos\gamma\,\cos\left(\gamma+\frac{\alpha_{K1\max}}{2}\right)\right]P_1 - \frac{R_{x1}}{m_k},\\
\ddot{z}_1 = &\frac{1}{m_k}\left[\frac{\cos\delta\, tg\beta}{\sqrt{tg^2\gamma+1+tg^2\beta}} - f\cos\delta\,\sin\left(\gamma+\frac{\alpha_{K_1\max}}{2}\right)\sin\delta\right]H\sin\omega t +\\
&\frac{2}{m_k}\left[\frac{\sin\gamma\, tg\beta}{\sqrt{tg^2\gamma+1+tg^2\beta}} - f\sin\gamma\,\sin\left(\gamma+\frac{\alpha_{K_1\max}}{2}\right)\sin\delta\right]P_1 - \frac{R_{z_1}}{m_k} - g,\\
&\omega t\in\left[2k\pi,\, 2(k+1)\pi\right],\; k=0,1,2,...
\end{aligned}\right\} \qquad (□)$$

$$\left.\begin{aligned}
m_k\ddot{x}_1 &= \frac{2P_1\sin\gamma\, tg\gamma}{\sqrt{tg^2\gamma+1+tg^2\beta}} + 2fP_1\sin^3\gamma\cos\delta + fP_1\sin 2\gamma\cos\gamma - R_{x1},\\
m_k\ddot{z}_1 &= \frac{2P_1\sin\gamma\, tg\beta}{\sqrt{tg^2\gamma+1+tg^2\beta}} - 2fP_1\sin^2\gamma\sin\delta - G_k - R_{z1},
\end{aligned}\right\} \qquad (□)$$

Thus the set of differential equations (4) describes the process of direct vibration extraction of a sugar beet root crop from soil (i.e. a length on which a periodic disturbing force acts on a root crop), and the set of differential equations (5) describes the process of a root crop extraction from soil when it is not acted on by a disturbing force. I.e. the same vibration digger in the different time intervals can realize the process of the root crop digging as a usual share digger.

Let's solve the received sets of differential equations.

For the given sets of differential equations (4), (5) initial conditions will be the following: at $t = 0$:

$$\dot{x}_1 = 0, \qquad \dot{z}_1 = 0, \tag{□}$$

$$x_1 = x_{10}, \qquad z_1 = -\frac{1}{3}h_k. \tag{□}$$

The set of differential equations (4) is the set of linear differential equations of the second order. □s it is known, it is solved in quadratures. For the simplification of the record set of dif□ferential equations (4) let's designate:

$$\frac{1}{m_k}\left[\frac{\cos\delta\, tg\gamma}{\sqrt{tg^2\gamma+1+tg^2\beta}} + f\cos^2\delta\sin\left(\gamma+\frac{\alpha_{K1\max}}{2}\right)\sin\gamma + \right. \tag{□}$$
$$\left. + f\cos\delta\cos\left(\gamma+\frac{\alpha_{K1\max}}{2}\right)\cos\gamma\right] = \phi_1,$$

$$\frac{2}{m_k}\left[\frac{\sin\gamma\, tg\gamma}{\sqrt{tg^2\gamma+1+tg^2\beta}} + f\sin^2\gamma\sin\left(\gamma+\frac{\alpha_{K1\max}}{2}\right)\cos\delta + \right. \tag{□}$$
$$\left. + f\sin\gamma\cos\gamma\cos\left(\gamma+\frac{\alpha_{K1\max}}{2}\right)\right] = \psi_1,$$

$$\frac{1}{m_k}\left[\frac{\cos\delta\, tg\beta}{\sqrt{tg^2\gamma+1+tg^2\beta}} - f\cos\delta\sin\left(\gamma+\frac{\alpha_{K1\max}}{2}\right)\sin\delta\right] = \phi_2, \tag{□0}$$

$$\frac{2}{m_k}\left[\frac{\sin\gamma\, tg\beta}{\sqrt{tg^2\gamma+1+tg^2\beta}} - f\sin\gamma\sin\left(\gamma+\frac{\alpha_{K1\max}}{2}\right)\sin\delta\right] = \psi_2. \tag{□□}$$

□onsidering expressions (□) □ (□□), the set of differential equations (4) will get the form:

$$\left.\begin{aligned} \ddot{x}_1 &= \phi_1 H\sin\omega t + \psi_1 P_1 - \frac{R_{x1}}{m_k}, \\ \ddot{z}_1 &= \phi_2 H\sin\omega t + \psi_2 P_1 - \frac{R_{z1}}{m_k} - g. \end{aligned}\right\} \tag{□2}$$

Let's integrate the set of differential equations (□2). □fter twofold integration and finding of any arbitrary constants we receive the following solutions of differential equations (4) in a final form:

$$\left.\begin{aligned} \dot{x}_1 &= -\frac{\phi_1 H}{\omega}\cos\omega t + \psi_1 P_1 t - \frac{R_{x1}t}{m_k} + \frac{\phi_1 H}{\omega}, \\ \dot{z}_1 &= -\frac{\phi_2 H}{\omega}\cos\omega t + \psi_2 P_1 t - \frac{R_{z1}t}{m_k} - gt + \frac{\phi_2 H}{\omega}. \end{aligned}\right\} \tag{□□}$$

$$\left.\begin{aligned} x_1 &= -\frac{\phi_1 H}{\omega^2}\sin\omega t + \frac{\psi_1 P_1 t^2}{2} - \frac{R_{x1}t^2}{2m_k} + \frac{\phi_1 Ht}{\omega} + x_{10}, \\ z_1 &= -\frac{\phi_2 H}{\omega^2}\sin\omega t + \frac{\psi_2 P_1 t^2}{2} - \frac{R_{z1}t^2}{2m_k} - \frac{gt^2}{2} + \frac{\phi_2 Ht}{\omega} - \frac{1}{3}h_k. \end{aligned}\right\}$$

[illegible]

[illegible]

$$\frac{1}{m_k}\left(\frac{2\sin\gamma\, tg\gamma}{\sqrt{tg^2\gamma + 1 + tg^2\beta}} + 2f\sin^3\gamma\cos\delta + f\sin 2\gamma\cos\gamma\right) = \psi_1',$$

$$\frac{1}{m_k}\left(\frac{2\sin\gamma\, tg\beta}{\sqrt{tg^2\gamma + 1 + tg^2\beta}} - 2f\sin^2\gamma\sin\delta\right) = \psi_2'.$$

[illegible]

$$\left.\begin{aligned} \ddot{x}_1 &= \psi_1' P_1 - \frac{R_{x_1}}{m_k}, \\ \ddot{z}_1 &= \psi_2' P_1 - \frac{G_k}{m_k} - \frac{R_{z_1}}{m_k}, \end{aligned}\right\}$$
$$\omega t \in \left[(2k-1)\pi,\ 2k\pi,\ \right],\ k = 1, 2, ...$$

[illegible]

$$\left.\begin{aligned} \dot{x}_1 &= \psi_1' P_1 t - \frac{R_{x_1}}{m_k}t, \\ \dot{z}_1 &= \psi_2' P_1 t - \frac{G_k}{m_k}t - \frac{R_{z_1}}{m_k}t, \end{aligned}\right\}$$
$$\omega t \in \left[(2k-1)\pi,\ 2k\pi,\ \right],\ k = 1, 2, ...$$

$$\left.\begin{aligned} x_1 &= \psi_1' P_1 \frac{t^2}{2} - \frac{R_{x_1}t^2}{2m_k} + x_{10}, \\ z_1 &= \psi_2' P_1 \frac{t^2}{2} - \frac{G_k t^2}{2m_k} - \frac{R_{z_1}t^2}{2m_k} - \frac{1}{3}h_k, \end{aligned}\right\}$$
$$\omega t \in \left[(2k-1)\pi,\ 2k\pi,\ \right],\ k = 1, 2, ...$$

Sets of equations (18) and (19) accordingly describe the laws of the speed change and moving of the root crop mass center during its direct extraction from soil at the absence of disturbing force action.

Let's set up the differential equation of the root crop turn around of its center of mass, or around of a conditional axis Cy_c which passes through the center of mass (point C) in parallel axis O_1y_1. According to [Butenin et al. 1985], the specified equation in a general view will be of the form:

$$I_{y_c} \frac{d^2\theta}{dt^2} = M^e_{y_c}, \tag{20}$$

where: θ – an angle of the root crop turn around axis Cy_c; I_{yc} – the moment of inertia of a root crop concerning an axis Cy_c; $M^e_{y_c}$ – the rotary moment around an axis Cy_c (the sum of the moments of all external forces which act on a root crop, concerning an axis Cy_c).

The moment of inertia I_{yc} of a root crop concerning an axis Cy_c is defined according to [Butenin et al. 1985] of such expression:

$$I_{y_c} = \left(\frac{3}{80} + \frac{3}{20} tg^2\varepsilon\right) m_k h_k^2. \tag{21}$$

Substituting expressions (2), (21) in the differential equation (20) and carrying out the necessary transformations we shall receive the differential equation of turn of a root crop around axis Cy_c at direct vibrating extraction out from soil (i.e. at the action of disturbing force on it) which has the form:

$$\begin{aligned}
&\left(\frac{3}{80} + \frac{3}{20} tg^2\varepsilon\right) m_k h_k^2 \frac{d^2\theta}{dt^2} = -H\left(-h_k + h - z_1\right)\sin\theta\sin\omega t + 2P_1\cos\theta\left(-h_k + h - z_1\right) + \\
&+2\left(\frac{1}{2} f H\cos\delta\sin\omega t + f P_1\sin\gamma\right)\sin\left(\gamma + \alpha_{K1\ \max}\sin\omega t\right)\cos\varepsilon\left(-h_k + h - z_1\right)\sin\theta + \\
&+2\left(\frac{1}{2} f H\cos\delta\sin\omega t + f P_1\sin\gamma\right)\cos\left(\gamma + \alpha_{K1\ \max}\sin\omega t\right)\cos\gamma\left(-h_k + h - z_1\right)\cos\theta - M, \\
&\omega t \in \left[2k\pi,\ (2k+1)\pi\right], \quad k = 0, 1, 2, ...
\end{aligned} \tag{22}$$

The differential equation of the root crop turn around axis Cy_c at usual extraction (i.e. at the absence of disturbing force), has the form:

$$\begin{aligned}
&\left(\frac{3}{80} + \frac{3}{20} tg^2\varepsilon\right) m_k h_k^2 \frac{d^2\theta}{dt^2} = 2P_1\cos\theta\left(-h_k + h - z_1\right) + 2fP_1\sin^2\gamma \times \\
&\times\cos\varepsilon\left(-h_k + h - z_1\right)\sin\theta + fP_1\sin 2\gamma\cos\gamma\left(-h_k + h - z_1\right)\cos\theta - M, \\
&\omega t \in \left[(2k-1)\pi,\ 2k\pi\right], \qquad k = 1, 2, ...
\end{aligned} \tag{23}$$

Let's analyze the received differential equations (22) and (23). The differential equation (22) is nonlinear. It is possible to solve it by the approached numerical methods with application of computer, and for each step of application of numerical algorithm it is necessary to find magnitude z_1 from the second equation of set (14) for the corresponding moment of time t_k. The differential equation (23) which includes variable quantity z_1, is also nonlinear, and for each moment of time t_k the magnitude z_1 is necessary to define from the second equation of set (19).

Thus, it is finally possible to consider, that the mathematical model of the process of a sugar beet root crop direct extraction from soil at its vibration digging is developed. The received results enable to define kinematic modes of root crops vibration digging at the conditions of inviolate and constructive parameters of vibration diggers.

CONCLUSION

1. Two sets of differential equations, which describe plane-parallel motion of a root crop in soil at its direct extraction realized under act of vertical disturbing force transmitted from root crop from vibrating digger, and traction effort which arises owing to translation movement of digger.

2. The solved differential equations give an opportunity to find out the law of a root crop movement in longitudinal-vertical plane at direct extraction from soil.

3. The received results enable also to define kinematic modes of root crops vibration digging, considering safety of root from damage and to find rational constructive parameters of vibration diggers.

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SYMULACJA WIBRACJI KORZENI BURAKA CUKROWEGO W ZESPOLE WYORUJĄCYM

Streszczenie. W pracy przedstawiono nowy model matematyczny opisujący wyciąganie korzeni buraków cukrowych z gleby w wyniku działania sił przenoszonych na korzeń z wibracyjnych lemieszy. Przedstawiono kilka układów równań różniczkowych, których rozwiązanie pozwala określić prawa ruchu korzenia podczas wyciągania z gleby.

Słowa kluczowe: burak cukrowy, korzeń, wibracyjny wyorywacz, sprężysty ośrodek, równania różniczkowe ruchu, drgania, amplituda, częstotliwość.