

THEORY OF ASYMMETRIC IMPACT INTERACTION BETWEEN VIBRATING DIGGING TOOL AND BODY OF SUGAR BEET ROOT

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Abstract: One of the most important characteristics of the high performance operation of a state-of-the-art sugar beet harvester is the provision of the conditions that make impossible the damaging of sugar beet roots immediately during their digging out of the ground as well as their loss in the form of broken off tails, which either remain in the ground or get left on the field surface. It is quite obvious that the highest probability of damaging sugar beet roots exists at the instant of their impact interaction with the digging tools, because then the bodies of the roots are tight in the ground. This is to the greatest extent applicable to vibrating digging tools, which can be found on the majority of up-to-date sugar beet harvesters manufactured worldwide, when they operate under the conditions of dryer and harder soil. Therefore, we have carried out theoretical research into the process of impact interaction between the body of a sugar beet root fixed tight in the ground and the vibrating digging tool, the results of which provide sufficient grounds for determining the optimal kinematic and design parameters of the vibrating digging tool stipulated by the requirement to eliminate the damage of roots during their digging out of the ground. At first, we developed an equivalent schematic model of the force interaction between a sugar beet root fixed tight in the ground, which was approximated by a regular cone, and two shares of the vibrating digging tool simultaneously oscillating in the vertical longitudinal plane at the preset amplitude and frequency and moving onward. Under these conditions, the body of the sugar beet root made contact at one point with only one share of the digging tool, i.e. they came in asymmetric contact and their impact interaction took place. We introduced the axes of a three-dimensional Cartesian coordinate system and found the analytical expressions for all forces applied to the sugar beet root at the specified point and also for the force of its bond with the soil. Also, we took into account that an impact momentum was applied at the point of contact at the moment of impact, its value was found analytically, and further we found its projections on the coordinate axes. Then we applied the theorem of variation of the momentum during impact and, following the substitution into it of all found values and transformations, we obtained a new system of equations that characterised the impact interaction process under consideration. The obtained system of equations was solved using Cramer's rule on a PC with the software programme developed for this purpose. As a result, we found the digging share vibration frequency and soil running depth ranges, within which the requirement to eliminate the damage of tail parts of root bodies fixed rather tight in the ground was met. Applying the devised theory it becomes possible to determine the kinematic and design parameters of the vibrating digging tool that ensure observance of the requirement to eliminate the breakage of root bodies during their lifting from the ground, within a wide range of the soil's mechanical and physical characteristics.

Keywords: SUGAR BEET ROOT, VIBRATING DIGGING TOOL, THREE-DIMENSIONAL MOTION, LIFTING, MODELLING.

1. Introduction

The theoretical and field research into the work processes and the use of its results for the development of improved tools for digging sugar beet roots out of the ground are critically important tasks for the sugar beet growing industry, because just this final operation is the most complex and energy-intensive work process in the cultivation of sugar beet (Gu et al., 2014; Bulgakov & Ivanovs, 2010; Lammers, 2011; Lammers & Schmittmann, 2013). The extensive use of vibrating digging tools for the digging out of beet roots observed recently is stipulated by the lowest energy input for the break-up of the soil surrounding roots, the reduced loss and damage of roots in the harvesting process in this case. However, the described advantages are achieved under relatively favourable harvesting conditions, especially when the soil has low hardness indices and a sufficient moisture content. Under all other conditions vibrating digging tools do not display the said advantages.

Most sugar beet harvesters produced in the world today are equipped with vibrating digging tools (Pogorely & Tatyanko, 2004; Sarec et al., 2009; Wang & Zhang, 2013; Wu et al., 2013)). Their tractive resistance is significantly lower and the harvest quality indicators higher than those of passive digging tools. This advantage is achieved by working in favourable harvesting conditions with soft and relatively moist soil. If the soil happens to be more dense at the time of harvest (in dry harvesting conditions), a sugar beet harvester's vibrating digging tools may cause significant damage to the roots (Alizadeh & Segerlind, 1997; Bentini et al, 2005), loss of crop in the form of ripped-off root tips left behind in the soil, and, in some cases, the crop becomes unusable. Thus, there is a need for in-depth research into harvesting technology in relation to the mechanisation of beet cultivation, which would allow choosing the constructive and kinematic

parameters of vibrating digging tools based on the physical and mechanical characteristics of soil and harvesting conditions, while also reducing the specific expenditure on harvesting and minimising root damage.

The damage to beet roots most likely occurs when digging shares impart force on them in the course of harvesting. The harvester and its digging shares move on the field at the speed of 2.0 m s^{-1} , applying a significant force on the roots in the soil. Vibrating digging shares move translationally and oscillate on the longitudinal vertical plane.

The aim of the current paper is to form a theory that would describe the impact of a vibrating digging share in the case of an asymmetrical contact with the root and, based on the results, to find the digging share's constructive and kinematic parameters, while also taking into account the conditions necessary for not damaging the roots.

2. Materials and Methods

When a vibrating digging share makes contact with a beet root, the effect can be described with contact impulse (Bulgakov, 2005; Bulgakov et al., 2014; Dubrovski, 1968; Vasilenko et al., 1970; Vermeulen & Koolen 2002). Since the contact does not last long, the perturbing force has a significant effect. Since the beet root stands quite firmly in the soil, the force may break or crush it (Pogorely et al., 1983; Bulgakov et al., 2005).

In order to solve the posed problem, an equivalent schematic model was construed, describing the force interaction between the vibrating digging share and the beet root. The vibrating digging share is represented with two wedges, $A_1B_1C_1$ and $A_2B_2C_2$, and each of the wedges is described with the angles α , β and γ . The

wedges are positioned so that they form a narrowing working passage at the rear (Fig. 1).

A force is applied on the beet root, represented by a conical shape, by the work face $A_1B_1C_1$ at the point K_1 (Fig. 1) of the digging share, i.e., it is in an asymmetrical contact with the root. The contact may be made via a sufficiently thin layer of soil between the work face and root.

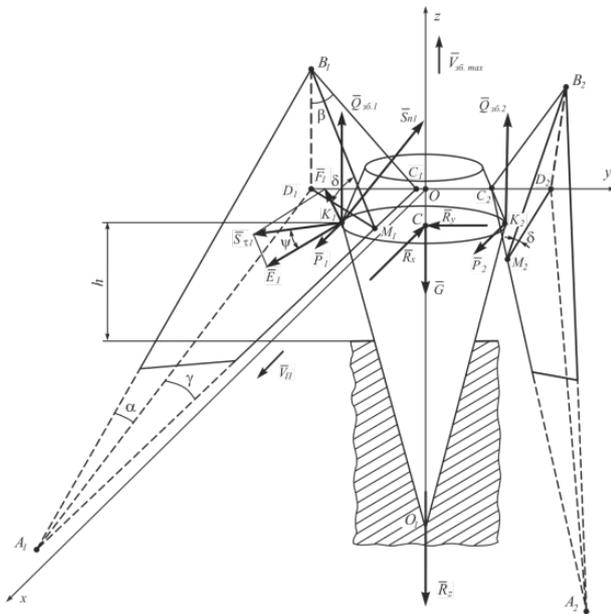


Fig. 1 Equivalent schematic model of determining the perturbing force between the vibrating digging tool and beet root in case of asymmetrical contact

In order to describe the impact process analytically, the vibrating digging tool was placed in the Cartesian coordinate system $Oxyz$, the centre of which, O , is in the middle of the narrowing working passage representing the digging tool. The axis Ox is in line with the direction of the tool's translational motion, Oz is pointing upwards and Oy is pointing towards the right side of the digging tool (Fig. 1).

Now, let's consider the forces originating from the interaction between the vibrating digging tool and the beet root.

Since the digging tool, as it has been stated, is a vibrational tool, it imparts the vertical perturbing force $\overline{Q}_{3\delta}$, which varies under the following harmonic law:

$$\overline{Q}_{3\delta} = H \sin \omega t, \tag{1}$$

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

That force plays the primary role in the process of soil breaking in the zone of the digging tool's work passage and the direct lifting of the beet root out of the ground. The perturbing force $\overline{Q}_{3\delta}$ is applied to the beet root or the soil surrounding it on two sides, therefore, it is represented in the equivalent schematic model by two components $\overline{Q}_{3\delta.1}$ and $\overline{Q}_{3\delta.2}$, which apparently have the following values:

$$\overline{Q}_{3\delta.1} = \overline{Q}_{3\delta.2} = \frac{1}{2} H \sin \omega t \tag{2}$$

3. Results and discussion

The normal component of the digging share's perturbing force has been found analytically and it is expressed as follows:

$$S_{n1} = - \frac{m(1+\varepsilon) \times}{tg^2 \beta + f \sin \psi \sin \delta \, tg \beta \sqrt{tg^2 \gamma + 1 + tg^2 \beta} + 1 -} \times \frac{\times (V_{\Pi} tg \gamma + V_{3\delta, \max} tg \beta) \times}{-(f \cos \psi \sin \gamma + f \sin \psi \cos \delta \cos \gamma) \sqrt{tg^2 \gamma + 1 + tg^2 \beta} + tg^2 \gamma} \tag{3}$$

$$\times \frac{\times \sqrt{tg^2 \gamma + 1 + tg^2 \beta}}{+(f \cos \psi \cos \gamma - f \sin \psi \cos \delta \sin \gamma) \, tg \gamma \sqrt{tg^2 \gamma + 1 + tg^2 \beta}}$$

The equation (3) describes how the normal component of the perturbing force S_{n1} is dependent of the constructive and kinematic parameters of the vibrating digging tool. The negative sign in the equation (3) signifies the force imparted on the digging tool by the beet root. The perturbing force applied on the sugar beet root by the digging tool is marked with a positive sign and it is equal to the force the root applies on the tool.

The law that governs changes in the perturbing force is unknown, but it changes during a very short time interval $t_{y\delta}$, first increasing from zero to the maximum value, and then decreasing back to zero. Its maximum value is approximately two times greater than its average during the time interval $t_{y\delta}$. The projections of the perturbing force $F_{y\delta}$ on axes Ox , Oy and Oz are expressed as follows:

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

$$F_{y\delta.y} = \left(\frac{2}{\sqrt{tg^2 \gamma + 1 + tg^2 \beta}} - 2f \cos \psi \sin \gamma - 2f \sin \psi \cos \delta \cos \gamma \right) \frac{S_{n1}}{t_{y\delta}} \tag{5}$$

$$F_{y\delta.z} = \left(\frac{2tg \beta}{\sqrt{tg^2 \gamma + 1 + tg^2 \beta}} + 2f \sin \psi \sin \delta \right) \frac{S_{n1}}{t_{y\delta}} \tag{6}$$

where the value S_{n1} is determined via the expression (3) using a positive sign, and the duration of the impact $t_{y\delta}$ must be determined on a trial basis (according to literature $t_{y\delta} \approx 0,6 \cdot 10^{-2}$ s).

The condition for not damaging the beet root upon the first approximation is the inequality

$$\sqrt{F_{y\delta.x}^2 + F_{y\delta.y}^2} h \leq [M_{3z}] < M_{on} \tag{7}$$

where $[M_{3z}]$ marks the allowed bending moment of the root body at which it is not broken; M_{on} – resisting moment of unbroken soil, which actually holds the beet root in the soil.

The following equality can be written based on the balance principle: $M_{on} = M_{o1}(\overline{F}_{y\delta.xy})$. Based on the conditions for not damaging the beet root (5) as the vibrating digging tool makes contact with the root, the speed limit for the advancing digging tool is determined as follows:

$$V_n \operatorname{tg} \gamma + V_{\beta, \max} \operatorname{tg} \beta \leq \frac{[M_{\beta}] t_{y0}}{ABhm(1+\varepsilon)} \quad (8)$$

If the speed of the advancing beet harvester V_n is given, the maximum oscillation speed of the vibrating digging share $V_{\beta, \max}$ can be expressed as follows:

$$V_{\beta, \max} = \frac{1}{\operatorname{tg} \beta} \left(\frac{[M_{\beta}] t_{y0}}{ABhm(1+\varepsilon)} - V_n \operatorname{tg} \gamma \right) \quad (9)$$

where

$$\sqrt{\left(\frac{2}{\sqrt{\operatorname{tg}^2 \gamma + 1 + \operatorname{tg}^2 \beta}} - 2f \cos \psi \sin \gamma - 2f \sin \psi \cos \delta \cos \gamma \right)^2 + \left(\frac{2 \operatorname{tg} \gamma}{\sqrt{\operatorname{tg}^2 \gamma + 1 + \operatorname{tg}^2 \beta}} + 2f \cos \psi \cos \gamma - 2f \sin \psi \cos \delta \sin \gamma \right)^2} = A,$$

and

$$\frac{\sqrt{\operatorname{tg}^2 \gamma + 1 + \operatorname{tg}^2 \beta}}{\operatorname{tg}^2 \beta + f \sin \psi \sin \delta \operatorname{tg} \beta \sqrt{\operatorname{tg}^2 \gamma + 1 + \operatorname{tg}^2 \beta} + 1 -} \times \frac{1}{-(f \cos \psi \sin \gamma + f \sin \psi \cos \delta \cos \gamma)} \times \frac{1}{\sqrt{\operatorname{tg}^2 \gamma + 1 + \operatorname{tg}^2 \beta} + \operatorname{tg}^2 \gamma + (f \cos \psi \cos \gamma - f \sin \psi \cos \delta \sin \gamma)} \times \frac{1}{\operatorname{tg} \gamma \sqrt{\operatorname{tg}^2 \gamma + 1 + \operatorname{tg}^2 \beta}} = B.$$

If the amplitude of the digging share is given, the necessary angular frequency for the digging share, while also taking into account the necessary conditions for not breaking the sugar beet root (7), is expressed as follows:

$$\omega = \frac{1}{\operatorname{atg} \beta} \left(\frac{[M_{\beta}] t_{y0}}{ABhm(1+\varepsilon)} - V_n \operatorname{tg} \gamma \right) \quad (10)$$

and the oscillation frequency of the digging tool is expressed as follows:

$$\nu = \frac{1}{2\pi \operatorname{atg} \beta} \left(\frac{[M_{\beta}] t_{y0}}{ABhm(1+\varepsilon)} - V_n \operatorname{tg} \gamma \right) \quad (11)$$

The allowed bending moment is expressed as follows:

$$[M_{\beta}] = [\sigma]_d \frac{\pi (D_k - 2z \operatorname{tg} \gamma_k)^3}{32} \quad (12)$$

where D_k is the diameter of the root; γ_k – cone angle of the root; z – digging tool's running depth; $[\sigma]_d$ – temporal bending resistance when dynamic force is applied.

4. Conclusion

1. An equivalent schematic has been compiled, describing the force interaction between a vibrating digging tool and a sugar beet root attached in soil in case of an asymmetrical contact.
2. The contact impulse and maximum perturbing force occurring in case of the described contact have been determined based on force impact equations.
3. Based on the conditions necessary for not damaging sugar beet roots, an equation was devised to determine the allowed oscillation frequency of the vibrating digging

tool, taking into account its constructive parameters and translational speed.

4. According to model calculations, the allowed oscillation frequency decreases when the oscillation amplitude and the translational speed of the vibrating digging tool increase.
5. The theory describing the force interaction between sugar beet roots attached in the soil and a vibrating digging share, as well as the calculated algorithm based on it allow calculating the kinematic operating conditions of the digging tool, considering its constructive parameters and the conditions necessary for not damaging the sugar beet roots.

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