Research into geometric parameters of digging shares used for lifting sugar beet roots from soil with assistance of vibration

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Abstract. One of the important conditions in securing the high quality, when performing the work process of vibrational root lifting, is to avoid damaging the roots. It is obvious that the greatest probability of damaging and even breaking the lifted root arises, when the tool interacts with the root body during their first contact and in the time of the root passing in the throat between the operating shares. The aim of the study is to substantiate the rational design length for the working throat of the vibrational root lifter in its interaction with the sugar beet root while lifting the latter from the soil. As a result of the completed research, the minimum permissible tool oscillation frequencies have been determined for the specific values of the lifter's translational velocity and the working throat rear part length, at which the event of the vibrational lifting tool gripping the root will occur at least one time. For example, when the length of the lifter's working throat rear part is equal to 0.1 m and the oscillation frequency is equal to $v = 20.3$ Hz, the satisfactory quality of the vibrational root lifting process is ensured, when the velocity of the translational motion performed by the vibrational lifter stays within the range of 1.3–2.55 m s^{-1}. In order to ensure the good quality of the vibrational root lifting process at the lifter's translational velocity equal to $V = 2.0$ m s^{-1} and the frequency of its tool's oscillations equal to $v = 10$ Hz, it is necessary that the length of the lifter's working throat rear part is equal to 0.2 m, at a tool oscillation frequency of 6.7 Hz - 0.3 m. As a result of the completed numerical calculations, the permissible values have been determined for the tool oscillation frequency, which can be recommended for the translational velocities within the range of 1.3–2.2 m s^{-1}, taking into account the limitation set for the tool oscillation frequency by the pre-condition of the guaranteed gripping of each root by the digging shares.

Key words: amplitude, frequency, oscillation, sugar beet root, vibrational lifting tool.

INTRODUCTION

Not damaging sugar beet roots and preventing their loss are important conditions in securing the high quality, when performing the work process of vibrational sugar beet root lifting from the soil (Dobrovsky, 1968; Vasilenko et al., 1970; Sarec et al., 2009; Schulze Lammers, 2011). The greatest probability of damaging the roots and even breaking them arises during the interaction between the digging tool and the root body in the time of their vibrational contact and when the root moves in the throat between the faces of the vibrational lifter. In view of the fact that the above-mentioned interaction takes place during the first contact between the vibrational lifting tool and the root body, when the latter is still strongly bonded with the surrounding soil and a side face of the lifter positively acts on it (one or both faces), damage to the roots appears to be even inevitable because of the lifter's translational motion velocity and the velocity of its oscillatory motion, especially in case the roots are lifted from the dry and firm soil (Bulgakov et al., 2014; 2015a, 2015b). During such a contact within a rather short time interval, the conditions arise that can result in the complete break-off and loss of the root's tail part.

An important issue in the theoretical investigation of the work process under consideration is to determine the length of the vibrational lifter's working throat rear part that begins at the point of its first contact with the beet root and ends at the end of the working throat (where the final lifting takes place), that is, the length of the lifter's working faces, within which their continuous contact with the root and the latter's direct lifting from the soil occur. The said length can vary (taking into account the difference in the design solutions that take into consideration the irregular sizes of the roots, their depth of sitting in the soil etc.), however, it has to have some mean value l, which could in the future be used in the designing of such vibrational tools for sugar beet root lifting that are appropriate for the successful use in state-of-the-art root harvesters.

Hence, a topical problem arises of researching into the above-mentioned interaction between the sugar beet root body sitting in the soil and the digging shares of the vibrational lifting tool, which would enable determining the rational design and kinematic parameters of the tool, under the pre-condition of not damaging (no break-off and no loss of) the roots during the said interaction that takes place in the time of their vibrational lifting.

Sufficiently thorough studies on the process of lifting sugar beet roots from the soil with the use of vibration are presented in the papers (Vasilenko et al., 1970; Vermeulen & Koolen 2002; Bulgakov, 2005; Bulgakov et al., 2005; Gruber, 2005, 2007; Bulgakov & Ivanovs, 2010; Gu et al., 2014). Among other issues, these studies examine in detail the interaction between the vibrational lifting tool and the sugar beet root body, when the latter is imparted a vibrational action with the parameters that ensure its lifting from the soil. In many vibrational lifting tool designs, the construction features stipulate that the direct lifting of the root from the soil takes place in its interaction with different parts of the lifter, in particular, in the time of the root being gripped and during its further translation along the tapered working throat. The vibrational lifting tools installed in many root harvesters feature lifting faces (digging shares) not only of different sizes, but also with working edges (blades) of different shapes and having different positions, inclinations in space etc. (Schulze Lammers & Schmittmann, 2013; Boson et al., 2019).

In the above-noted articles, the interaction between the sugar beet root body and the shares of the vibrational lifting tool is discussed for only one or two points of contact, while in reality the sugar beet root body in the process of its lifting from the soil makes in a successive order contact with different points of the digging shares during the translational motion of the vibrational lifting tool. The points of contact change their positions along both the longitudinal and the vertical axes of the shares gripping the root body on its both sides. Hence, the progression of the sugar beet root body along the tapered throat of the vibrational lifting tool, first of all, in terms of the basis for determining the length of the working throat in the vibrational lifting tool is not discussed in the papers.

Only the studies (Pogorely et al., 1983; Pogorely & Tatyanko, 2004) provide some results of the experimental investigations on the frequency of the interaction between the root body and the lifting tool, which depends not only on the translational velocity of the lifter, but on the length of the working throat in the vibrational lifting tool as well.

All the described circumstances make it necessary to carry out the theoretical research that would enable establishing the geometrical and kinematic parameters of the digging shares, which form a vibrational lifting tool for sugar beet roots.

The aim of the research is to justify the rational geometric parameters of the new design of digging shares for the vibrational lifting of sugar beet roots from the soil in relation to the frequency and amplitude of their oscillation and the velocity of their translational motion.

MATERIALS AND METHODS

The authors have developed a design of the vibrational lifting tool for sugar beet roots (Bulgakov et al., 2020). The 3D model and the schematic process model of the design are presented in Fig. 1. This lifting tool has been subjected to comprehensive production testing, which has proved the tool's high efficiency in lifting sugar beet roots from the soil. In order to validate the design and kinematic parameters of the discussed vibrational lifting tool that would ensure minimising the damage to and loss of sugar beet roots, the authors have carried out theoretical and experimental investigations of the tool.

In the new design, the digging shares 1 of the vibrational tool under consideration are linked with the use of the kinematic tie link 3 with the vibration generation device (not shown in Fig. 1) that imparts to the digging shares 1 oscillatory motion in the longitudinal and vertical plane with pre-set amplitudes and frequencies. The vibration generation device provides for setting different amplitudes and frequencies of the oscillations performed by the digging shares 1 in the above-mentioned plane, depending on the condition of the soil at the time of lifting sugar beet roots. In order to prevent the fallout and loss of sugar beet roots lifted from the soil at the final stage of their lifting from the soil, on the back sides of the posts 3, immediately above the rear parts of the digging shares 1, the cylinder-shaped extension pins 4 are installed with appropriate spacing. The sets of extension pins 4 placed on each of the posts 2, i.e. on both sides of the rear part of the tapered throat, effectively make a grill-shaped extension of the throat, which travels during the lifter's operation above the soil surface and at the same time performs oscillatory motion in the longitudinal and vertical plane. The kinematic tie link 3 has such a design that not only it is possible to impart to the posts 2 and the digging shares 1 the parameters of the vibration process, but also the shares 1 are capable of

self-aligning (within relatively narrow limits) with respect to the row of planted sugar beet roots.
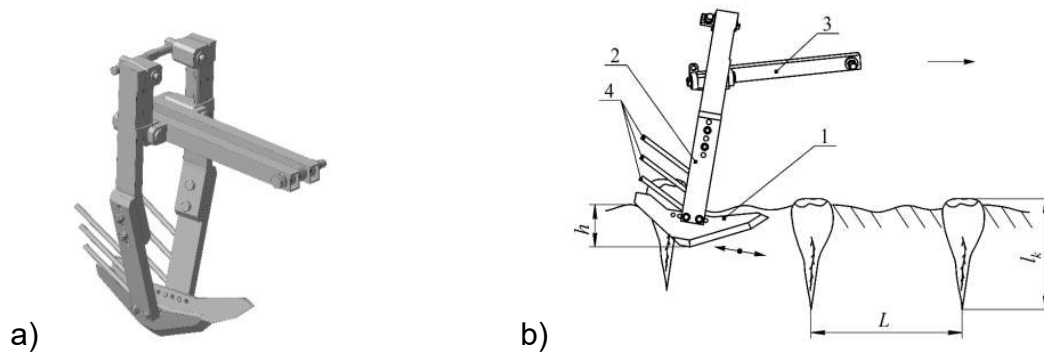

Figure 1. 3D model (a) and design and process schematic model (b) of vibrational lifting tool for sugar beet roots: 1 – digging shares; 2 – posts; 3 – kinematic tie link between posts and vibration generation device; 4 – extension pins.

The digging shares of the vibrational lifting tool under consideration run at the preset depth h in the soil, the value of which is within the range of 0.06–0.1 m. The depth, through which the sugar beet roots sit in the soil, i.e. the actual length of the roots, is designated h_k and is equal to 0.23–0.30 m for the majority of sugar beet varieties. In fact, the said root length represents the sugar-bearing mass content in the root body, therefore, any loss of or damage to the sugar beet roots in the process of their vibrational lifting are undesirable. The spacing between any two adjacent beet root bodies in the sowed row designated L is a random value. In order to provide for the optimum yield, it has to stay within the range of $L = 0.16–0.23$ m. In that case, one running metre of planted sugar beets contains 4–6 pcs of sugar beet roots.

For the purpose of theoretically substantiating the design parameters of the vibrational lifting tool, the principal dimensions of one of its digging shares and of the working throat in the lifting tool as a whole are shown in Fig. 2.
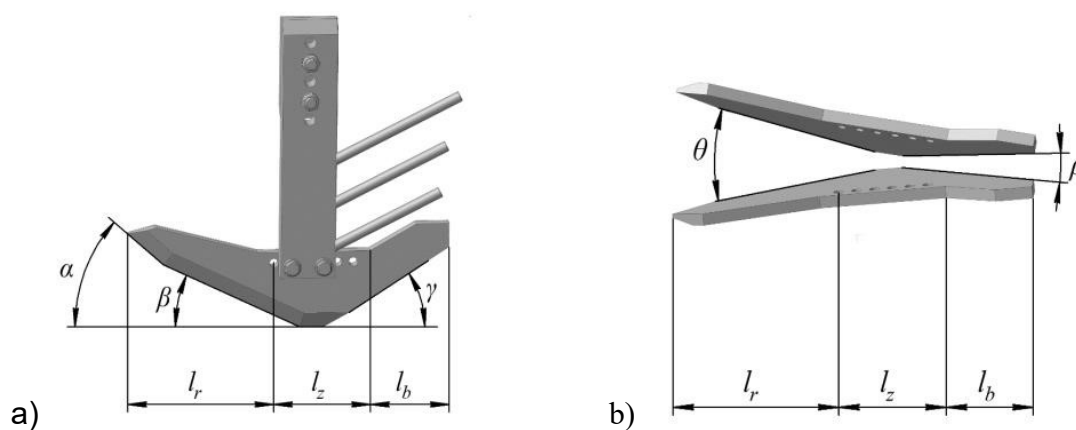

Figure 2. Structural dimensions of digging share (a) and working throat (b) of vibrational lifting tool.

As can be seen in the schematic model in Fig. 2, the most forward part of the digging share defined by the length l_r and featuring a complex shape in the longitudinal and vertical plane has a tapered cutting edge of the blade defined by the following two

angles: α – angle of inclination to the horizon of the blade's pointed end section, β – angle of inclination to the horizon of the front blade's lower edge. At the same time, the angle of inclination to the horizon α of the blade's pointed end edge is of greater importance, than the angle of inclination to the horizon β of the blade's lower edge. It is exactly in the forward section of the vibrational lifting tool, where the distance between the fore ends of the shares in the horizontal plane is the greatest, and, correspondingly, which is the part that forms the angle θ of the fore part (mouth) in the working throat of the vibrational lifting tool, and this angular part ensures catching all the roots positioned in the row with some deviations from its centreline. The middle section of the share defined by the length l_z is, effectively, the area of the first contact between the share and the sugar beet root body, which by this moment is still fixed in the soil. Within this length not only the first contact with the root body is made, but also the root becomes firmly gripped in the working throat that gradually gets narrower and entrained in the movement and moves further along the whole narrowed throat of the vibrational lifter. It is exactly that part of the share, where the throat is at its narrowest, and which has a tilt with respect to the longitudinal and vertical plane. These features of the part make it possible to pull the root body out from the soil within a short time interval due to the upward motion of the shares' working faces in their vibrational oscillations. Finally, the rear parts of the digging shares are defined by the length l_b, the shortest of the three lengths, and are inclined upward at an angle of γ to the horizon, while the working throat here features some divergence (at an angle of ρ), because exactly at this part of the vibrational lifting tool the sugar beet root body must be released from the vibrational lifter for its prompt feeding onto the cleaning tool.

In order to substantiate the design parameters of the vibrational lifting tool, first of all, of its working shares, it is necessary to analyse the above-mentioned contact between the root body and the tool and to find the analytical relation between the number of oscillations performed by the vibrational lifting tool in its interaction with the root within the time, when the latter resides in the area of the working throat, on the one hand, and the length of the working throat's rear part, the oscillation frequency and the translational velocity of the lifter, on the other hand (Babakov, 1968; Schmitz & Smith, 2012). If l – distance from the point of the first contact with the root to the end of the lifter's working throat and V – velocity of the translational motion performed by the lifter, the duration of the period, when the root resides in the said area of the working throat, is equal to:

$$t_p = \frac{l}{V}. \tag{1}$$

Within this time, the tool performs the following number of oscillations:

$$k = \nu \frac{l}{V}, \tag{2}$$

where ν – vibrational tool oscillation frequency (Hz).

For example, assuming in accordance with Pogorely & Tatyanko (2004), that $V = 2$ m s^{-1}, $\nu = 20$ Hz, $l = 0.1$ m (the minimum possible value of the length), the vibrational lifting tool will perform one oscillation ($k = 1$) within the time that the root is found in the rear part area of the lifter's working throat.

The next task is to determine the number of times that the vibrational lifting tool grips the root within the time that the latter resides in the rear part area of the lifter's working throat, if $k = 1$, that is, in case the tool completes one full oscillation within the above-mentioned time.

The process under consideration can follow two possible scenarios.

The first scenario. The first direct contact between the tool and the root occurs at the moment, when the tool is in its upward movement from its lowest position to the highest one. The period of the tool's oscillation is designated τ. As, in this scenario, the perturbing force is vectored upward, the above-mentioned first contact between the tool and the root is also the first time, when the tool grips the root, which initiates the process of breaking up the bonds between the root and the soil. The gripped condition continues up to the moment, when the tool reaches its highest position. The duration of this condition is designated t_1. It is obvious that:

$$t_1 = s_1 \tau , \tag{3}$$

where $0 \leq s_1 \leq 0.5$ – factor that indicates, during what part of the oscillation period the first gripping of the root by the tool takes place.

For example, if $s_1 = 0.5$, it means that the first gripping of the root starts in the lowest position, therefore, $t_1 = 0.5\tau$. If $s_1 = 0$, it implies that the first contact starts in the highest position, consequently, $t_1 = 0$. All the other values of s_1 that comply with the above in equation correspond to the start of the gripping at any instant of time during the movement of the tool from its lowest position to the highest one.

Having reached the highest position, the tool starts moving downwards. In view of the conical shape of the root, the perturbing force stops acting on the root, hence, the gripping of the root is absent. However, the loss of contact between the root and the tool is rather unlikely in view of the translational motion of the lifter and the tapered shape of its working throat. As the perturbing force no longer acts on the root, the latter will attempt returning into the vertical position due to the elastic stiffness of the soil and its own elastic stiffness. In this case, the root will possibly have a small forward inclination as a result of the lifter's translational motion. The described situation will be observed within the period of time $t_2 = 0.5\tau$, during which the tool moves from its highest position to the lowest one. After that, the tool again switches to moving upwards from its lowest position to the highest one.

Hence, within the period of time $t_3 = \tau - (t_1 + t_2)$, the second instant of the root being gripped by the tool will take place, which will initiate the further process of disrupting the bonds between the root and the soil right up to the direct lifting of the root. In case the time of the root residing in the rear part of the working throat (after the first contact) does not exceed τ, the root must without fail be completely lifted from the soil within the time of the second gripping. Otherwise, the root will be left in the soil, i.e. either it will be sheared off by the shares or it will obstruct the lifter's working throat.

But if the root is fixed in the soil not that strongly, it is not improbable that its lifting from the soil can take place immediately during its first gripping by the vibrational lifting tool.

The second scenario. The first direct contact between the tool and the root occurs at the moment, when the tool is in its downward movement from its highest position to the lowest one. This will take place during the period of time $t_1 = s_1\tau$, where $0 \leq s_1 \leq 0.5$.

In this case, no perturbing force generated by the vibrational tool acts on the root. After the tool reaches its lowest position, it starts moving in the opposite direction, i.e. upwards from its lowest position to the highest one. At this instant of time, the root is gripped by the tool for the first time and this gripping lasts for a time of $t_2 = 0.5\tau$, until the tool reaches its highest position. After that, the tool starts its downward movement and, within the time period of $t_3 = \tau - (t_1 + t_2)$, again no perturbing force acts on the root, i.e. there is no gripping of the root within this time interval.

In the second scenario, within the time period of $t_1 + t_2 + t_3 = \tau$, the root is gripped by the tool only once. If in this scenario the time of the root residing in the rear part of the working throat (after the first contact) does not exceed τ, the complete lifting of the root from the soil must take place during this single gripping. Otherwise, the root will be left in the soil not lifted.

Solely the act of gripping can be insufficient for digging out the root that has strong bonds with the soil. In such a case, it is necessary to increase significantly the gripping force. However, that can result in the disintegration and rupture of the root body itself. It is quite obvious that a single gripping of the root at a certain depth, which promotes its separation from the surrounding and holding it soil, and the further movement of the root in the narrowed throat of the lifting tool on the inclined faces of the shares are sufficient for the complete lifting of the root.

In case of $k < 1$ (vibrational lifting tool has no time to complete one full oscillation within the time of the root residing in the rear part of the working throat), under the first scenario only one instant of the root being gripped by the tool can occur, under the second scenario - none. Hence, the root has to be lifted from the soil either within one act of gripping by the tool or, in the last resort, during its movement in the narrowed working throat of the lifter due to the latter's translational motion (as happens in the standard share-type lifting tool). However, an attempt to lift a root firmly fixed in the soil through its movement in the narrowed throat due to the lifter's translational motion can result in the sudden tilting of the root in the direction of the lifter's motion and its breaking off. Also, at $k < 1$ a root firmly fixed in the soil can be not lifted within one act of gripping by the vibrational lifting tool.

The relation between the vibrational lifting tool's oscillation frequency, its translation velocity and the length of the working throat must be such that the tool is capable of performing more than one full oscillation within the time of the root residing in the rear part of the working throat, that is, the condition $k > 1$ must be satisfied.

For example, if $k = 2$ (when the length l of the rear part of the lifter's working throat is equal to 0.2 m) and the first scenario takes place (the first contact between the tool and the root occurs during the tool's upward movement), the tool will grip the root twice within the period of the first oscillation and once - within the period of the second oscillation. In case the second scenario takes place (the first contact between the tool and the root occurs during the downward movement of the tool), the tool will grip the root once within the periods of both the first and the second oscillations. That is, at $k = 2$, the digging shares of the vibrational tool will grip the root either three times or, at worst, two times.

In the general case, at $k = n$, where n – some natural number, it follows from the above considerations that the tool can perform $n + 1$ or n acts of gripping the root.

The greater k is, the smoother and higher-quality the process of lifting the root from the soil by the vibrational lifting tool will be, because in case of greater numbers of oscillations per root it is possible to apply smaller perturbing forces for lifting the roots and, accordingly, to reduce the probability of rupturing the root bodies. Moreover, the greater k is, the greater number of oscillations the root performs together with the tool and, consequently, the better it is cleaned from the soil stuck to it.

An increase in the value of k can be achieved either by increasing the tool's oscillation frequency and the length of its working throat or by reducing the velocity of the lifter's translational motion. Still, even in case of $k = 1$, where the tool effects only two acts of gripping the root within the time that the root resides in the rear part of the lifter's working throat, the oscillatory process takes place and the root is displaced by the perturbing force, then returns to the original position under the action of the restoring forces (elastic force of the soil and elastic force of the root itself). At $k > 1$, the oscillatory process that promotes the guaranteed lifting of the root from the soil takes place.

After specifying the number k ($k \geq 1$) of the oscillations performed by the vibrational lifting tool during the time, in which one root passes the lifter's working throat, it is always possible to find the relation between the parameters v, l and V in accordance with the expression (2). For specific values of l and V, the following can be derived from the expression (2):

$$v = \frac{kV}{l}. \tag{4}$$

In this way, the minimum vibrational lifting tool oscillation frequency that ensures the rational performance of the vibrational root lifting process is determined. If $k = 1$ (one oscillation of the tool per root), the following is derived from the expression (4):

$$v = \frac{V}{l}. \tag{5}$$

When the frequency of the oscillations performed by the vibrational lifting tool is set below the value obtained in the expression (4), the conditions required for the vibrational lifting of roots are not provided. That means that some roots will not be gripped by the tool in the vibrational process and, therefore, will remain not lifted or will be broken in their tail parts, which will be left in the soil. All that will result in the undesirable loss of the roots in the process of their lifting.

RESULTS AND DISCUSSION

The unjustified relation between the parameters k, v, l and V is one of the principal reasons for the loss of part of the roots during their vibrational lifting with the existing beet harvesters.

As may be inferred from the graphs (Fig. 3) generated in accordance with the expression (4), the growth of the lifter's translational velocity results in the increase of the minimum permissible tool oscillation frequency that ensures the single gripping of the root by the tool.

In order to analyse in more detail the relation between the minimum permissible frequency v of the oscillations performed by the vibrational lifting tool and the length l of its working throat rear part, the diagram of the relation has been generated for the specific values of the velocity V of the translational motion performed by the lifting tool (Fig. 4).

As is proved by the graphs (Fig. 4), at a pre-set velocity V of the translational motion performed by the vibrational lifting tool, an increase in the length l of its working throat rear part results in the decrease of the value of the minimum permissible frequency v in accordance with the hyperbolic law.
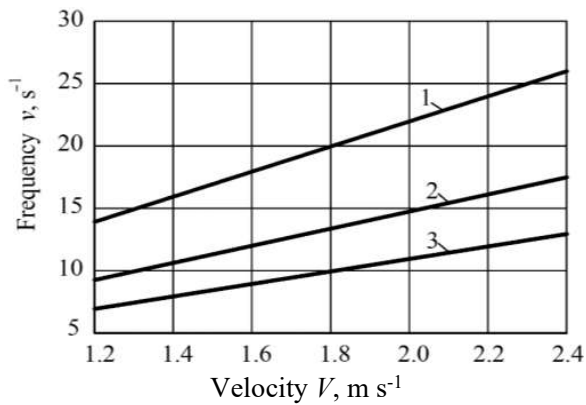

Figure 3. Relation between minimum permissible frequency v of oscillations performed by vibrational lifting tool and velocity V of its translational motion at following values of length of working throat rear part: 1) $l = 0.10$ m; 2) $l = 0.15$ m; 3) $l = 0.20$ m.
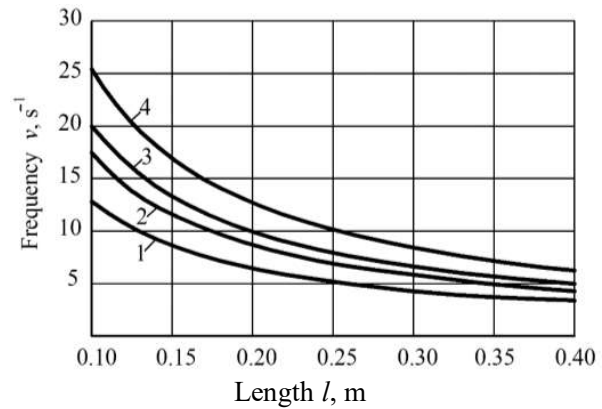
Figure 4. Relation between minimum permissible frequency v of oscillations performed by vibrational lifting tool and length l of its working throat rear part at following values of tool's translational motion velocity: 1) $V = 1.30$ m s⁻¹; 2) $V = 1.75$ m s⁻¹; 3) $V = 2.00$ m s⁻¹; 4) $V = 2.55$ m s⁻¹.

The use of the presented graphic relations provides a possibility to determine the minimum permissible frequencies v for various values of the length l at the pre-set velocity of translational motion $V = 2.0$ m s⁻¹, which corresponds to the operational rate of travel of the state-of-the-art root harvesters. The following is obtained:

at $l = 0.1$ m: $v = 20$ Hz;
at $l = 0.2$ m: $v = 10$ Hz;
at $l = 0.3$ m: $v = 6.7$ Hz;
at $l = 0.4$ m: $v = 5.0$ Hz.

At a translational velocity of $V = 2.0$ m s⁻¹, the values obtained for the minimum frequency v of the oscillations performed by the vibrational lifting tool ensure that the digging shares perform at least one act of gripping and impart to the root body the upward vibrational motion, which guarantees the proper performance quality of the vibrational lifting of the roots from the soil.

For each specific value of the velocity V of the lifter's translational motion and the length l of its working throat rear part, the specific value of the minimum frequency exists, below which the vibrational root lifting process is impaired, that is, some roots are not lifted by the vibrational lifting tool. As is seen in the graph (Fig. 3), at $l = 0.1$ m a frequency of $v = 20$ Hz ensures the satisfactory vibratory process of lifting roots from the soil for all values of the velocity V of the lifter's translational motion below 2.0 m s⁻¹, while at $l = 0.15$ m a frequency of $v = 20$ Hz ensures the satisfactory vibratory root lifting process for all values of the velocity V below 3.0 m s⁻¹.

At $l = 0.1$ m, if it is necessary to ensure the operation at the lifter's translational velocity equal to $V = 2.0$ m s^{-1}, all the permissible frequency value ranges obtained under the pre-condition of not damaging the roots during their force interaction with the tool must be limited from below by the frequency value $v = 20$ Hz.

On the other hand, in case the frequency values permissible for impact interaction obtained for some kinematic conditions are below $v = 20$ Hz, they automatically do not meet the requirements to the satisfactory performance of the vibratory root lifting process at the length of the working throat rear part $l = 0.1$ m and the lifter's translation velocity $V = 2.0$ m s^{-1}.

The results obtained in the theoretical investigations were verified by conducting experimental investigations under field conditions. The experimental investigations were carried out in a plot with sugar beet roots planted in the soil, the physical and mechanical properties of which had already been analysed by the authors. The primary properties of the soil, in which the sugar beet roots were sitting, determined by the authors were its moisture content and hardness. The soil parameters had been measured in multiple replications as in the inter-row spacing so in the rows.

During the investigations, the soil moisture content W was equal to 18%, its value was determined with the use of the weight method based on the dehumidification of the soil sample and its further weighing. According to the said method, the soil moisture content W (%) was found with the use of the following formula:

$$W = \frac{m_1 - m_2}{m_2 - m} \cdot 100, \qquad (6)$$

where m_1 – mass of humid soil complete with container and lid (g); m_2 – mass of dry soil complete with container and lid (g); m – mass of empty container (g).

The hardness of the soil was determined with the use of the Revyakin hardness tester and the standard method (Medvedev, 2009) that stipulates measuring the hardness as the magnitude of the force needed for the indenter with known parameters to penetrate into the soil. Hence, the soil hardness T (Pa) was obtained with the use of the following expression:

$$T = \frac{P}{S}, \qquad (7)$$

where P – mean force of the soil's resistance to the penetration of the indenter into it (N); S – area of indenter (m^2).

In accordance with the scale proposed by Medvedev (2009), the hardness value of 1.8 MPa obtained by the authors for the soil in the analysed beet root field plot corresponded to a firm soil, which is typical for heavy loam soils in the autumn season, that is, the period of sugar beet harvesting.

The data of the theoretical conclusions have been rather accurately proved by the experimental investigations carried out by the authors for determining the mass of the lost sugar beet roots. It has been established that at the velocity of the translational motion performed by the vibrational lifting tool $V = 2.1$ m s^{-1} and the frequency of the oscillations performed by its digging shares $v = 20.3$ Hz the mass of the lost sugar beet roots amounts to 0.64%, at the frequency $v = 15.7$ Hz – 2.2%, at the frequency 8.5 Hz – 3.48% (Table 1).

At the velocity of translational motion equal to $V = 2.1$ m s^{-1}, the oscillation frequency $v = 20.3$ Hz ensures the satisfactory performance of the vibrational sugar beet root lifting from the soil, while the frequencies $v = 15.7$ Hz and $v = 8.5$ Hz deliver the insufficient quality of the beet root lifting from the soil, i.e. some roots are not lifted by the tool or get broken off in their tail parts. That is supported by the calculations carried out in accordance with the expression (4).

The same patterns are observed also at the lifter's translational motion velocities $V = 1.3; 1.75; 2.55$ m s^{-1} (Table 1).

Table 1. Mass of lost sugar beet roots (%)

Translational velocity (m s^{-1})	Oscillation frequency (Hz) (X_1)								
	8.5			15.7			20.3		
	Running depth in soil (m) (X_2)								
	0.06	0.09	0.12	0.06	0.09	0.12	0.06	0.09	0.12
1.3	2.7	2.7	1.9	1.7	0.5	0.4	0.4	0.1	0.2
	2.9	2.7	1.8	1.9	0.5	0.5	0.4	0.3	0.4
	2.8	2.8	1.9	1.7	0.4	0.5	0.3	0.4	0.4
	2.6	2.7	1.8	1.8	0.5	0.3	0.4	0.4	0.3
	2.7	2.6	1.8	1.8	0.6	0.4	0.4	0.5	0.4
1.75	2.9	1.8	2.0	1.9	0.4	0.6	0.3	0.4	0.5
	2.9	2.0	2.1	2.0	0.5	0.6	0.6	0.4	0.5
	3.0	1.9	2.6	1.9	0.5	0.7	0.5	0.5	0.6
	3.2	2.0	2.0	1.8	0.4	0.8	0.4	0.3	0.4
	2.8	1.9	2.4	1.9	0.5	0.7	0.3	0.4	0.5
2.1	3.5	0.6	2.7	2.3	0.2	0.9	0.7	0.5	0.6
	3.5	0.4	2.4	2.2	0.4	0.8	0.6	0.6	0.6
	3.2	0.6	2.7	2.1	0.2	0.9	0.6	0.4	0.4
	3.6	0.5	2.6	2.2	0.3	1.0	0.6	0.5	0.5
	3.6	0.6	2.8	2.2	0.2	0.9	0.7	0.5	0.3
2.55	4.2	0.9	3.1	2.6	0.6	1.2	0.9	0.8	0.3
	4.3	0.9	3.2	2.1	0.8	1.1	1.1	0.5	0.6
	4.2	0.8	2.9	2.4	1.2	1.2	1.4	0.6	0.4
	4.5	0.9	2.8	2.5	0.7	1.3	1.2	0.7	0.6
	4.3	0.9	2.9	2.6	0.8	1.2	1.1	0.7	0.6
(X_3)	(Y_1)								

When the translational velocity is equal to $V = 1.3$ m s^{-1}, at the oscillation frequency $v = 20.3$ Hz the mass of the lost beet roots amounts to 0.38%, at the frequency $v = 15.7$ Hz – 1.78%, at the frequency $v = 8.5$ Hz – 2.74%. The frequencies $v = 20.3$ Hz and $v = 15.7$ Hz provide for the satisfactory performance of the vibrational root lifting, the frequency $v = 8.5$ Hz does not.

When the translational velocity is equal to $V = 1.75$ m s^{-1} and the running depth in the soil is equal to 0.06 m, at the oscillation frequency $v = 20.3$ Hz the mass of the lost roots amounts to 0.42%, at the frequency $v = 15.7$ Hz – 1.9%, at the frequency $v = 8.5$ Hz – 2.96%.

If the velocity of translational motion is equal to $V = 2.55$ m s^{-1} and the lifter's running depth is the same, at the oscillation frequency $v = 20.3$ Hz the mass of the lost roots will amount to 1.14%, at the frequency $v = 15.7$ Hz – 2.44%, at the frequency $v = 8.5$ Hz – 4.3%.

This pattern can be seen rather clearly in the results of the experimental investigations carried out by the authors, as presented in Table 2, where the mass of the lost roots (%) is determined for the tool oscillation frequency $v = 8.5$ Hz.

The obtained research results provide grounds for stating that, when the running depth in the soil of the vibrational lifting tool is equal to 0.06 m, the mass of the lost roots has the following (mean) values:

at $V = 1.4$ m s^{-1} – 1.2%;
at $V = 1.65$ m s^{-1} – 4.9%;
at $V = 2.1$ m s^{-1} – 6.2%.

When the running depth in the soil of the lifting tool is equal to 0.08 m, the following results have been obtained with regard to the root loss rate:

at $V = 1.4$ m s^{-1} – 1.2%;
at $V = 1.65$ m s^{-1} – 2.1%;
at $V = 2.1$ m s^{-1} – 4.2%.

The above losses arise from breaking off the tail parts of sugar beet roots and outright not lifting some part of them due to the fact that the tool oscillation frequency $v = 8.5$ Hz does not ensure the proper gripping of each root by the digging shares.

It is obvious that the root loss rate at the running depth of the vibrational lifting tool's digging shares in the soil equal to 0.06 m is greater than at the running depth in the soil equal to 0.08 m. This is due to the increase in the number of the roots not lifted from the soil.

Table 2. Mass of lost sugar beet roots (%) at oscillation frequency equal to 8.5 Hz (when soil penetration resistance is equal to 1.8 MPa (at the maximum digging share running depth in the soil equal to 0.12 m), soil moisture content is equal to 18.0% (mean value at the digging share running depth in the soil))

Translational velocity (m s^{-1})	Running depth in soil (X_2) (m)			
	0.06	0.08	0.10	0.12
	3.0	1.0	0.0	0.0
	3.0	1.5	0.0	0.5
1.4	2.9	1.0	1.0	1.0
	3.1	1.2	0.0	0.0
	3.0	1.3	1.0	1.0
	5.0	2.0	0.0	0.0
	4.9	2.5	1.0	0.0
1.65	4.8	2.0	1.0	1.0
	4.9	2.0	0.0	0.0
	5.0	2.0	1.0	0.5
	6.0	4.0	2.0	0.0
	6.5	4.5	2.5	1.0
2.1	6.0	4.0	2.0	0.0
	6.2	4.5	2.0	1.0
	6.1	4.2	1.8	1.0
(X_1)	(Y_4)			

According to Pogorely & Tatyanko (2004), in the course of the rapid development of vibrational lifting tools for the beet harvesters produced by the leading manufacturers, the frequency of the oscillations performed by the vibrational lifting tools has grown from 3.3–6.0 Hz to 10 Hz, that is, under production conditions, oscillation frequencies above 10 Hz are still not achievable in view of the insufficient reliability of the tool oscillation generating devices. The above calculations imply that the satisfactory conditions for performing the process of the vibratory sugar beet root lifting from the soil at the lifter's translational velocity equal to $V = 2.0$ m s^{-1} and the tool oscillation frequency $v = 10$ Hz will be ensured, if the relations between the geometrical parameters of the tool provide for the length of the lifter's working throat meeting the condition $l \geq 0.2$ m. Otherwise, at the velocity of translational motion equal to $V = 2.0$ m s^{-1}, the vibrational lifting process will be impaired.

The next step is to select from the results obtained by the completed numerical calculations the permissible vibrational lifting tool oscillation frequency values that could be recommended for use within the translational motion velocity range of 1.3–2.2 m s^{-1}, taking into account the limits set for the tool oscillation frequency by the requirement of each root being gripped without fail by the digging shares. This can be done, and for that purpose the reduced mass of the vibrational lifting tool must also be taken into account:

– for the reduced mass of the tool equal to $m = 0.8$ kg: at a running depth in the soil of 0.08 m and an oscillation amplitude of 0.008–0.024 m, the permissible oscillation frequency is equal to 21.2 Hz; at a running depth of 0.10 m - 10.0 Hz; at a running depth of 0.12 m - 9.0 Hz;

– for the reduced mass of the tool equal to $m = 1.0$ kg: at a running depth in the soil of 0.08 m and an oscillation amplitude of 0.008–0.024 m, the permissible oscillation frequency is equal to 16.4 Hz; at a running depth of 0.10 m and an oscillation amplitude of 0.008–0.018 m, the permissible oscillation frequency is equal to 10.0 Hz, at an amplitude of 0.020–0.024 m - 8.3 Hz;

– for the reduced mass of the tool equal to $m = 1.5$ kg: at a running depth in the soil of 0.08 m and an oscillation amplitude of 0.008–0.024 m, the permissible oscillation frequency is equal to 10.0 Hz; at a running depth of 0.10 m and an oscillation amplitude of 0.008–0.010 m, the permissible oscillation frequency is equal to 10.0 Hz, at an amplitude of 0.012 m - 8.0 Hz;

– for the reduced mass of the tool equal to $m = 2.0$ kg: at a running depth in the soil of 0.08 m and an oscillation amplitude of 0.008–0.016 m, the permissible oscillation frequency is equal to 10.0 Hz, at an oscillation amplitude of 0.018–0.020 m - 8.1 Hz.

In view of the requirement to minimise the damage to and loss of sugar beet root bodies in the process of their vibrational lifting from the soil, it is necessary to take into account and comply with the conditions presented in Table 3 in the process of designing advanced lifting tools for state-of-the-art root harvesters.

Table 3. Recommended oscillation frequencies v (Hz) for vibrational lifting tools

Reduced mass of tool m (kg)	Tool running depth in soil (m)								
	0.08			0.10					0.12
	Oscillation amplitude (m)								
	0.008–0.016	0.018–0.020	0.008–0.024	0.008–0.024	0.008–0.018	0.020–0.024	0.008–0.010	0.012	0.008–0.024
0.8	–	–	21.2	10.0	–	–	–	–	9.0
1.0	–	–	16.4	–	10.0	8.3	–	–	–
1.5	–	–	10.0	–	–	–	10.0	8.0	–
2.0	10.0	8.1	–	–	–	–	–	–	–

Accordingly, if the results obtained by the authors in their experimental investigations aimed at determining the rate of sugar beet root loss in vibrational lifting are compared to the results of other investigations and tests, it becomes obvious that, at the recommended length of the rear narrowed part of the working throat l_z and l_b equal to 0.1 m and the lifter's translational motion velocity equal to 2.0 m s^{-1}, the root loss rate decreases to 1.0%, which is 2–3 times lower than the similar indices obtained for the known vibrational lifters (Zuyev, 1970; 1980; 1989; Pogorely et al., 1980; 1983;

Bulgakov, 2005). Taking into account the fact that the research accomplished by the authors and the relations established for the geometric parameters of the digging shares in the vibrational lifting tool for harvesting sugar beet roots are tied up with the characteristics of the vibrational action applied to the roots, the obtained results open up opportunities for designing also other different tools, which will deliver virtually zero root loss and damage rates. That said, the above-mentioned parameters can be easily changed (before the start of the harvesting operations) in accordance with the properties of the soil, in which the sugar beet roots (or other root crops) are cultivated, the dimensions and shape of the roots, the travel rate that the multiple-row root harvester can maintain, the engine power rating etc.

The literature currently available in the world does not contain any theoretical studies on the relation between the sugar beet root harvesting quality and the length of the working throat between the digging shares, their oscillation frequency and amplitude as well as their translation velocity.

Also, it should be noted that, in view of the earlier mentioned fact that sugar beet roots are often spaced within the row at different distances (L – some average distance between the roots shown in Fig. 1), it can be expected in some cases that the following root is situated quite close to the root already being lifted at the moment. As a result of that, it can happen so that at the instant of time, when the lifted root is still in the area of the lifter's working throat rear part, the digging shares will already grip the next root. Before the next root reaches the rear part of the working throat, the lifted root will already depart from the lifter's working throat, moving back and upwards, and move to the area of the cleaning tools, freeing the space in the working throat rear part for the movement there of the next root. The lengths l_z and l_b of the rear narrowed part of the working throat are just what provides for such consecutive lifting of beet roots from the soil despite their positions in the row close to each other. In the worst case, if the previous root remains not extracted from the soil, all the same, it will depart from the working throat due to the lifter's translational motion - the tool will crush it pressing it down. In such a case, the root will become lost, but the working throat will least likely be obstructed by not lifted roots. However, even in this case the loss of the roots in view of their close spacing in the row will be minimal, because the angles of inclination in space of the working throat in the vibrational lifting tool under consideration, specifically in its rear narrowed part defined by the lengths l_z and l_b, are such that they promote the advancement of the root bodies backward and upward, i.e. operate on the principle of the conventional share lifter.

CONCLUSIONS

1. The relation between the number of the oscillations completed by the vibrational lifting tool within the time of the sugar beet root residing in the lifter's working throat, on the one hand, and the tool oscillation frequency, the length of the working throat rear part and the lifter's translational velocity, on the other hand, under the pre-condition of ensuring the good performance quality of the vibrational sugar beet root lifting process, has been obtained.

2. The minimum permissible tool oscillation frequencies, which ensure at least one instant of the root being gripped by the vibrational lifting tool, have been determined for several specific values of the lifter's translational motion velocity and the length of the working throat rear part.

3. When the length of the lifter's working throat rear part is equal to 0.1 m, the oscillation frequency $v = 20.3$ Hz ensures the satisfactory performance of the vibratory root lifting process for the lifter's translational motion velocity within the range of 1.3–2.55 m s^{-1}, the oscillation frequency $v = 15.7$ Hz - for the lifter's translational motion velocity within the range of 1.3–1.75 m s^{-1}, while the frequency $v = 8.5$ Hz does not ensure the satisfactory performance of the vibratory root lifting process for the above-mentioned ranges of translational velocity, that is, some part of the sugar beet roots will not be lifted by the tool or they will be broken off in their tail parts.

4. In order to ensure the good quality of the vibrational sugar beet root lifting from the soil at the lifter's translational motion velocity equal to $V = 2.0$ m s^{-1} and the tool oscillation frequency equal to $v = 10$ Hz, it is necessary for the length of the lifter's working throat rear part to be equal to 0.2 m, at a tool oscillation frequency of 6.7 Hz - 0.3 m.

5. As a result of the PC-assisted numerical calculations, the values of the permissible tool oscillation frequencies, which can be recommended for the translational velocity range of 1.3–2.2 m s^{-1}, taking into account the limitation of the tool oscillation frequency under the pre-condition of each root being gripped without fail by the digging shares, have been determined.

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