CONTACT INTERACTION COEFFICIENT BETWEEN ROOT AND SCREW TURN

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Abstract. Increasing the production of sugar raw materials while reducing their cost constitutes a relevant economic challenge. This is associated with the substantial demand for products derived from sugar raw materials, including additional supplies of livestock feed in Ukraine and the high demand for sugar on the international market. The purpose of the study is to substantiate the parameters of the working elements of the combined cleaner based on the analysis of the dynamic interaction coefficient. It consists of a cleaning slide, which is inclined to the horizontal; a transverse or longitudinal screw cleaner, which is located behind the lower step of the cleaning slide. The screw cleaner comprises horizontally arranged pairs of helical screw conveyors (augers) installed with a clearance between their shafts. A theoretical analysis of the process and interpretation of the values of the coefficients of dynamic interaction of the root crop with the screw turn for two possible cases of contact movement of the root crop along the working surface of the slide are presented. It is established that for certain combinations of screw parameters, the value of the coefficient of dynamic impact interaction is greater than unity. In the first case, when the root crop rolls along the inclined surface of the cleaning slide to contact with the screw turn, this condition is met for a screw diameter in the range of 0.18-0.25 m and an angular velocity of 34-42 rad·s^{-1}. In the second case, when the root crop is detached from the surface of the cleaning slide and is in free fall until it contacts the screw turn, the necessary condition is achieved for the same diameter range of 0.18-0.25 m and angular velocity of 44-55 rad·s^{-1}.

Keywords: impurities, separation, cleaning slide, impact velocity, angular velocity, analytical model, parameters.

Introduction

Mechanized harvesting of sugar beet root crops is a complex technological process in which the operation of cleaning the roots from soil and plant impurities plays a particularly important role [1].

One of the major reserves for increasing the productivity of root-harvesting machines is the improvement of the technological process of cleaning root crops from impurities. This can be achieved through the intensification of soil and plant residue separation by means of combined cleaning devices. The main criteria that meet the operational requirements of root-harvesting machines are, first of all, the quality of root excavation and the efficiency of impurity separation from the harvested roots [2; 3].

The primary indicators determining the technological level of harvesting quality include the degree of impurity separation from root crops and the level of mechanical damage caused by the kinematic motion and dynamic interaction of root crops with the working surfaces of cleaning devices [4]. The main causes of root crop damage are associated with dynamic phenomena occurring during the technological process of impurity separation when combined cleaning mechanisms operate.

According to the analysis of the results of the conducted experimental studies [5], it was established that the maximum permissible velocity of a single impact of a sugar beet root crop of average diameter against a metal surface is 3.7 m·s^{-1}. In addition, the change in the mean values of the interaction rate of root crops with the working branch of the cleaning slide is in the range from 1.3 to 1.7 m·s^{-1}, and the angle of inclination ε of the trajectory of root crops relative to the working branch is from 40 to 45 degrees [6].

The aim of this study is to further develop methods for optimizing the parameters of the operation of combined root crop cleaners used for impurity removal. An analysis of recent studies and publications [7-10] has shown that theoretical investigations describing the optimization processes of combined cleaner parameters based on the analysis of the dynamic interaction coefficient between root crops and the working surfaces of cleaning mechanisms are practically absent. This circumstance determines the necessity of conducting further theoretical and experimental research in this field.

DOI: 10.22616/ERDev.2026.25.TF177

Materials and methods

Let us consider the process of interaction of the root crop 1 (Fig. 1) with the turn 2 of the screw 3. Let us assume that the root crop after contact with the working surface of the slide 4 acquires a total velocity V_ε and interacts with the screw turn at the impact point O. Let us denote the mass of the root crop by the index m_k. The screw rotates with an angular velocity ω, and the impact point O is located at a distance $R = 0.5D$ from the centre of rotation O_e, where D is the diameter of the screw, m.

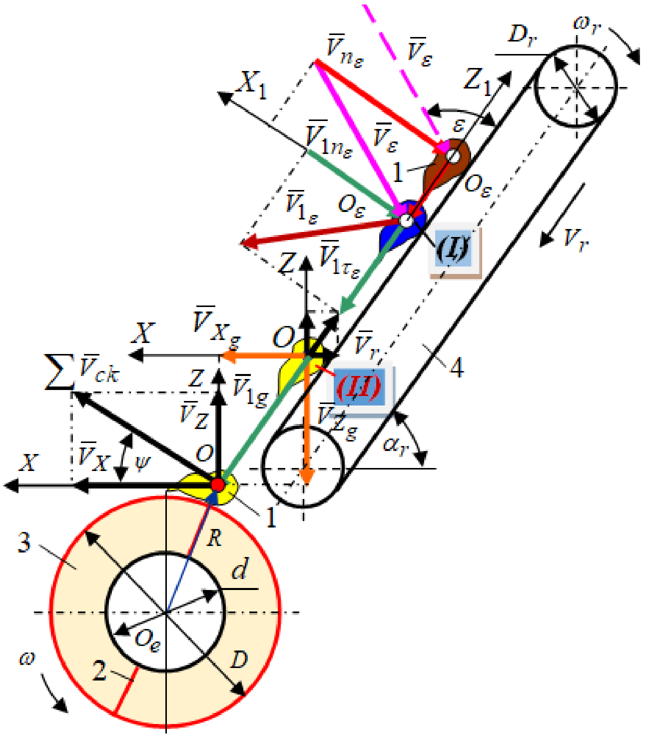

Fig. 1. **Scheme for calculating the speed of the root crop until the moment of contact with the screw turn:** 1 – root crop; 2 – screw turn; 3 – screw; 4 – cleansing slide

After the root crop has been moved from the previous working element (for example, a scraper conveyor located at an angle to the horizon) and the root crop has come into contact with the working surface of the slide, we will consider two possible cases of its further movement.

- The first case (I): the root crop rolls down the working surface of the slide with an initial velocity $V_\varepsilon = 0$ (Fig. 1) until it touches the screw turn at point O with a velocity V_{1g};
- The second case (II): the root crop bounces off the working surface of the branch with the initial speed V_ε (Fig. 1), acquiring new values of the normal $V_{1n\varepsilon}$ and tangential $V_{1\tau\varepsilon}$ speeds and remains in free flight until it touches the screw turn at point O with the speed $V_{1\varepsilon}$. In this case, the speed $V_{1n\varepsilon}$ decreases depending on the value of the recovery coefficient k, and $V_{1\tau\varepsilon}$ increases with a certain increment, the value of which depends on the angular speed $\Delta\omega_k$ of the root crop rotation at the moment of its contact with the screw turn and the speed V_r.

To estimate the root crop damage degree, maximal amount of which appears while interacting with the screw check, we offered to use the root crop dynamic interrelation factor K_V. The physical essence of this coefficient K_V is expressed through the ratio of the total momentum of the root crop q_{ki} during its collision with the screw turn to the maximum permissible momentum $[q_{\max}]$ during the collision of sugar beet roots with a metal surface. Under the condition $q_{ki} \geq [q_{\max}]$, we have

$$K_V = q_{ki} / \left[q_{k_{\max}}\right] = V_{pi} / \left[V_{k_{\max}}\right] \geq 1, \tag{1}$$

where V_{pi} – total speed of movement of the root crop at the moment of contact with the screw turn, m·s^{-1};

$[V_{k\max}]$ – maximum permissible speed of movement of the root crop at the moment of contact with the screw turn, m·s^{-1}.

To determine V_{pi} in the first and second cases, consider the scheme shown in Fig. 1. Let the average velocity of the root crop at point O_ε (the moment of contact with the working surface of the slide, which is located at an angle α_r to the horizon) be equal to V_ε, and its vector is directed towards the working surface of the slide at the angle of inclination ε of the flight path.

Let us consider the movement of the root crop after rebounding from the working surface of the slide as the movement of a body thrown at an angle to the horizon, case (II). The root crop moves in the plane $O_\varepsilon XZ$ according to the equations $X = V_n t \cos\varepsilon$, $Z = V_n t \sin\varepsilon - 0.5gt^2$, and its trajectory is a parabola whose equation is $Z = X\mathrm{tg}\,\varepsilon - gX^2 / 2V_n^2\cos^2\varepsilon$. The second case (I), where the root crop rolls down the slide under the action of gravity m_kg, is considered in the $O_1X_1Y_1Z_1$ coordinate system.

In this regard, let us consider the graphic construction of the velocity plan of the oblique impact of the root crop with the screw turn in the horizontal plane $O_1X_1Y_1$ (Fig. 2).

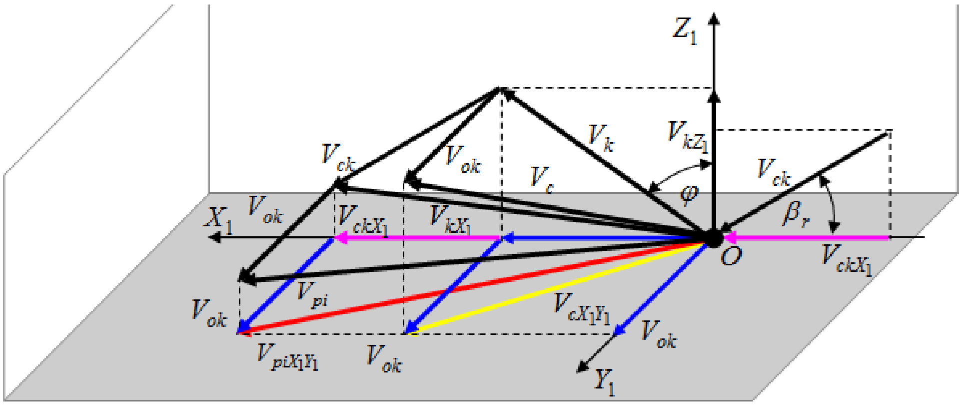

Fig. 2. **Plan of the speeds of oblique impact of the root crop with the screw turn**

Then, for the cases (I) and (II), the vector form for the resulting velocity of the body's impact in the horizontal plane $O_1X_1Y_1$ will be as follows:

$$\left.\begin{aligned}\vec{V}_{1p_iX_1Y_1} &= \vec{V}_{kX_1} + \vec{V}_{1ckX_1} + \vec{V}_{ok} = \left(\vec{V}_k \sin\hat{\varphi} + \vec{V}_{1ck}\cos\hat{\alpha}_r\right) + \vec{V}_{ok};\\ \vec{V}_{2p_iX_1Y_1} &= \vec{V}_{kX_1} + \vec{V}_{2ckX_1} + \vec{V}_{ok} = \left(\vec{V}_k \sin\hat{\varphi} + \vec{V}_{2ck}\cos\hat{\alpha}_r\right) + \vec{V}_{ok}\end{aligned}\right\}, \tag{2}$$

where $\vec{V}_{1p_iX_1Y_1}$, $\vec{V}_{2p_iX_1Y_1}$ –respectively the vector value of the resulting velocity of the impact of the root crop with the screw turn in the first and second cases;

$\vec{V}_k$, $\vec{V}_{ok}$ – respectively the vector value of the peripheral velocity of the centre of mass and the velocity of movement of the root crop along the axis of rotation of the auger;

$\vec{V}_{kX_1}$ – the projection of the peripheral velocity vector of the root crop onto the axis OX_1;

$\vec{V}_{1ckX_1}$, $\vec{V}_{2ckX_1}$ – respectively the projection of the velocity vector of the body at the moment of its contact with the screw turn onto the axis OX_1 in the first and second cases;

$\vec{V}_{1ck}$, $\vec{V}_{2ck}$ – respectively the vector value of the velocity of the body at the moment of its contact with the screw turn in the first and second cases;

φ – the angle of rotation of the auger riffle, degree.

The scalar value of the speed of movement of the centre of mass of the root crop at the moment of its contact with the screw turn in the first V_{1ck} and second V_{2ck} cases is equal to

$$\left.\begin{aligned}V_{1ck} &= \sqrt{\left(V_{nn}^2 + V_{\tau n}^2\right)\cos^2\varepsilon + \left[\left(\sqrt{V_{nn}^2 + V_{\tau n}^2}\right)\sin\varepsilon - gt\right]^2};\\ V_{2ck} &= \sqrt{\left(\frac{V_{O_\varepsilon Z_1}}{\sin\beta_r}\right)^2 + \left(0.5\omega_k D_k\right)^2 - V^2} = \sqrt{\frac{2g\Delta Z}{\sin^2\beta_r} + 0.25\left(\omega_k^2 D_k^2 - D_r^2\left(\frac{d\varphi_r}{dt}\right)^2\right)}\end{aligned}\right\}, \tag{3}$$

where $V_{nn} = \dot{Z} = V_n \sin\varepsilon - gt$ – the normal component of the velocity, m·s^{-1};

g – the acceleration of free fall of the root crop, m·s^{-2};

t – the free fall time of the root crop before contact with the screw turn, s;

$V_{\tau n} = \dot{X} = V_n \cos\varepsilon$ – the tangential component of the velocity V_n, m·s^{-1};

$V_{O_\varepsilon Z_1} = \sqrt{2g\Delta Z}$ is the rate of change of free fall of the root crop along the $O_\varepsilon Z_1$ axis, m·s^{-1},

ΔZ – the height of the flight of the root crop relative to the $O_\varepsilon Z_1$ axis, m;

$V_{O_{\varepsilon c}} = 0.5\omega_k D_k$ – the rolling speed of the centre of mass of the root crop, m·s^{-1}, where ω_k is the angular velocity of rotation of the root crop, rad·s^{-1};

$V = 0.5\omega_r D_r = 0.5D_r\left(d\varphi_r / dt\right)$ – speed of movement of the cleaning slide, m·s^{-1}, where D_r is the diameter of the drive shaft of the cleaning slide, m;

φ_r is the angle of rotation of the drive shaft of the cleaning slide, degree.

The components of the projections of the velocity V_n onto the axes of the general coordinate system $O_1X_1Y_1Z_1$ are equal to

$$\left.\begin{aligned} V_{nX_1} &= kV_\varepsilon\cos(\varepsilon-\beta_r)\sin\beta_r - V_\varepsilon\sin(\varepsilon-\beta_r)cos\beta_r - 0.5(\Delta\omega_{kX_1}D_k - D_r\frac{d\varphi_r}{dt})cos\beta_r;\\ V_{nY_1} &= 0.5\Delta\omega_{kY_1}D_k;\\ V_{nZ_1} &= kV_\varepsilon\cos(\varepsilon-\beta_r)\cos\beta_r + V_\varepsilon\sin(\beta_r-\varepsilon)\sin\beta_r - 0.5(\Delta\omega_{kZ_1}D_k - D_r\frac{d\varphi_r}{dt})\sin\beta_r \end{aligned}\right\}, \tag{4}$$

where k is the velocity recovery coefficient V_ε;

$\Delta\omega_{kX_1}$, $\Delta\omega_{kY_1}$, $\Delta\omega_{kZ_1}$ – angular velocity losses of the root crop due to contact with the working surface of the slide along each axis of the coordinate system $X_1Y_1Z_1$, rad·s^{-1}.

The height of the root crop flight ΔZ relative to the $O_\varepsilon Z_1$ axis, which we express through the range of the root crop flight relative to the $O_\varepsilon X$ axis, or the root crop rolling path l_c determined

$$\Delta Z = \left(V_{nn}^2 + V_{\tau n}^2\right)\sin2\varepsilon\sin\beta_r / g\;;\quad l_c = O_\varepsilon O_1 = V_n^2\sin2\varepsilon / g = \left(V_{nn}^2 + V_{\tau n}^2\right)\sin2\varepsilon / g\,. \tag{5}$$

Substituting the values of V_{nX1}, V_{nZ1} which are authentic for the normal V_{nn} and tangential $V_{\tau n}$ components of the velocity projection onto the $O_1X_1Y_1Z_1$ axis from the system of equations (4), (5) in dependence (3), we obtain:

$$V_{1p_iX_1Y_1} = \sqrt{\left[0.5\left(D+D_k\right)\left(\frac{d\varphi}{dt}\right)\sin\varphi + \sqrt{\left[\Omega_k - 0.5(\Delta\omega_{k_X}D_k - D_r\frac{d\varphi_r}{dt})\cos\beta_r\right]^2 + 0.25\Delta\omega_{kY}^2D_k^2}\right]^2 + \Psi\left(\frac{d\varphi}{dt}\right)^2}\;; \tag{7}$$

$$V_{2p_iX_1Y_1} = \sqrt{\left[\begin{aligned} &0.5\left(D+D_k\right)\left(\frac{d\varphi}{dt}\right)\sin\varphi + \\ &+\sqrt{\begin{aligned}&\left\{\left[\Omega_k - 0.5(\Delta\omega_{k_X}D_k - D_r\frac{d\varphi_r}{dt})\cos\beta_r\right]^2 + \Theta\right\}\times \\ &\times\frac{2\sin2\varepsilon}{\sin\beta_r} + 0.25\left(\omega_k^2D_k^2 - D_r^2\left(\frac{d\varphi_r}{dt}\right)^2\right)\end{aligned}}\;\cos\beta_r\end{aligned}\right]^2 + \Psi\left(\frac{d\varphi}{dt}\right)^2}\,. \tag{8}$$

where $\Omega_k = kV_\varepsilon\cos(\varepsilon-\beta_r)\sin\beta_r - V_\varepsilon\sin(\varepsilon-\beta_r)cos\beta_r$; $\Theta_k = 0.25\Delta\omega_k^2D_k^2\cos^2\beta_r$; $\Psi = 0.25D^2tg^2\beta_nk_V^2$.

Then the coefficient K_{iV} of the kinematic interaction of the root crop according to (3), (7), (8) will be for the first case K_{1V} (9) and the second case K_{2V} (10)

$$K_{1V} = \frac{1}{\left[V_{k\max}\right]}\sqrt{\left[0.5\left(D+D_k\right)\left(\frac{d\varphi}{dt}\right)\sin\varphi + \sqrt{\left[\Omega_k - \Delta\omega_k + 0.5D_r\frac{d\varphi_r}{dt}\cos\beta_r\right]^2 + \Delta\omega_k^2}\right]^2 + \Psi\left(\frac{d\varphi}{dt}\right)^2}\,, \tag{9}$$

$$K_{2V}=\frac{1}{\left[V_{k\max}\right]}\sqrt{\left[0.5\left(D+D_k\right)\left(\frac{d\varphi}{dt}\right)\sin\varphi+\cos\beta_r\sqrt{\begin{array}{l}\left\{\left[\Omega_k-\Delta\omega_k+0.5D_r\dfrac{d\varphi_r}{dt}\cos\beta_r\right]^2+\Delta\omega_k^2\right\}\times\\ \times\dfrac{2\sin 2\varepsilon}{\sin\beta_r}+\Theta_k^2-0.25D_r^2\left(\dfrac{d\varphi_r}{dt}\right)^2\end{array}}\right]^2+\Psi\left(\frac{d\varphi}{dt}\right)^2}\,. \quad (10)$$

Thus, the obtained dependencies (9), (10) are mathematical models that characterize the change in the coefficient K_V of the kinematic interaction of the centre of mass of the root crop depending on the main design and kinematic parameters of the cleaner, while the optimization criterion $K_V \geq 1$.

Results and discussion

the initial conditions $[V_{k\max}] = 3.4$ m·s^{-1}, $V_\varepsilon = 1.4$ m·s^{-1}, $\beta_r = 55$ degrees, $\Omega - \Delta\omega_k = 1.5$ m·s^{-1}, $\beta_n = 45$ degrees – $0.5\alpha_k$ a dependence and a two-dimensional cross-section of the dependence of the change in the coefficient K_{iV} of the kinematic interaction of the root crop with the screw turn on the diameter D and the angular velocity of the screw ω are constructed according to formulas (9), (10) as a function of $K_{iV} = f(D;\ \omega)$, Fig. 3, 4.

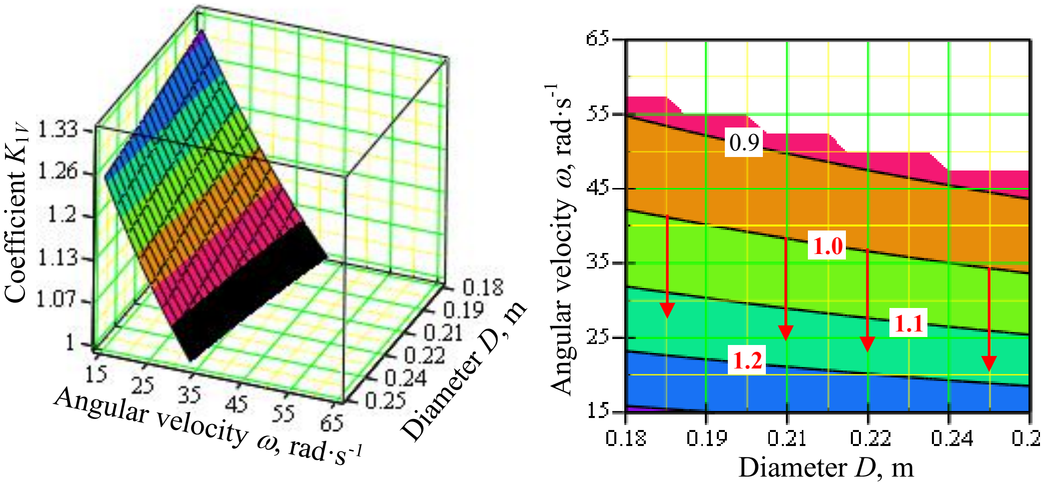

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Fig. 3. **Dependence of the coefficient K_{1V} on the angular speed ω and the screw diameter D as a functional $K_{1V} = f(\omega;\ D) \geq 1$**

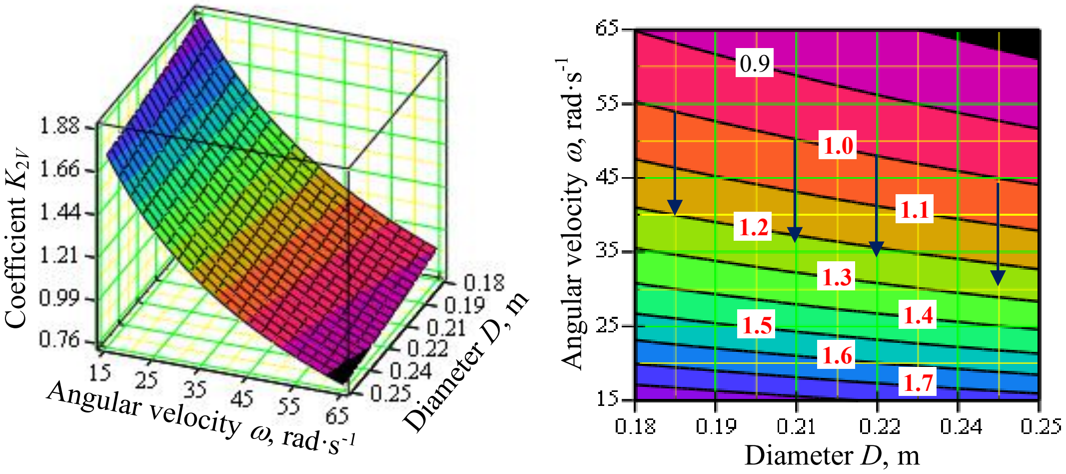

Fig. 4. **Dependence of the coefficient K_{2V} on the angular speed ω and the screw diameter D as a functional $K_{2V} = f(\omega;\ D)$**

Analysis of the given graphical dependencies (Fig. 3, 4) shows that the criterion for optimizing the design and kinematic parameters of the combined cleaner, or the $K_{iV} \geq 1$ condition, is ensured with the following ratios of the design and kinematic parameters of the cleaner:

- for the first case (Fig. 3): within the range of the diameter variation of 0.18-0.25 m, the main range of change in the angular velocity of the screw is 34-42 $rad \cdot s^{-1}$ (≈325-400 rpm);
- for the second case (Fig. 4): within the range of the diameter variation of 0.18-0.25 m, the main range of change in the angular speed of the screw is 44-55·$rad \cdot s^{-1}$ (≈420-525 rpm).

The determining parameter that has a significant impact on the increase in the K_{iV} coefficient, or the decrease of which leads to a significant increase in the degree of damage to root crops, is the angular speed of the screw ω: with an increase in ω in the range from 15 to 42 $rad \cdot s^{-1}$, the K_{1V} coefficient decreases by 1.33 times, or from 1.33 to 1.0 (case I, Fig. 3); with an increase in ω in the range from 15 to 65 $rad \cdot s^{-1}$, the K_{2V} coefficient decreases by 2.5 times, or from 1.88 to 0.76 (case II, Fig. 4).

Thus, at the corresponding value of the K_{iV} coefficient, root crops will receive damage: for $K_{iV} < 1$ – greater than the permissible values according to agrotechnical requirements, or more than 1.5%; for $K_{iV} = 1$ – equal to critically permissible damage, or 1.5%; for $K_{iV} > 1$ – less than critically permissible, or less than 1.5%.

Conclusions

The second case (II) of the movement of root crops, or their rolling along the working surface of the slide, is more rational compared to the first case (I) in which the root crops bounce off the working surface of the slide and are in free flight until contact with the screw turn. The permissible angular velocity of the screw in the second case (II) can be 1.3 times greater compared to the permissible angular velocity of the screw in the first case (I), which allows to intensify the process of cleaning root crops from impurities with equivalent damage to the root crops of the first (I) and second (II) cases.

At an angular speed of the auger $\omega > 42$ $rad \cdot s^{-1}$ (auger rotation frequency ≈ 400 rpm) and $\omega > 55$ $rad \cdot s^{-1}$ (auger rotation frequency ≈ 525 rpm), damage to root crops will exceed the established maximum standards according to the agrotechnical requirements for the operation of root harvesting machines.

The results obtained are treated as a promising method for optimization of the technological parameters of the root crop harvesting machine bit systems.

Author contributions

Conceptualization, Viktor Baranovsky and Valentin Potapenko; methodology, Natalia Dubchak and Vasyl Ramsh; software, Viktor Baranovsky and Maria Pankiv; formal analysis, Valentin Potapenko and Maria Pankiv; investigation, Viktor Baranovsky and Natalia Dubchak; structural diagram of the cleaner, Vasyl Ramsh; writing – original draft preparation, Maria Pankiv; writing – review and editing, Viktor Baranovsky and Valentin Potapenko. All authors have read and agreed to the published version of the manuscript.

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