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Research of a contact impact of a root crop with a screw auger

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Abstract: The purpose of this research is the further development of the methodology and methods of optimising the parameters of root pile combined cleaners of a root crop harvesting machine. We have conducted theoretical and experimental studies of the combined cleaning system's functioning process. By executing the analysis, we found the motion of the fodder beet through the working surfaces of the feeding conveyor and the auger installed above it. We have got an analytical and empirical process model for the fodder beet's oblique sub-hit on the auger turn. It characterises the dependence of the total rate of the sub-hit coefficient of the technological interaction of the roots and the depth of the root damage, which depend on the main parameters of the combined cleaning system. We found out the rational limits of the basic structural and kinematic parameters of the combined cleaning system by the provided minimum fodder beet damage. It is theoretically justified that the minimum damage to roots of the beet roots will be at a contact angle of zero ($\gamma \cong 0$) or close to it. This condition is protected with the following combinations of parameters: a screw diameter of D = 0.4, 0.6, 0.8 m and a screw speed of n = 99, 72, 50 rpm, respectively.

Keywords: cleaner; conveyor; koper; speed; coefficient

Improvement in the structural and technological level and the individual work of root crop harvesting machines needs particular attention in the general issues of machinery engineering design. Improvement of the working bodies and other structural elements of root crop harvesting machines should be based on the deeper analysis taking the physical and mechanical properties of root crops into account (Pogorely, Tatyanko 2004). The characteristics of the fodder beet as an element of the "machine-work body-root" should be considered as a set of different mechanical properties and parameters that are decisive in the total mechanical action on the object of treatment, its acceptable level and range of the structural and kinematic parameters of the working parts (Pogorily 2000).

During the parameter optimisation of the transport and technological systems of root crop harvesting machine, which have screw mechanisms for the working bodies, it is advisable, at first, at the stage of design to construct a mathematical model of the process of the combined cleaning system to obtain the patterns of its functioning according to the fundamental structural and kinematic parameters (Baranovsky et al. 2012; Hevko et al. 2014).

The operation quality of the existing cleaners separating the impurities from the roots does not meet the parameters set by the agro-technical requirements for a root crop's harvesting due to the usage of imperfect processes. As a result, it follows that the tools for cleaning the root crop piles from the impurities do not separate the haulm remnants from the root crop

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heads, which represents 5 to 10% (Storozhuk, Pankiv 2015) of the weight of the harvested root crops, and, thus, a significant amount of root crops is lost (from 3 to 5%) (Bulgakov, Korenko 2007).

To develop specific processes and operations and to determine the parameters and modes of the agricultural machines physical and mechanical properties, the plants themselves need to be taken in consideration. Industrial use of a machine's cleaning bodies for harvesting fodder beets showed that the total damage to the root crops can be up to 40% depending on their agro-biological characteristics (Bulgakov et al. 2009; Baranovsky, Potapenko 2017).

Improving the working bodies and other structural elements of the root crop machinery should be based on a deep analysis taking the physical and mechanical properties of fodder beet (Baranovsky et al. 2017) into account.

At this stage, we presented a generalised picture of the behaviour of fodder beet at different sub-hit speeds and, above all, those working bodies, which in real terms are used in the design schemes of root crop harvesting machine.

The purpose of the scientific research is to improve the methodology and methods for optimising the parameters of the combined cleaners of the heaps of root crops.

MATERIAL AND METHODS

To establish the patterns of change in the total sub-hit speed ϑ_{ck} coefficient of the technological interaction of the root damage K_T and the root crops depends on the parameters of the combined cleaning system. Complex experimental research of the root's sub-hit process on an auger turning using apendulum copra was conducted (Figure 1).

It consists of a bracket 1, on which it a ball joint is mounted 2, a spherical bearing 3, which is fixed on pendulum axle 4. On the shorter upper end of the pendulum 5, a body 6 is set with a spring-loaded pencil 7, on which there is hemisphere surface 8 mounted on lifting pipe 9, which are rigidly connected to the bracket. At the longer bottom end of the pendulum, a root 11 is fixed to it, which rests on the screen 10. A scale is applied to the inner surface of the hemisphere that shows the angle from the vertical position and the pendulum.

This pendulum copra A is set by a screw 12 so that the pattern of the root 11 at rest (the vertical position of the pendulum) touches the auger rotation 13 at point M, which is located in the horizontal plane situated on the axis of the auger rotation. The sub-hit angle γ is adjustable between from 0 to 90°. The hemisphere surface radius is equal to the distance from the centre of the ball bearings, or the axis of rotation of the pendulum to the spring-loaded pencil tip. At the time of passage of the lowest point of the root crops, when the pendulum copra declined from the vertical position at the fixed angle γ, the root surface is hit (contact is made) by the auger rotation that rotates forward with the movement speed of the root crops *n*. As a result of the hit (contact), the root deviates from the auger with the overall rate of the sub-hit ϑ_{ck}, with the pencil's writing line on the inside surface of the hemisphere. Its length and direction depend on the deflection γ of the pendulum copra axis from the vertical (the initial rate of the root sub-hit ϑ_e with the auger, the weight of the root m_k, the type of the sub-hit surface (metallic surface) and the auger options). The resulting speed of the root sub-hit ϑ_p with the surface of the screw coil was determined by the length of the line, which the pencil wrote after the sub-hit and it was consistent with the direction of the vector with regard to certain sizes. The velocity scale was determined by dividing the calculated numerical value ϑ_c that had been determined by the known

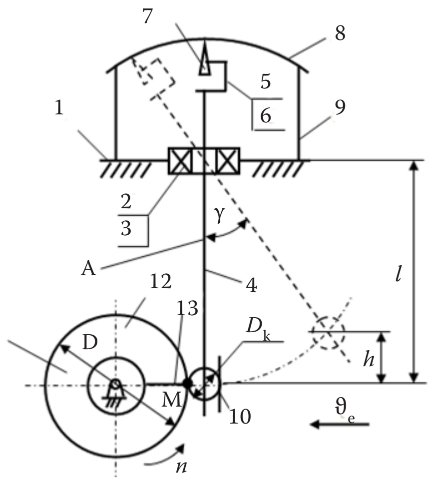

Figure 1. Construction scheme of the laboratory setup

1 – bracket; 2 – ball joints; 3 – spherical bearing; 4 – lower axle pendulum; 5 – upper pendulum axle; 6 – the body; 7 – loaded pencil; 8 – hemisphere surface; 9 – proper; 10 – screen; 11 – root; 12 – screw; 13 – round; A – pendulum copra; *D* – screw diameter; *n* – screw rotation speed; M – point of contact of the root with the screw round; γ – sub-hit angle; D_k – diameter of root crop; *h* – height of deviation of center of root relative to point of contact M; ϑ_e – initial rate of the root sub-hit; *l* – length of the pendulum

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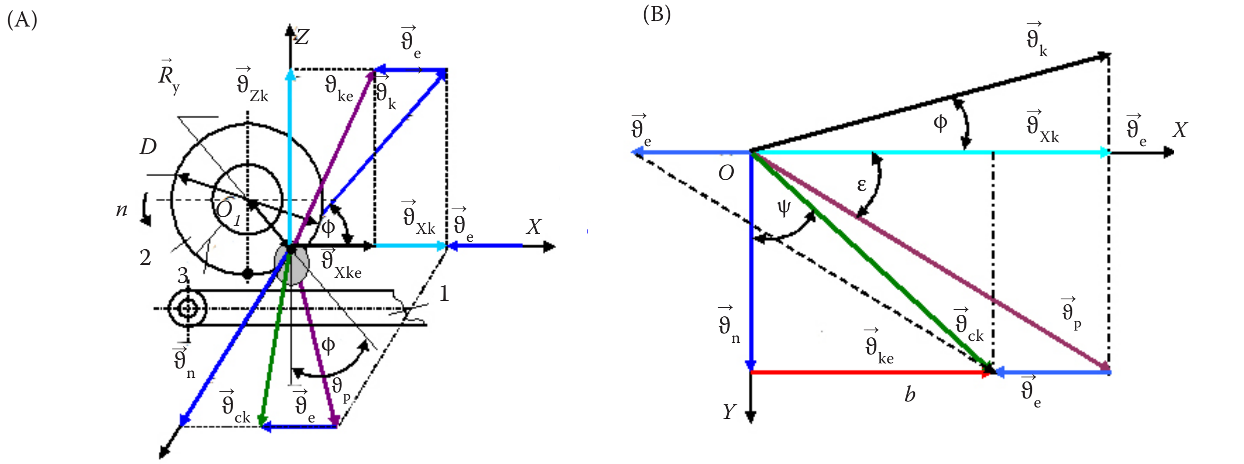

Figure 2. (A) Circuit design and (B) plan of the velocity of the oblique impact of the root with the working surfaces of the combined cleaning system

1 – elevator; 2 – screw; 3 – turn screw; $\vec{\vartheta}_{ke}$ – screw speed vector of difference wheel and translational speed of the elevator; $\vec{\vartheta}_k$ – angular velocity vector of the screw; $\vec{\vartheta}_e$ – vector of the translational speed of the elevator rod; $\vec{\vartheta}_p$ – vector of the resulting screw speed; $\vec{\vartheta}_{Xk}$ – angular velocity of the vector projection of the screw on the axle OX; $\vec{\vartheta}_{Xke}$ – the projection of vector $\vec{\vartheta}_{ke}$ on the x axis; $\vec{\vartheta}_{Zk}$ – angular velocity vector projection of screw on the axle OZ; $\vec{\vartheta}_n$ – velocity vector of the root along the axis of the screw rotation; φ – angle between the vector $\vec{\vartheta}_k$ and the axis OX (rad); $\vec{\vartheta}_{ck}$ – total impact of the root velocity (m·s^{-1}); $\vec{R}_y$ – radius vector of the point of hit; *D* – screw diameter (m); O_1 – screw rotation center; O – reference point of the coordinate system XOY; ψ – angle between the vector projection $\vec{\vartheta}_{ck}$ on a horizontal plane OXY and vector $\vec{\vartheta}_n$ (°); ε – the angle between the velocity vector of the screw and the axis OX

methods of the pendulum copra motion, on the measured length of the corresponding line. Then the length of the line (vector) ϑ_p was multiplied by the scale. The main criteria that characterise the technological process of the dug pile's separation is the degree of separation of the impurities from the roots and the exponent of the roots damaged in the process of the interaction with the combined cleaning system work surfaces. To assess the degree of the damage to the roots, the maximum values that arise during their interaction with screw 2 of rotation 3 of the combined cleaning system (Figure 2A), we introduced the rate of the technological root interaction, which expresses the ratio $K_T = [\vartheta_{max}]/\vartheta_{ck} \geq 1$. The maximum permissible hit speed of $[\vartheta_{max}]$ the fodder beet with the working surfaces is limited by the allowable data (Baranovsky et al. 2001), which when exceeded, gets root damage not exceeding the limits of the deeply and non-deeply damaged roots according to the requirements (State Standard 2258-93, Ukraine). To determine the total speed rate ϑ_{ck}, there is the design scheme (Figure 2A). In this case, the interaction of the root of screw 2 of rotation 3, we looked at the striking force action on the material's body, and the root interactions with the surface of the screw coil's screw at point O, which rotates with frequency *n*. The initial impact velocity ϑ_e is denoted by a root crop which value corresponds to the speed of the elevator rod 1. The point O of impact is at a distance R_y from the axis of rotation O_1 of the screw. After impact, the root reflected from the surface of the final round of the screw's overall rate ϑ_{ck} and moves in its direction at an angle ψ. The general case of the hit interaction of the two bodies is characterised by a change in the angular and translational velocities of the coordinate axes spatial system OXYZ.

In an oblique hit, there are various types of frictional interaction and compression deformations of a root's body to the tangential and normal hit pulse, respectively, the result of the compression deformation is the appearance of cracks in the body of the root. Reducing the normal possible pulse hit by reducing the total ϑ_{ck} speed, the implementation of which is achieved by reducing the normal component ϑ_{ck} or as a result – by reducing the angle sub-hit surface β. In this regard, let us consider the terms of the oblique speed of the root's hit and screw rotation in the horizontal plane OXY (Figure. 2B), assuming that speed before and after the sub-hit changes the roots only.

The schema of the analysis of the speeds is as follows Equaution (1).

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$$\left.\begin{aligned}\bar{\vartheta}_{ke} &= \sqrt{\bar{\vartheta}_k^2 - \bar{\vartheta}_e^2};\\ \bar{\vartheta}_p\sqrt{\bar{\vartheta}_{Xk}^2 + \bar{\vartheta}_n^2} &= \sqrt{\bar{\vartheta}_k^2\cos^2\varphi + \bar{\vartheta}_n^2};\\ \bar{\vartheta}_{ck} = \sqrt{\bar{\vartheta}_{ke}^2 + \bar{\vartheta}_e^2} &= \sqrt{(\bar{\vartheta}_k - \bar{\vartheta}_e)^2 + \bar{\vartheta}_n^2}\end{aligned}\right\}; \quad (1)$$

$$\left.\begin{aligned}\bar{\vartheta}_k &= \frac{d\bar{R}_y}{dt} = \bar{\omega}\times\bar{R}_y;\ \omega = \frac{d\varphi}{dt} = \dot{\varphi} = 2\pi n;\\ \vartheta_n = \vartheta_{nT}K_{\vartheta n} &= TnK_{\vartheta n} = \frac{TK_{\vartheta n}\omega}{2\pi}; T = \pi D_y\tan\beta;\\ \bar{\vartheta}_e &= \frac{d\bar{r}_e}{dt} = \bar{\omega}_e\times\bar{r}_e;\ \omega_e = \frac{d\varphi_e}{dt} = \dot{\varphi}_e = 2\pi n_e\end{aligned}\right\}$$

where: $\vec{\vartheta}_{ke}$ – crew speed vector of difference wheel and translational speed of the elevator rod; $\vec{\vartheta}_k$ – angular velocity vector of the screw; $\vec{\vartheta}_e$ – the vector of translational speed of the elevator rod; $\vec{\vartheta}_p$ – the vector of the resulting screw speed; $\vec{\vartheta}_{Xk}$ – the angular velocity vector projection of the screw on the axle OX; $\vec{\vartheta}_n$ – the velocity vector of the root along the axis of the screw rotation; φ – the angle between the vector $\vec{\vartheta}_k$ and the axis OX (rad); ϑ_{ck} – the total impact root velocity (m·s^{-1}); $\vec{R}_y$ – radius vector of the point of the hit; $\vec{\omega}$ – the vector of the angular velocity (rad·s^{-1}); ω – the angular velocity of the screw rotation (rad·s^{-1}); n – the speed of the auger drive shaft (rps); ϑ_n – the velocity of the roots (m·s^{-1}); ϑ_{nT} – the theoretical velocity of the turns of the screw (m·s^{-1}); $K_{\vartheta n}$ – factor for the decline of ϑ_n in comparison with ϑ_{nT}; T – the step of the coil turn (m); $\vec{D}_y$ – adius vector of the point of hit (m); β – lifting turn angle at the point of the root hit (°); r_e – the sprocket of the drive shaft of the elevator; $\vec{\omega}_e$ – the vector angular velocity (rad·s^{-1}); ω_e – angular velocity of the drive shaft of the elevator (rad·s^{-1}); φ_e – rotation angle of the elevator shaft (rad) ; n_e – the elevator rod (rps).

From Equation (1) we have the differential equation (Equation 2) of the scalar total speed ϑ_{ck} or the simplification dependence from Equation (2) and the conditions $K_T = [\vartheta_{max}]/\ \vartheta_{ck} \geq 1$ in Equation (3).

$$\vartheta_{ck} = \sqrt{\left(\frac{D\cos\varphi}{2}\frac{d\varphi}{dt} - \frac{D_e}{2}\frac{d\varphi}{dt}\right)^2 + \left(\frac{DK_{\vartheta n}\tan\beta}{2}\frac{d\varphi}{dt}\right)^2} \quad (2)$$

where: D – the screw diameter (m); D_e – the diameter of the sprocket driving the elevator (m); dt – derivative mathematical notation.

The resulting differential equation (Equation 4) describes the adaptability of the combined cleaning system or the technological dependence of the coefficient of interaction of the root auger's spiral on the basic parameters of the cleaning system:

$$K_T = \frac{[\vartheta_{max}]}{\pi\sqrt{D^2n^2\left(\cos^2\varphi + K_{\vartheta n}^2\tan^2\beta\right) + D_e n_e\left(D_e n_e - Dn\cos\varphi\right)}} \geq 1 \quad (4)$$

where: K_T – the coefficient of technological interaction of root damage; for more explanation see Equations (1) and (2).

Analysis of Figure 2A shows that after hitting the root, it reflects from the surface of the screw coil with the ultimate total speed ϑ_{ck} and moves in the direction of vector ϑ_{ck} which projects on the horizontal plane OXY of the velocity vector which turns axial movement of the screw ϑ_n, which forms an angle ψ. Upon reaching speed $\vartheta_{ck} = 0$, by the root feeding conveyor, the root moves back toward the screw and re-experiences the hit interaction with the working surface of the screw coil.

In this case, it can be concluded that the minimal damage to the roots and the maximum adaptability of the combined cleaning system will also be provided when the angle is of ψ ≤ 0 or when the roots move along the axis of the screw rotation.

According to Figure 2B we have (Eqaution 5A):

$$\vartheta_{ke}^2 = \vartheta_n^2 + \vartheta_{ck}^2 + 2\vartheta_n\vartheta_{ck}\cos\varphi \quad (5A)$$

Or Equation 5B:

$$\vartheta_{ck}^2 + 2\left(\frac{DK_{\vartheta n}\tan\beta}{2}\frac{d\varphi}{dt}\right)\vartheta_{ck}\cos\psi + \left(\frac{DK_{\vartheta n}\tan\beta}{2}\frac{d\varphi}{dt}\right)^2 - \left(\frac{D\cos\varphi}{2}\frac{d\varphi}{dt} - \frac{D_e}{2}\frac{d\varphi}{dt}\right)^2 = 0 \quad (5B)$$

For explanation see Equations (1) and (2).

Substituting in Equation (5) through the appropriate parts (Equation 5C) we obtain the harmonised quadratic equation, the solution according to x looks like Equation (6).

$$\vartheta_{ck} = \frac{1}{2}\sqrt{D^2\left(\cos^2\varphi + K_{\vartheta n}^2\tan^2\beta\left(\frac{d\varphi}{dt}\right)^2 + D_e\frac{d\varphi_e}{dt}\left(D_e\frac{d\varphi_e}{dt} - 2D\cos\varphi\right)\right)} \quad (3)$$

where: ϑ_{ck} – total impact root velocity (m·s^{-1}); D – the screw diameter (m); $K_{\vartheta n}^2$ – factor for the decline of ϑ_n in comparison with ϑ_{nT}; D_e – diameter of the sprocket driving the elevator (m). For more explanation see Equation (2).

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$$DK_{\vartheta n}\tan\beta\cos\frac{d\varphi}{dt}=p;\vartheta_{ck}=x;\ \left(\frac{DK_{\vartheta n}\tan\beta}{2}\frac{d\varphi}{dt}\right)^2-\left(\frac{D\cos\varphi}{2}\frac{d\varphi}{dt}-\frac{D_e}{2}\frac{d\varphi}{dt}\right)^2=q \quad (5C)$$

$$\vartheta_{ck}=\frac{DK_{\vartheta n}\tan\beta}{2}\frac{d\varphi}{dt}\pm\frac{1}{2}\sqrt{\left(DK_{\vartheta n}\tan\beta\frac{d\varphi}{dt}\right)^2\left(\cos^2\varphi-1\right)-\left(D\cos\varphi\frac{d\varphi}{dt}-D_e\frac{d\varphi_e}{dt}\right)^2} \quad (6)$$

For explanation see Equations (1) and (2).

Thus, the theoretical dependence that characterises the correlation coefficient K_T and the basic parameters of the cleaning system is as follows (Equation 7):

$$K_T=\frac{2[\vartheta_{max}]}{-DK_{\vartheta n}\tan\beta\frac{d\varphi}{dt}\pm\frac{1}{2}\sqrt{\left(DK_{\vartheta n}\tan\beta\frac{d\varphi}{dt}\right)^2\left(\cos^2\varphi-1\right)-\left(D\cos\varphi\frac{d\varphi}{dt}-D_e\frac{d\varphi_e}{dt}\right)^2}}\geq 1 \quad (7)$$

For explanation see Equations (1) and (2).

Given (Equation 1), for the practical use of the dependency (Equations 3 and 9) we can write Equation (8):

$$\left.\begin{aligned}\vartheta_{ck}&=-DnK_{\vartheta n}\tan\beta\pm\pi\sqrt{\left(DnK_{\vartheta n}\tan\beta\right)^2\left(\cos^2\varphi-1\right)-\left(Dn\cos\varphi-D_en_e\right)^2};\\ K_T&=\frac{2[\vartheta_{max}]}{-DnK_{\vartheta n}\tan\beta\pm\pi\sqrt{\left(DnK_{\vartheta n}\tan\beta\right)^2\left(\cos^2\varphi-1\right)-\left(Dn\cos\varphi-D_en_e\right)^2}}\geq 1\end{aligned}\right\} \quad (8)$$

where: for explanation see Equations (1) and (2).

The dependence of angle ψ between the vector projections $\vec{\vartheta}_{ck}$ on a horizontal plane of OXY axial movement, the velocity vector screw turns $\vec{\vartheta}_n$ on the basic parameters of the combined cleaning system can be represented as Equation (9) (Dubchak 2013):

$$\psi=\sin^{-1}\left(1+\frac{D^2\tan^2\beta\left(\frac{d\varphi}{dt}\right)^2}{\pi\left(D\cos\varphi\frac{d\varphi}{dt}-D_e\frac{d\varphi_e}{dt}\right)^2}\right)^{-1} \quad (9)$$

where: ψ – angle between the vector projection $\vec{\vartheta}_{ck}$ on horizontal plane OXY and vector $\vec{\vartheta}_n$. For more explanation see Equations (1) and (2).

The step of spiral T and the angle lifting spiral β on the outside diameter in the design of the screw's working bodies is selected by the condition of the free passage of the fodder beet (at their total length). The maximum speed of the movement along the centreline of rotation of the screw, where $\beta = 45 - 0.5\ \varphi_k$, when φ_k from 35 to 36° (Baranovsky et al. 2002), then β is from 27 to 27.5°.

Minimising fodder beet damage and getting the maximum adaptability of the combined cleaning system will be provided when the angle of $\psi = 0$ or the expression $\cos^2\psi - 1 = 0$ [the adequacy of which follows from the analysis of dependence (Equation 6), the mathematical models (Equations 13 and 14)] are given as follows. Wherein, substituting the data (Equation 9) in relation (Equation 6) we obtained the mathematical model that describes the technological process of the kinematic interaction of the fodder beet with the screw's rotation. This functionally connects the magnitude and direction of the total sub-hit velocity of the roots ϑ_{ck} and the coefficient K_T with the options of the combined cleaning system (Equation 10):

$$\left.\begin{aligned}&2\vartheta_{ck}+DK_{\vartheta n}\tan\left(45-\frac{\varphi_k}{2}\right)\frac{d\varphi}{dt}=D_e\frac{d\varphi_e}{dt}-D\cos\varphi\frac{d\varphi}{dt};\\ &K_T=\frac{2[\vartheta_{max}]}{-DK_{\vartheta n}\tan\left(45-\frac{\varphi_k}{2}\right)\frac{d\varphi}{dt}\pm D_e\frac{d\varphi_e}{dt}-D\cos\varphi\frac{d\varphi}{dt}}\geq 1\end{aligned}\right\} \quad (10)$$

For explanation see Equations (1), (2) and (9).

The obtained dependences (Equation 10) are mathematical models which functionally regulate the kinematic technological process of the interaction of the fodder beet with the screw revolution by minimising their damage.

In terms of the implementation of this theoretical hypothesis, taking (Equation 9) into account, it can be written that the condition $\cos^2\psi - 1 = 0$ will be realised when (Equation 11A) rad, that will be (Equation 11B).

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$$\cos\psi = \sqrt{1-\cos^2\psi} = 1,\ \cos^2\psi = 1,\ \sin\psi = 0 \tag{11A}$$

$$\sin\psi = \left(\sqrt{1+\frac{D^2\tan^2\beta\left(\frac{d\varphi}{dt}\right)^2}{\pi\left(D\cos\varphi\frac{d\varphi}{dt}-D_e\frac{d\varphi_e}{dt}\right)^2}}\right)^{-1} = \frac{1}{1+\frac{D^2\tan^2\beta\left(\frac{d\varphi}{dt}\right)^2}{\pi\left(D\cos\varphi\frac{d\varphi}{dt}-D_e\frac{d\varphi_e}{dt}\right)^2}} = 0 \tag{11B}$$

For explanation see Equations (1), (2) and (9).

In the analysis of Figurs 3 and 4, we found that the condition to ensure the minimal damage of the fodder beet's (ψ = 0) functionality implemented in the following ratio of the combinations of diameter D and the rotational speed of the screw n: D = 0.4 m, n = 1.65 rps (99 rpm); D = 0.5 m, n = 1.5 rps (90 rpm); D = 0.6 m, n = 1.2 rps (72 rpm); D = 0.7 m, n = 1.0 rps (60 rpm); D = 0.8 m, n = 0.85 rps (50 rpm).

But these assertions are quite likely in the condition to provide the necessary computational performance of the screw and its permissible angular velocity (Bulgakov et al. 2007) which the technology delivers this performance in the cleaning system with the condition to minimise the root damage.

To confirm the theoretical assumptions of the total sub-hit speed change ϑ_{ck} and the technological interaction of the root with screw rotation K_T. Experimental research into the hit process was conducted using a laboratory setup according the requirements (Dubchak et al. 2010). To implement the experiments, a laboratory setup was used (Figure 1).

The study was conducted based on the realisation of a planned three-factor experiment type PFE 3^3. The screw step was constant and was T = 0.5 m, the lifting spiral angle β = 27.5°.

The diameter of the screw was changed by the mounting on the main screw diameter of 0.4 m, with additional turns of the respective heights.

The nature of the fodder beet damage was determined by the depth of the body damage h_n: deeply damaged – when the depth of the root damage was h_n > 30 mm; non-deeply damaged – when $10 \leq h_n \leq 30$ mm (State Standart 2258-93, Ukraine).

The optimisation parameter, i.e., the total change in the sub-hit velocity coefficient ϑ_{ck} of the technological interaction of root K_T with the screw spiral and damage to the roots (the depth of the body damage of the

(A)

(B)

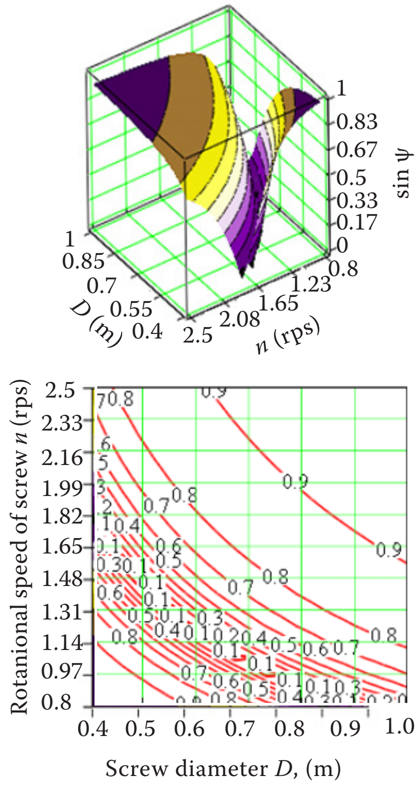

Figure 3. (A, B) The dependence of angle Ψ change: sinΨ = *f*(*D*, *n*)

D – the screw diameter (m); n – screw rotation speed; ψ – angle between the vector projection ϑ_{ck} on a horizontal plane OXY and vector ϑ_n (°); ϑ_{ck} – total impact root velocity (m·s^{-1}); ϑ_n – velocity vector of the root along the axis of the screw rotation

fodder beet h_n), depended on three factors (the frequency of the screw rotation $n\ x_1$, the screw diameter $D \rightarrow x_2$, the mass of roots $m_k \rightarrow x_3$ by the sub-hit initial speed ϑ_e = 1.6 m·s^{-1}). Determined by experiment, were found a mathematical model in the form of a polynomial second degree and logarithmic function.

RESULTS

As a result of the experimental data set, a regression equation was obtained for the experimental data changes ϑ_{ck}^{ie} (Equation 12B) and K_T^{ie} (Equation 13) of speed n and screw diameter D and the mass customised fodder beet as a functional of a second degree polynomial in the natural values (Equation 12A):

$$\vartheta_{ck}^{ie} = f(n, D),\ K_T^{ie} = f(n, D) \tag{12A}$$

For explanations see Equations (1) and (2)

Analysis of the regression equations (Equations 12 and 13) constructed according to these surfaces cor-

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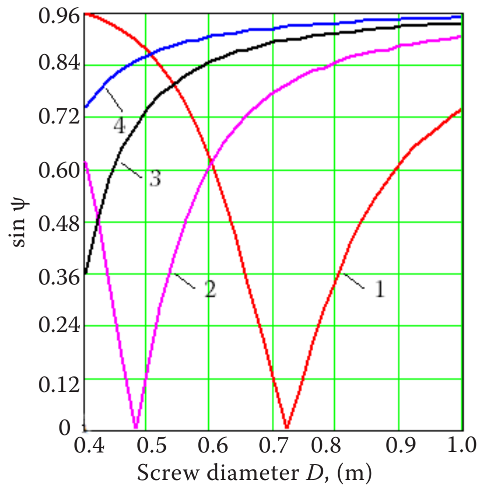

Figure 4. Dependence of angle ψ change: $\sin\Psi = f(D)$

Ψ – angle between the vector projection ϑ_{ck} on a horizontal plane *OXY* and vector ϑ_n (°); ϑ_{ck} – total impact root velocity (m·s^{-1}); ϑ_n – velocity vector of root along the axis of screw rotation; 1 – *n* = 50 rpm; 2 – *n* = 90 rpm; 3 – *n* = 120 rpm; 4 – *n* = 150 rpm

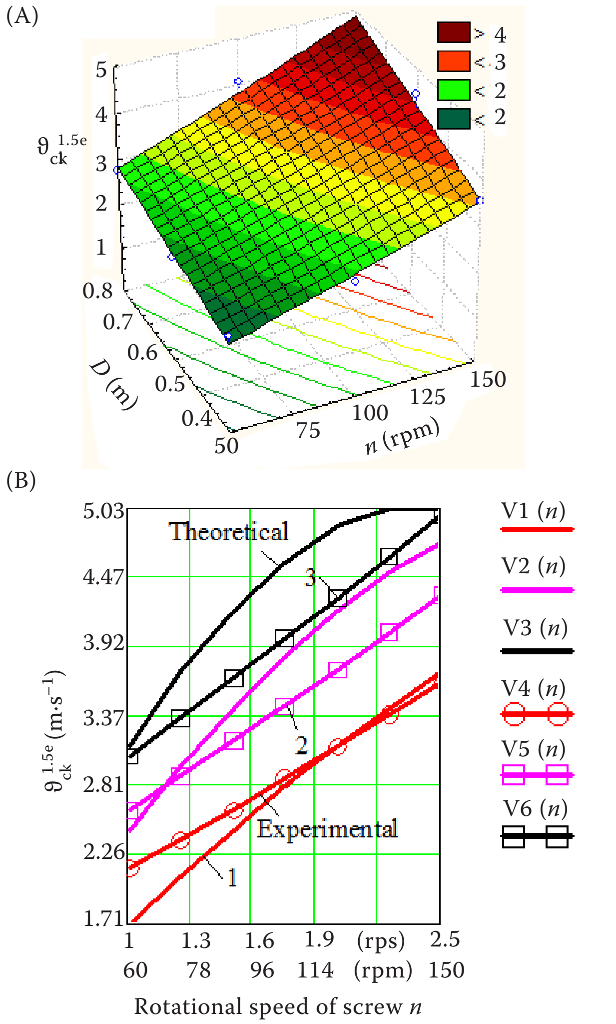

Figure 5. (A) Surface response of dependencies $\vartheta_{ck}^{1.5e}$, (B) theoretical dependencies $K_T = f(n)$, experimental dependencies $\vartheta_{ck}^{1.5e} = f(n)$

n – screw rotation speed; *D* – screw diameter; 1 – *D* = 0.4 m; 2 – *D* = 0.6 m; 3 – *D* = 0.8 m

respond to the dependencies (Equation 12A) which are shown in Figures 4 and 5A. It is shown that the change $\vartheta_{ck}^{ie}\,K_T^{ie}$ depending on the mass of the roots that sub-hit the auger within the change 1 kg ≤ m_k ≤ 2 kg has an unsustainable character – the corresponding growth rate of the total sub-hit is $\Delta\vartheta_{ck} \approx 0.2–0.4$ m·s^{-1} and the reduction of $\Delta K_T^e \approx 0.06–0.13$.

Therefore, for practical calculations ϑ_{ck}^{ie}, K_T^{ie} are recommended as the appropriate regression amounts depending on the average values of the mass of the roots that $\vartheta_{ck}^{ie}\,K_T^{ie}$ and the dependencies (Equations 12 and 13).

Analysis of the image dependencies, built on the empirical regression equation (Equation 13) shows the condition $K_T^{1.5e} \geq 1$ in which the roots get damaged, are not beyond the agronomic requirements of the root crop harvesting machine (State Standard 2258:93) when provided with the following limits of correlation of the structural and kinematic parameters of

$$\left.\begin{aligned}
\vartheta_{ck}^{1.0e} &= 0.48 + 0.009n + 2.43D + 0.012nD + 1.33\times10^{-5}n^2 - 0.67D^2;\\
\vartheta_{ck}^{1.5e} &= 0.44 + 0.009n + 2.33D + 0.012nD + 1.33\times10^{-5}n^2 - 0.67D^2;\\
\vartheta_{ck}^{2.0e} &= 0.46 + 0.009n + 2.38D + 0.012nD + 1.33\times10^{-5}n^2 - 0.67D^2;
\end{aligned}\right\} \qquad (12B)$$

For explanation see Equations (1) and (2).

$$\left.\begin{aligned}
K_T^{1.0e} &= 2.37 - 0.01n - 1.38D + 0.003nD + 1.6\times10^{-5}n^2 + 0.25D^2;\\
K_T^{1.5e} &= 2.45 - 0.01n - 1.35D + 0.003nD + 1.6\times10^{-5}n^2 + 0.17D^2;\\
K_T^{2.0e} &= 2.40 - 0.01n - 1.32D + 0.003nD + 1.6\times10^{-5}n^2 + 0.17D^2;
\end{aligned}\right\} \qquad (13)$$

For explanation see Equations (1), (2) and (12).

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the combined cleaning system: D = 0.6 m, $n \leq 80$ rpm; D = 0.5 m, $n \leq 100$ rpm; D = 0.4 m, $n \leq 140$ rpm.

For D = 0.8 m, the diameter changes within 50 rpm ≤ n ≤ 150 rpm , the condition is not satisfied. The discrepancy between the experimental , $K_T^{1.5e}$ and theoretical ϑ_{ck}, K_T values of the total sub-hit speed factor and the technological interaction of the root with the screw revolution is within 13–15% (Figures 5B and 6B), which is a theoretical mathematical model (Equation 8). These indicators are adequate to actually accurate to the existing process and significantly describe the interaction of the roots with the screw revolution considering the formalised research object.

After processing the experimental data and the statistical significance and obtaining the coefficients and verifying the adequacy of the distribution of the random variables of the mathematical model of the real process according to the criteria of Fisher and Student, we obtained the empirical regression equation (Equation 14) that describes the dependence of the damage to the root crops of the fodder beet with these limit changing factors: the frequency of rotation of the screw 50 rpm ≤ n ≤ 150 rpm; the screw diameter of 0.4 m ≤ D ≤ 0.8 m; the root mass of 1.0 kg ≤ m_k ≤ 2.0 kg (the natural factors):

$$h_n = -67.15 + 20.32 \log n + 21.22 \log D + 20.05 \log m_k \quad (14)$$

where: h_n – the depth of the body damage.

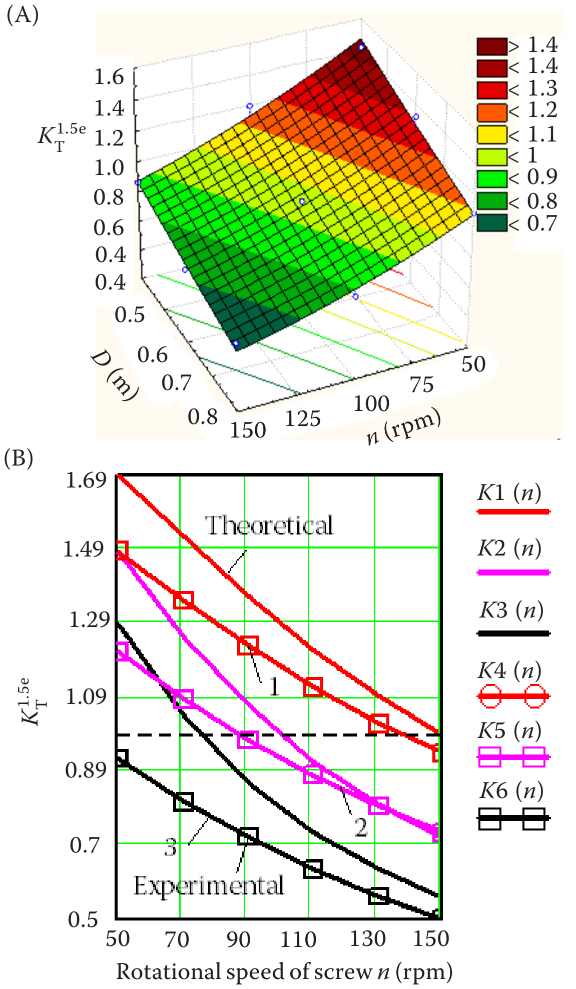

Figure 6. (A) Surface response of dependencies coefficient of technological interaction of root damage $K_T^{1.5e} = f(D, n)$ and (B) theoretical and experimental $K_T^{1.5e} = f(n)$

K – The designation of the corresponding curve when plotting.; n – screw rotation speed; D – screw diameter; 1 – D = 0.4 m; 2 – D = 0.6 m; 3 – D = 0.8 m

According to the obtained regression equation (Equation 14) we constructed a nomogram predicting the likely damage to the body of the fodder beet corresponding to the size-mass characteristics of the variety "Kyivski" depending on the installed options in the cleaning system (Dubchak et al. 2010).

We used the nomogram as follows: For example, the selected parameters of the auger, a speed of n = 100 rpm and diameter D = 0.6 m, the depth of the probable forecast damage of the fodder beet's body weight of m_k = 1.0 kg will be about 15 mm, m_k = 1.5 – about 23 mm, m_k = 2.0 kg – about 29 mm, which corresponds to the non-deep damaged roots. The general character changes depending on the depth of the body damage of the fodder beet m_k = 1.0, 1.5, 2.0 kg customised weight in the range of 10 mm ≤ h_n ≤ 30 mm (non-deep damaged roots) implemented on the basis of the construction, this limited range of response surface (Figure 7). The limit of the deeply damaged roots (h_n > 30 mm) occurs at these screw parameter values (Figure 8): root weighing m_k = 1.0 kg – with values n ≥ 150 rpm, D ≥ 0.8 m; root mass m_k = 1.5 kg – with values n ≥ 100 pm, D ≥ 0.8 m; n ≥ 120 rpm, D ≥ 0.7 m; n ≥ 150 rpm, D ≥ 0.6 m; root m_k = 2.0 kg – with values n ≥ 80 rpm, D ≥ 0.8 m; n ≥ 90 rpm, D ≥ 0.7 m; n ≥ 110 rpm, D ≥ 0.6 m; n ≥ 130 rpm, D ≥ 0.5 m. At the lower values, given above, the parameters of the screw, the proper combinations of the rotational speed n and diameter D of the screw, the depth h_n of the root damage will conform to the limits of 10 mm ≤ h_n ≤ 30 mm. The results of the analysis given above of the possible damage to the body of the fodder beet in their interaction with the spiral screw's cleaning

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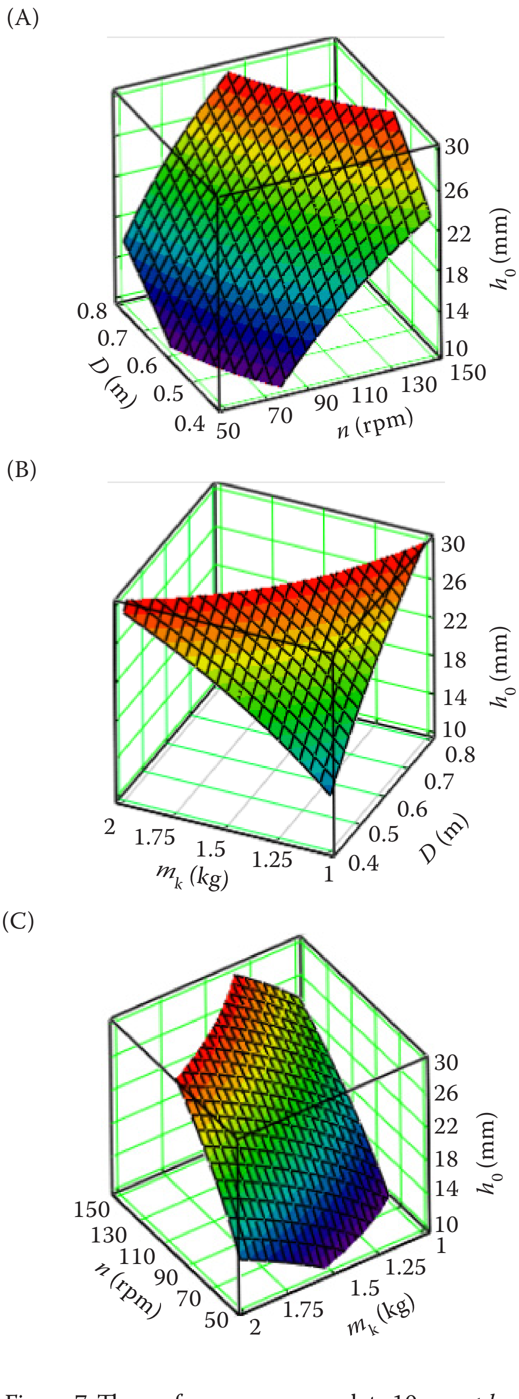

Figure 7. The surface response update 10 mm ≤ h_n ≤ 30 mm: (A) $h_n = f(D, n)$ (B) $h_n = f(D, m_k)$ and (C) $h_n = f(n, m_k)$

D – screw diameter; *n* – screw rotation speed; h_n – depth of the body damage; m_k – mass of root crop

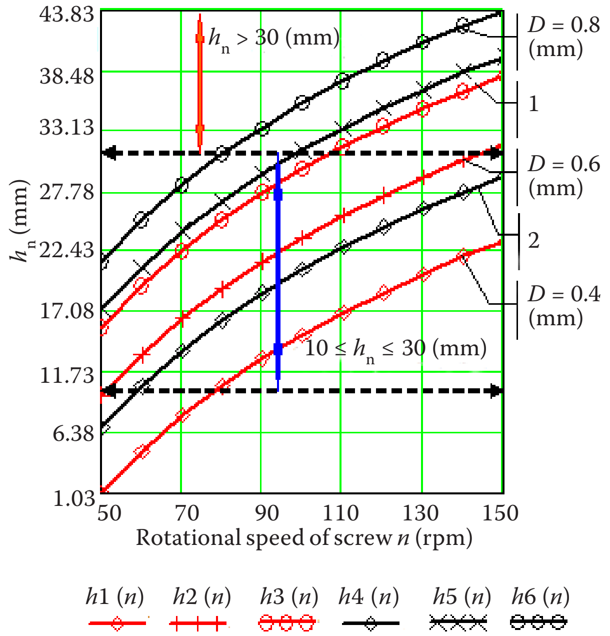

Figure 8. Dependence of the root damage depth (h_n) on the screw rotation speed (*n*)

D– screw diameter; 1 – root weigh m_k = 1.5 kg; 2 – root weigh m_k = 2 kg

system analysis also confirms the above graphic $h_n = f(n)$ (Figure 8).

In fact, if the soil is elastic between the turns of the auger and the roots at the time of the sub-hit imposed with the above limitation parameters of the cleaner auger, it can affect the non-deeply damaged roots. If the condition is adjusted in the direction of their increase according to a second supply of soil contaminants to the cleaner, and the thickness of the soil will "adjust" the depth of the body damage of the fodder beet, this process will be unstable and random.

For the analytical prediction of the possible damage to the root of the fodder beet, we obtained a specific regression equation describing the change in the depth of the root damage h_n of the fodder beet's customised weight depending on the rpm *n* and the diameter *D* of the screw as a function of $h_n^i = f(n, D)$ After the appropriate validation criteria of Fisher and Student, it is described by the polynomial second degree in the coded and natural values (Equation 15):

$$\left.\begin{aligned} h_n^{1.0e} &= 23.83 - 0.04n - 55.83D + 0.63nD + 0.001n^2 + 25.0D^2; \\ h_n^{1.5e} &= 15.94 - 0.01n - 83.33D + 0.28nD + 0.0003n^2 + 70.83D^2; \\ h_n^{2.0e} &= 7.61 - 0.01n - 63.33D + 0.23nD + 0.0005n^2 + 78.57D^2; \end{aligned}\right\} \quad (15)$$

where: h_n^e – the depth of damage to root crops, respectively, weighing 1.0, 1.5 and 2.0 kg; for more explanation see Equations (1) and (2).

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Thus, on the basis of the analysis, we can say that the structural and kinematic parameters of the screw that satisfies the condition and nature of the root damage 10 mm ≤ h_n ≤ 30 mm, the average yield of the fodder beet 50–55 t·ha^{-1}, the total length of 15 cm ≤ L_{kc} ≤ 20 cm (corresponding to a mass of the roots 1.5 kg ≤ m_k ≤ 2.0 kg) will be within D ≤ 0.6 m and 90 rpm ≤ n ≤ 110 rpm.

The conditions to eliminate the damage to h_n ≤ 10 mm, is provided at the following values of the parameters of the screw: 0.4 m ≤ D ≤ 0.6 m and n ≤ 75 rpm.

CONCLUSION

Based on the analysis of the movement of the root crops after its contact interaction with the screw auger, the following is established: the minimal damage to the root crops is ensured when the vector of the resultant collision velocity and the velocity vector of the axial movement of the screw turns are matched; this condition is functionally fulfilled with the following combinations of the screw parameters: an auger diameter of 0.5 m and a screw speed of 90 rpm or, 0.6 m and 70 rpm or 0.8 m and 60 rpm, respectively.

The following were established from the results of laboratory studies: the depth of the damage to the root crops weighing from 1.5 to 2.5 kg varies from 10 to 30 mm with a screw diameter of 0.6 m and a screw speed from 90 to 110 rpm; the conditions ensuring no damage to the fodder beet (h_n ≤ 10 mm) are performed by 0.4 m ≤ D ≤ 0.6 m and n ≤ 75 rpm; the optimal parameters of the screw are: an auger diameter from 0.5 to 0.6 m and a corresponding screw speed from 80 to 100 rpm at which the coefficient of the technological interaction is greater than 1; for an auger diameter of 0.8 m and a screw speed from 50 to 150 rpm, this dough is not performed.

The results of the theoretical and experimental studies are recommended for such rational parameters by a combined cleaning system: the speed of the feed conveyor from 1.5 to 1.6 m·s^{-1}; a screw diameter of 0.6 m; a screw speed from 80 to 100 rpm; the angle of the helix is 27.5°; the height of the screw auger of 0.25 m.

We built and determined the theoretical mathematical models (Equations 10 and 11) of the interaction of the root with the screw rotation of the combined cleaning system. The empirically derived regression equation (Equations 12–15) can be used for the further study of the structural and kinematic parameters of the transport-technological systems of the fodder beet pile cleaners of the root crop harvesting machine.

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