ANALYTICAL RESEARCH RESULTS OF THE COMBINED ROOT DIGGER
/
РЕЗУЛЬТАТИ АНАЛІТИЧНИХ ДОСЛІДЖЕНЬ КОМБІНОВАНОГО КОПАЧА КОРЕНЕПЛОДІВ

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ABSTRACT

This paper researches the operation principle structure of a combined root digger that consists of two spherical disks and, above them, a horizontal shaft with cleaning blades. Mechanical and technological justification of structural and kinematic parameters and operating modes of combined digger was carried out based on the analysis of technological process of roots excavation. The dependence of digger operation on the condition of providing complete digging of the root crops is obtained. Deterministic mathematical models of the interaction between the cleaning blade and the root head provided no not dumping and non-damaging of root, were developed.

РЕЗЮМЕ

Наведено будову та принцип роботи комбінованого копача коренеплодів, який складається з двох сферичних дисків і розташований над ними горизонтальний вал з очисними лопатями. На основі аналізу технологічного процесу викопування коренеплодів проведено механіко-технологічне обґрунтування конструктивно-кінематичних параметрів і режимів роботи комбінованого копача. Одержано залежності процесу роботи копача з умови забезпечення повноти викопування коренеплодів. Розроблено детерміновані математичні моделі процесу взаємодії очисної лопаті з головкою коренеплоду з умови невибивання та непошкодження тіла коренеплоду.

INTRODUCTION

Fodder beet as an important crop is a valuable component for feeding dairy herd. Currently in the country's agricultural sector fodder beets cultivated areas have been decreased due to defects of root harvesting machines and quality inconsistencies of their work concerning agrotechnical requirements (*Pogorely and Tatyanko, 2004; Herasymchuk and Baranovsky, 2009*). Work analysis of the blade, fork, vibrating and two-disc digging devices revealed that they significantly damage large roots and significant loss of small roots takes place. In addition, the constructive and technological parameters of these types of diggers make impossible to efficiently combine two technological operations of harvesting efficiently – digging of roots with simultaneous separation of residual tops of their heads (*Herasymchuk and Baranovsky, 2009; Kozachenko, 2004)*.

The tests performed on the cleaners that remove residual tops of fodder beets, showed that the cleaning technological process has a number of significant shortcomings. The main shortcomings appear because of the interaction between cleaning blade and the root head. It leads to the dumping of the roots and respectively to the losses during harvesting (*Baranovsky, 2006)*.

The eligibility criteria for modern requirements for the digging tools in the first place are indicators of the completeness of roots (loss) digging, their damage and mass of impurities that come to their cleaning transportation technological systems *(Bulgakov et al., 2009*).

One of the reserves to increase technological indicators of work quality of root crop machinery is to improve the technological process by application of diggers that combine passive spherical disk system and the shaft set above it that contains the elastic cleaning elements. The intensification of the digging process takes place due to the specific kinematic and dynamic factors arising from the simultaneous interaction between cleaning elements, the roots head and the root heap (*Golovach et al., 2012)*. It can be concluded that the installation of the drive shaft with blades allows digging out roots and separating remained tops simultaneously, reducing the supply of impurities by the interaction between clearing blades and heap components *(Baranovsky and Potapenko, 2017)*.

MATERIALS AND METHODS

A large number of working tools designs, digging tools assemblies and layout schemes require a differentiated approach in the selection, calculation, design, research and implementation of new outcomes into production. Therefore, classified approach, which takes peculiarities of working bodies, layout schemes and methods of operation into account, gives an opportunity for analysis and synthesis of the necessary structural and technological scheme of combined digger for peculiar work conditions. The variety of root diggers design schemes is connected with the process of harvesting and with structural and technological requirements to digging quality, roots cleaning and transportation.

Based on identification (analysis and synthesis) of digging tools analogues, the advanced designs of combined root diggers were submitted. They combine all the advantages and benefits of spherical single plate digger and usage possibilities in conditions of excessive soil moisture and weed-infested crops. The structural model and construction of a combined digger are shown in Fig. 1.

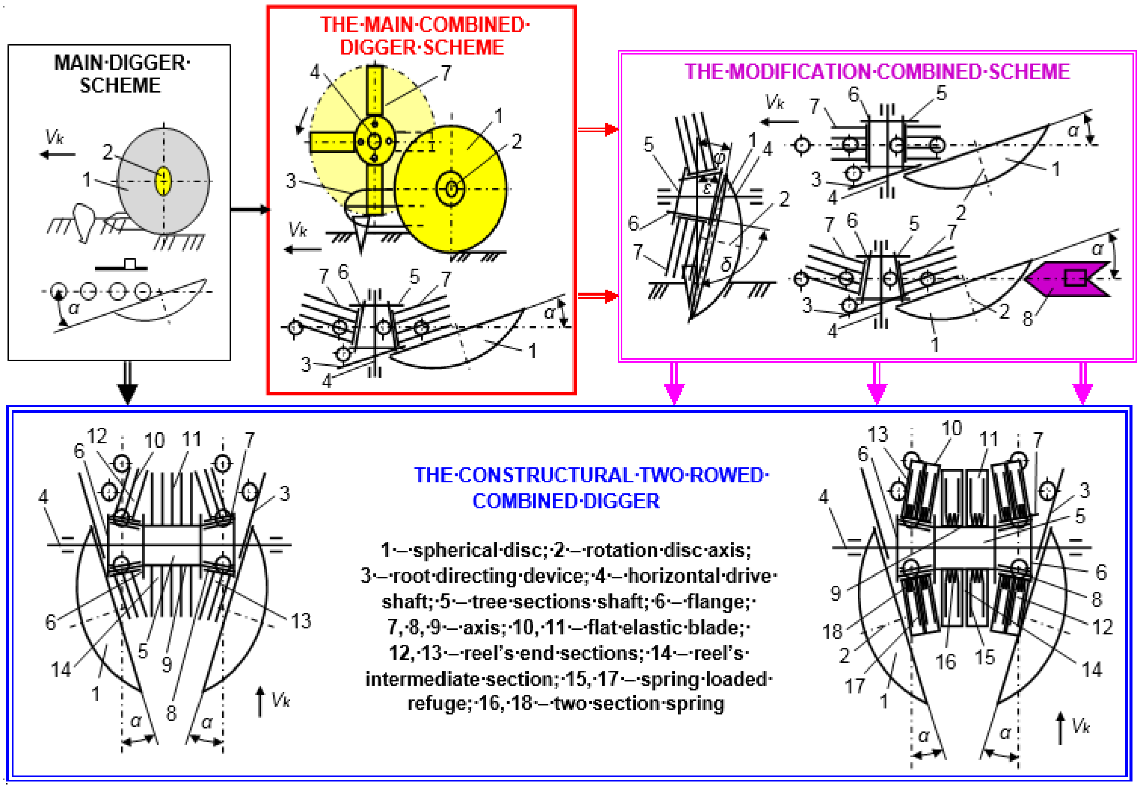

Fig. 1 – The development process identification of the combined digger structural and layout scheme

Combined digger consists of two spherical discs *1* set at an angle α to the axis of root row. Disks *1* are freely planted on their axes of rotation *2*. On the front area of the working edge of each spherical disc *1* the root directing device *3* is set. Above the discs, perpendicular to the direction of the digger motion speed V_k , a horizontal drive shaft *4* is set. The horizontal drive shaft includes a reel *5* that bears flanges *6*. The reel of the horizontal shaft is made of three sections. The axis *7*, *8*, *9* are set adherently between the flanges of the reel on its axis range; flat elastic blades *10*, *11* are fixed on them. Axis *7* and *8* of two end sections *12, 13* form a truncated cone, the end sections *12, 13* are directed to each other by smaller bases. Axis *9* of the intermediate section *14* forms a cylinder. The planes that pass through the axis *7, 9* or *8, 9* of contiguous sections *12, 14* or *13, 14* are set at an obtuse angle.

When the digger moves, root directing device *3*, shifts dumping the row roots to its centre and spherical disc *1* digs roots. Along with digging roots by rotating the drive shaft *4* flat elastic blades *10, 11* of the two end sections *12, 13* interact with the heads of roots, while simultaneously cleaning of heads of roots from residue tops of two adjacent rows and destruction of lumps of soil occur. In addition, flat elastic elements of intermediate section *14* simultaneously interact with roots and lumps of soil, purifying the roots surface, destroying soil clumps, and pushing the heap, located in the space of spherical disks. Its supply is speeded up to the following transport technology systems of root harvesting machinery.

The installation of the drive shaft with flat blades allows digging out the roots and separating the remained tops. It reduces the flow of impurities due to the contact interaction between the blades and the components of root heap. It also increases the technological reliability of the process of digging out the roots and, as a result, the performance of digger and machinery in general.

The purpose of the research is a further improvement of constructive optimization, kinematic and technological parameters methods of the functioning process of the harvesting machinery combined diggers.

RESULTS

The main structural and kinematic parameters of combined digger describing the technological process of digging out roots *1* (Fig. 2) with simultaneous separation of residual tops from their heads are:

- the speed V_k of the digger *2*; angular speed ω_o of the horizontal shaft *5* with cleaning blades *9*;
- the installation angle β of clearing blades *9* axle *8* to the axis O_o of cleaning shaft *5* relative to position O;
- or the length l of cleaning elements *9*; placement coordinates (H_o, b_o) of axis O_o of cleaning shaft *5* relative to position O or axis *3* of free rotation of disk *2* with the diameter D, which is set at a depth of stroke h and at the angle α to the axis of root row *1*.

The translational speed V_k of the digger is regulated by the requirements of the root harvesting technical process. Current requirements define the harvesting machinery root speed during the harvesting process within 1.8...2.0 m/s.

For the root loss elimination by ensuring the completeness of fodder beet digging, the condition (1) must be provided (Fig. 2):

$$b_e \geq 2\Delta s_{max} + 2\Delta z_{max} + 2r_k \tag{1}$$

where b_e – groove width, formed by the spherical disc, [m];

Δs_{max} – the maximum transverse deviation of the digger during its movement relative to the row axis, [m];

Δz_{max} – the maximum transverse deviation of root centre relative to the row axis, [m];

r_k – the average radius of the root head, [m].

According to *Husak and Brychykova (2012)* and taking into account (1) it can be written:

$$b_c = 2\sqrt{2hR - h^2}\ \text{, [m]}; \qquad b_e = b_c \sin\alpha\,; \tag{2}$$

$$2\sin\alpha\sqrt{h(D-h)} \geq 2\Delta s_{max} + 2\Delta z_{max} + 2r_k\,;\ \ \alpha \geq \arcsin\frac{2(\Delta s_{max} + \Delta z_{max}) + d_k}{2\sqrt{h(D-h)}}\,. \tag{3}$$

Last formulas (2), (3) describe the angle change α of setting of the spherical digging disc relative to the fodder beet longitudinal axes depending on the disk basic parameters and the root head diameter, provided completeness of digging out or losses elimination.

Fig. 3 shows the graphic representation of angle change α according to the dependence (2), (3) at $\Delta s_{max} = 3$ cm, $\Delta z_{max} = 5$ cm, which can be used as a monogram for determining the basic disc parameters, depending on root size characteristics.

The monogram is to be used as follows.

The field roots with the average diameter, such as $d_k = 12...15$ cm (Fig. 3*a*) and selected spherical discs standard diameters, such as $D = 40$ and 45 cm, determine the angle changing limits. The α of a disc installation is related to the longitudinal axis of the fodder beet location, which satisfies the condition of dependence (3): a disk with the diameter $D = 40$ cm, $0.61 \leq \alpha \leq 0.7$ rad or $34^0 \leq \alpha \leq 40^0$, and with the diameter $D = 45$ cm, $0.57 \leq \alpha \leq 0.66$ rad or $32^0 \leq \alpha \leq 37^0$.

Then, for defined change limits of the disc installation angle $0{,}61 \leq \alpha \leq 0{,}7$ rad and $0{,}57 \leq \alpha \leq 0{,}66$ rad relative to the longitudinal axis of the roots location, for the diameter of $d_k =$ 12…15 cm (Fig. 3*b*) find out the depth h of disc motion that satisfies the condition (4) and $h \geq 7.8$ and $h \geq 8.6$ cm.

In addition, for the disc spherical diameter $D = 45$ cm and $\alpha \leq 0.66$ rad. (Fig. 3*b*) the disc stroke depth $h \geq 8.6$ cm and for the diameter $D = 40$ cm and $\alpha \leq 0.7$ rad – $h \geq 9.0$ cm.

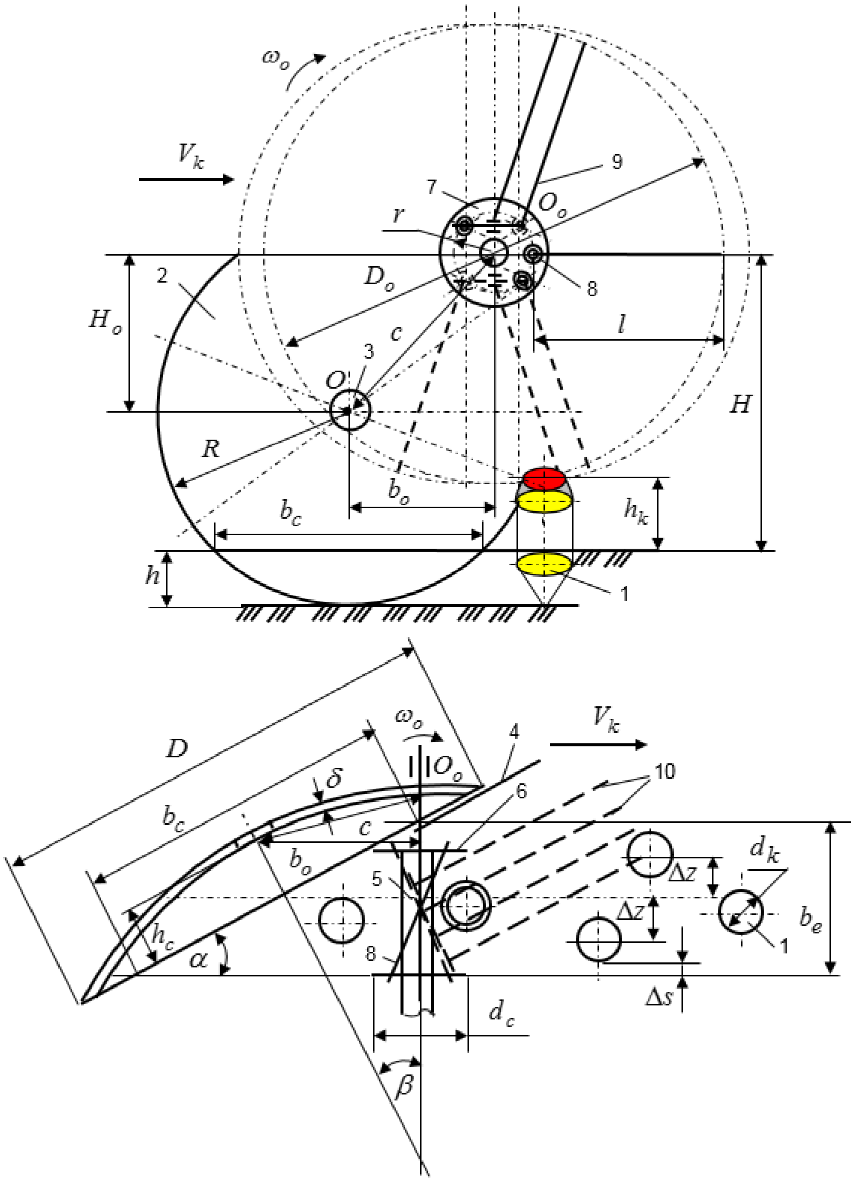

Fig. 2 – The scheme for calculating the parameters of the combined digger

1 – root; 2 – one-sided spherical disc; 3 – axis of disk rotation; 4 – root directing device; 5 – horizontal drive shaft; 6 – flange; 7 – reel; 8 – axis; 9 – cleaning blade; 10 – beater

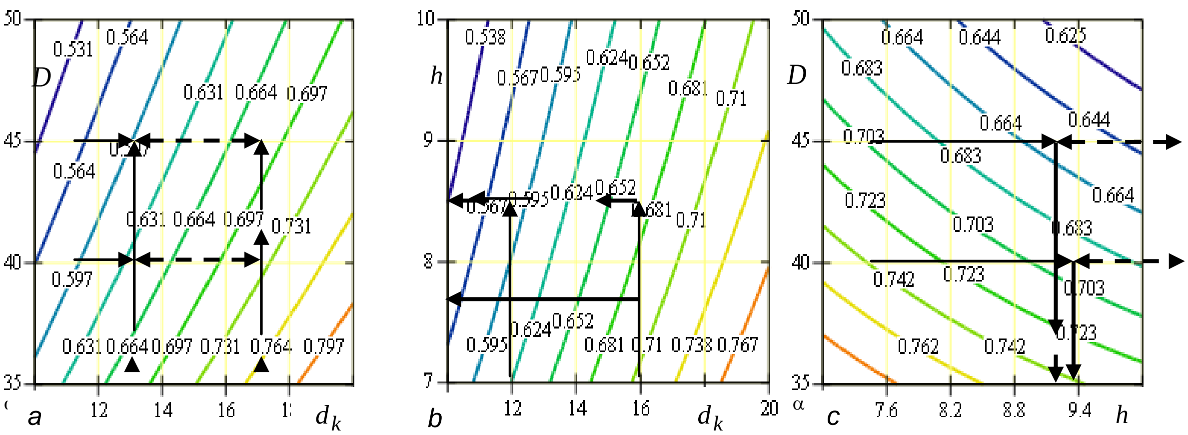

Fig. 3 – Changes dependencies on the angle of installation of the digging disk

a – $\alpha \geq f(d_k, D)$; *b* – $\alpha \geq f(d_k, h)$; *c* – $\alpha \geq f(h, D)$

Changes dependencies on the critical angular velocity of the digger drive shaft blade

As the rational (technological) effectiveness of the cleaning shaft is provided due to the blade contact plane on the root head, it is under the direct (or close to it) angle. Being related to the plane which passes through the external cutting edge of the disk, it can be considered the angle β, which characterizes the constructive installation of axes, on which the blades are set, will be equal to the attack angle α of the disk (or close to it), $\beta \cong \alpha$.

According to Fig. 2, it can be considered that the distance $OO_o = c \cong \sqrt{h_c^2 + R^2} + \Delta k \cos\alpha + 0{,}5 d_n \cos\alpha$, where h_c – depth of the disk [m]; Δk – the technological gap between the outer edge of the cutting disc and the outer surface of the cleaning shaft, [m]; $0{,}5 d_n$ – the diameter of the cleaning shaft [m].

Then the horizontal coordinate of the centre O_o of the clearing shaft is determined as:

$$b_o \cong c\cos\alpha \cong \left[\sqrt{h_c^2 + 0{,}25D^2} + (\Delta k + 0{,}5 d_n)\cos\alpha\right]\cos\alpha \tag{4}$$

The distance H and H_o that define the vertical coordinate of centre placement O_o of the clearing shaft is given by:

$$H = r + l + h_k\,; \quad H_o = \left[R_o + (\Delta k' + r_n)\sin\alpha\right]\sin\alpha \tag{5}$$

To analyse the cleaning blade and the root head interaction, one should consider that the axis O (Fig. 4) of the cleaning shaft is perpendicular to the plane of moving coordinate $Oxyz$ and to the row axis and it is above the soil surface at a distance H. The blade AM with the length l is pivotally suspended on the axis A, which is off-centre of the shaft in the value of the rotation radius *r* and rotated relatively to the axis O at angle β, or relatively to the axis of the row at the angle $90^0 - \beta$.

The blade end describes a radius circle R_o of the rotation with a constant angular velocity ω_o on the plane Oxz. The blade position AM is determined by the angle φ between the vertical and the described circle radius R_o.

The cleaning blade interaction with a root (the impact centre) is at a point M, located at the distance h_k from the surface. The rotation axis O of the clearing shaft moves with the constant forward speed V_k relatively to fixed coordinates $O_1x_1y_1z_1$.

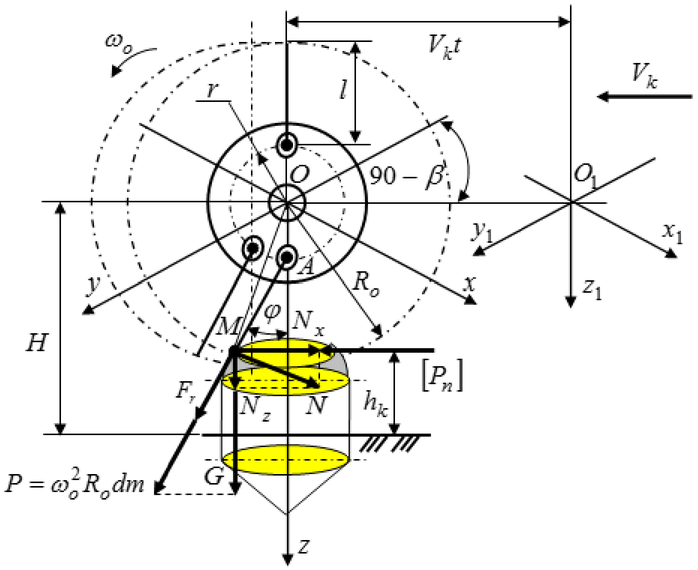

Fig. 4 – Scheme of interaction of the blade with the root crop

In this case there is the blade complex plane motion that is also involved in translational motion with digger speed V_k relatively to the fixed coordinates $O_1x_1y_1z_1$ and rotational motion around a fixed axis Oy.

The blade impact force on the root head at the point M is determined by Newton's Second Law (*Landau and Lifshitz, 2012*):

$$md / dt = F \text{, or } md = Fdt \tag{6}$$

where m –blade weight brought in the centre of impact, [kg];

F – impact force, [N];

t – impact time, [s]

The rotation axis A, on which the cleaning shaft blades are fixed, moves relatively to the fixed axes $O_1x_1y_1z_1$ with a constant speed V_o and is equal to:

$$V_o = V_k \cos\beta \tag{7}$$

where β – the angle between the axes directions of the roots row and the rotation axis A of the blades, [deg].

Absolute velocity vector of blade impact $\overline{V}_a$ is the vectors sum of the blade relative velocity $\overline{V}_r$ and transport velocity $\overline{V}_o$, hence:

$$\overline{V}_a = \overline{V}_r - \overline{V}_o = \overline{V}_r - \overline{V}_k \cos\beta \,. \tag{8}$$

Detailed research of cleaning root heads from the remained tops is conditionally divided into two stages: the first stage - blade contact with the root body; the second stage - the remained tops removal from a root head. Each stage is divided into three other stages: initial, intermediate and final. The first stage begins with the contact of the blade end with the root body and it ends when the blade takes a vertical position. This stage is characterized by the fact that the blade impact force on the root crop is initially directed upwards, while at the end – horizontally to the ground surface. The second stage finishes when the blade ends the contact first horizontally and then downward. The second stage ends when the root heads cleaning from the remained tops is finished.

For not damaging the roots the following condition should be fulfilled: allowable blade impact forcing on the root should not exceed the permissible specific pressure of compression of root's body. The allowed blade impact force (contact) to the root should not exceed the allowable force of dumping root from the soil *(Baranovsky et al., 2010)*:

$$\frac{F_k}{S_k} < [\sigma_{cm}]; \quad F_k < [P_n] \tag{9}$$

where S_k – contact area, [m^2];

F_k – blades contact force (impact), [N];

$[\sigma_{cm}]$ – allowable pressure of root body compression, [N/m^2];

$[P_n]$ – allowable power of root dumping from the soil, [N].

During the blade free rotation with angular velocity ω_o inertia centrifugal force F_r occurs, which is directed along the blade and forces the blade to take position along the radius direction r of the hinge A (*Bolotyn et al., 2010)*:

$$F_r = m\omega_o^2 R_o \cos\varphi \tag{10}$$

where F_r – the inertia centrifugal force, [N];

ω_o – blades rotation angular velocity, [rad/s];

R_o – cleaning shaft radius, [m];

φ – the angle between the vertical axis Oz and the radius of the circumscribed circle R_o, [rad].

In addition, during the first stage, the gravity force $G = mg$ has an effect on the blade, which is concentrated in the of blade mass centre, that is located at a distance $r + l$ from the rotation axis and is directed along the Oz-axis. What is more, there is the blades inertia force in the contact point, which is directed perpendicular to the blade in the direction of its rotation and Coriolis inertial force $K = -2mR_o\dot{\varphi}(\omega_o \times V_o)$, directed along the Ox-axis in the direction opposite to the direction of Coriolis acceleration $w_c = 2R_o\dot{\varphi}(\omega_o \times V_o)$, which does not affect the power balance in the $Oxyz$ coordinate system. From these forces action on the root head the reactive force N of coherence of the root with soil occurs, which can be decomposed into two components – horizontal force N_x, which affects the roots dumping from the soil and a vertical force N_z of pulling root from the soil.

The bodies system "the blade of the cleaner – a root" will be in equilibrium at the impact time, with the following condition:

$$\frac{m}{2}\left(\frac{dV_c}{dt}\right)^2 = \frac{d}{dt}(T) < [P_n] \times V_c \tag{11}$$

where T – the kinetic energy of the cleaner blade in the area of impact, [J];

V_c – impact velocity, [m/s].

The kinetic energy of cleaning shaft consists in the mass centre kinetic energy of the blade, which depends on the translational motion speed V_k related inertia axes $O_1x_1y_1z_1$ and kinetic energy of the axes $Oxyz$ that move. The rotation speed of the blade mass centre around the axis of the cleansing shaft at a speed V_r in the distance $(r + l = R_o)$, where r – the axes radius A is related to the shaft centre O, [m]; l – the blade's length, [m].

The speed module of the blade mass centre is relative to the axis of rotation (*Bolotyn et al., 2010)*:

$$V_r = R_o\dot{\varphi}\cos\varphi = (r + l)\omega_o\cos\varphi. \tag{12}$$

According to (*Landau and Lifshitz, 2012*) the material system kinetic energy is the sum of kinetic energies of all points that are in the bodies system, which is written in general terms:

$$T = \frac{1}{2}\sum_{i=1}^{n} m\left(V_c^2 + 2V_cV_r + V_r^2\right). \tag{13}$$

Considering (8) and after converting the blade kinetic energy, which also rotates around the axis with the tangential speed V_r and moves with forward speed V_k kinetic energy components are (*Bolotyn et al., 2010)*:

$$T = \frac{1}{2}mV_o^2 + mV_oV_r + T_r; \quad T_r = \frac{1}{2}I_n\left(\frac{d\varphi_o}{dt}\right)^2 = \frac{1}{2}I_n\omega_o^2; \quad I_n = \frac{m}{3}\left(a^2 + l^2\right) \tag{14}$$

where T_r – the kinetic energy of blade rotation, [J];

I_n – blade inertia moment relative to the rotation axis, that is shaped like a cuboid with sides $2a \times 2b \times 2l$ [kg m^2];

φ_o – blade rotation angle, [rad];

a – the blade width, [m].

The blade impact on the roots head that are above the soil is provided by the contact of the blade's free end, that is in the distance of traveling radius-vector $\rho = r + l$ from the axis of blade rotation.

According to the law of change in kinetic energy and considering that the brought blade's mass centre is centered on its free end, the equation (13) will be as follows:

$$T_n = \frac{1}{2}mV_k^2\cos^2\beta + mV_k\frac{d\omega_o}{dt}\rho\cos\beta\cos\varphi + \frac{m}{6}\left(\frac{d\omega_o}{dt}\right)^2\left(a^2 + l^2\right). \tag{15}$$

Full time t kinetic energy derivative of a material point is equal to a total elementary work of all active forces that applied to the forces point and a time t derivative of the work A_c [J] is equal to the total capacity of all powers N_c [J/s], that are applied to the system (*Landau and Lifshitz, 2012*):

$$\frac{d}{dt}\left(\frac{mV_a^2}{2}\right) = \frac{d'}{dt}(A_c) = [P_n] \times dr_k; \quad \frac{d}{dt}(A_c) = N_c = [P_n]\frac{dr_k}{dt} = [P_n] \times V_c; \quad [P_n] \times V_k\sin\beta = N_c = \frac{d}{dt}(T). \tag{16}$$

Considering the operating speed V_k of the combined digger (cleaning shaft) as linear and uniform ($V_k = const$), the first time derivative of equations (16) will look like:

$$\frac{d}{dt}(T_n) = m\left(\frac{dV_k}{dt}\right)V_k\cos^2\beta + m\left(\frac{dV_k}{dt}\right)\left(\frac{d\varphi_o}{dt}\right)\rho\cos\beta\cos\varphi + \frac{m}{3\cos\varphi}\left(\frac{d\omega_o}{dt}\right)\omega_o\left(a^2 + l^2\right). \tag{17}$$

Thus, for the cleaning shaft with blades that are performed in the form of a cuboid, the condition of not dumping the roots from the soil by the cleaning blades is:

$$[P_{n.n}] \geq mctg\beta\cos\beta\left(\frac{dV_k}{dt}\right) + \frac{m\rho ctg\beta\cos\varphi}{V_k}\left(\frac{dV_k}{dt}\right)\left(\frac{d\varphi}{dt}\right) + \frac{m\omega_0\left(a^2 + l^2\right)}{3V_k\sin\beta\cos\varphi}\left(\frac{d\omega_o}{dt}\right). \tag{18}$$

Dependence between the basic structural and kinematic parameters of the combined digger drive shaft, kinematic parameters of the process of residual tops remove from the root heads and the dimensional characteristics of root heads can be represented in the form *(Baranovsky et al., 2010)*:

$$z = \frac{\left(d_k + 2\sqrt{D_o h_k - h_k^2}\right)}{V_k} n_o z_o ; \quad V_k = \frac{\left(d_k + 2\sqrt{2\rho h_k - h_k^2}\right)}{2\pi z} \omega_o z_o \tag{19}$$

where z – the blade beats number on the root head for each rotation of the shaft, [pcs.];

h_k – height of the root head above ground, [m];

n_o – the cleaner blade rotational speed, [rpm];

z_o – number of axes, placed on the reel of the shaft, [pcs.].

Substituting the value V_k of equation (19) in equation (18) and taking into account the condition (9) we obtained the mathematical model of the process of cleaning shaft blade interaction combined digger with the root head depending on agro biological characteristics and parameters of the combined digger clearing shaft:

– which describes the condition of not dumping the root from soil by the cleaning shaft blades:

$$F_{k.n} = \frac{2\pi n_o z\rho ctg\beta}{z_o\left(d_k + 2\sqrt{2\rho h_k - h_k^2}\right)}\left(\frac{dV_k}{dt}\right)\left[\frac{z_o\left(d_k + 2\sqrt{2\rho h_k - h_k^2}\right)\cos\beta}{2\pi z\rho} + \frac{\cos\varphi}{\omega_o}\left(\frac{d\varphi}{dt}\right) + \frac{\left(a^2 + l^2\right)}{3\rho\cos\beta\cos\varphi}\left(\frac{d\omega_o}{dV_k}\right)\right] \le [P_n]; \tag{20}$$

– which describes the condition of not damaging the root by the blades of the cleaning shaft:

$$\sigma_{cm.n} = \frac{2\pi n_o z\rho ctg\beta}{S_k z_o\left(d_k + 2\sqrt{2\rho h_k - h_k^2}\right)}\left(\frac{dV_k}{dt}\right)\left[\frac{z_o\left(d_k + 2\sqrt{2\rho h_k - h_k^2}\right)\cos\beta}{2\pi z\rho} + \frac{\cos\varphi}{\omega_o}\left(\frac{d\varphi}{dt}\right) + \frac{\left(a^2 + l^2\right)}{3\rho\cos\beta\cos\varphi}\left(\frac{d\omega_o}{dV_k}\right)\right] \le [\sigma_{cm}]; \tag{21}$$

Accordingly, the blade critical angular velocity ω_o^{kp} of horizontal cleaning shaft, that provides the combined digger rational work of fodder beets can be defined:

– for the condition of not dumping the root by the cleaning shaft blades:

$$\omega_{o.n}^{kp} \le V_k \frac{\dfrac{[P_n]}{m\left(\dfrac{dV_k}{dt}\right)} - ctg\beta\cos\beta}{\dfrac{\left(a^2 + l^2\right)}{3\rho\sin\beta\cos\varphi} + \rho ctg\beta\cos\varphi}; \tag{22}$$

– or the condition of non-damaging the root body by the cleaning shaft blades:

$$\omega_{o.n}^{kp} \le V_k \frac{\dfrac{S_k[\sigma_{cm}]}{m\left(\dfrac{dV_k}{dt}\right)} - ctg\beta\cos\beta}{\dfrac{\left(a^2 + l^2\right)}{3\rho\sin\beta\cos\varphi} + \rho ctg\beta\cos\varphi}. \tag{23}$$

According to the obtained mathematical models (20) – (23) there are determined dependencies: force variation of dumping of the roots as a function $F_{k.i} = f(dV_k/dt)$ (Fig. 5*a*, *b*), compression pressure of a root as a function $\sigma_{cm.i} = f(S_k)$ (Fig. 5*c*, *d*), the blade critical angular velocity as a function $\omega_{o.n}^{kp} = f([P_n], m)$ (Fig. 6*a*), $\omega_{o.n}^{kp} = f([P_n], \rho)$ (Fig. 6*b*), $\omega_{o.n}^{kp} = f([\sigma_{cm}], m)$, (Fig. 6*c*), $\omega_{o.n}^{kp} = f([\sigma_{cm}], \rho)$, (fig. 6d) when $m = 0.5$ kg; $d_k = 0.15$ m; $h_k = 0.07$ m; $\rho = 0{,}2$ m; $l = 0.15$ m.

Graphic dependences analysis shows that the blades contact (impact) horizontal force with the roots head, in the shape of a cuboid, varies within 180...500 N depending on changes in angular velocity of the cleaning shaft of the combined digger, a specific blade pressure on the root body is in the range of 130...260 N/m^2. According to experimental studies (*Pogorely and Tatyanko, 2004; Herasymchuk and Baranovsky, 2009*) the power of root dumping from the soil, depending on the height h_k of the roots above the soil surface, the root diameter d_k and depth h of its bedding in the soil, is in the range of $[P_n]$= 0.15...0,4 kN, and permissible compression stress – $[\sigma_{cm}]$= 140...300 N/m^2.

Hence, the critical angular velocity value of the blade with the condition of not dumping the roots from the soil and the digger's speed $V_k = 1.5$ m/s depends on the change of blades mass $m = 0.1...0.5$ kg. It is in the range $\omega_{o.n}^{kp} = 23...100$ rad/s. The value of contact circumcircle radius of the blade with the root head is ρ = 0,3 m; depending on changes of ρ = 0.1...0.3 m at $m = 0,25$ kg - 69...82 rad/s (Fig. 6*a*, *b*), and accordingly, the condition of the non-damaging of roots - at critical values of angular velocity of $\omega_{o.n}^{kp} = 33...115$ rad/s and $\omega_{o.n}^{kp} = 54...100$ rad/s (Fig. 6*c*, d).

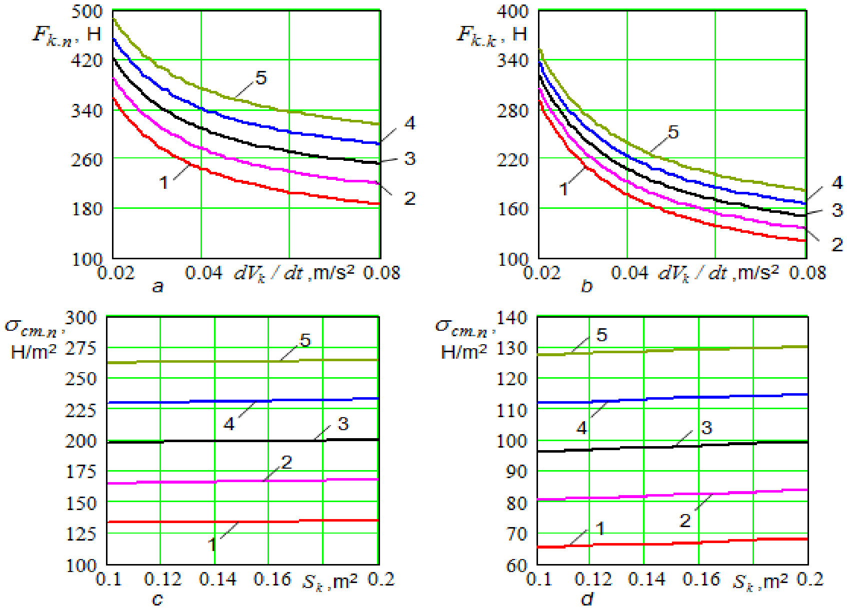

Fig. 5 – Dependence of change

a, b – $F_{k.i} = f(dV_k / dt)$; *c, d* – $\sigma_{cm.i} = f(S_k)$; *1, 2, 3, 4, 5 – respectively,* n_o *= 7, 8, 9, 10, 11 rev/s*

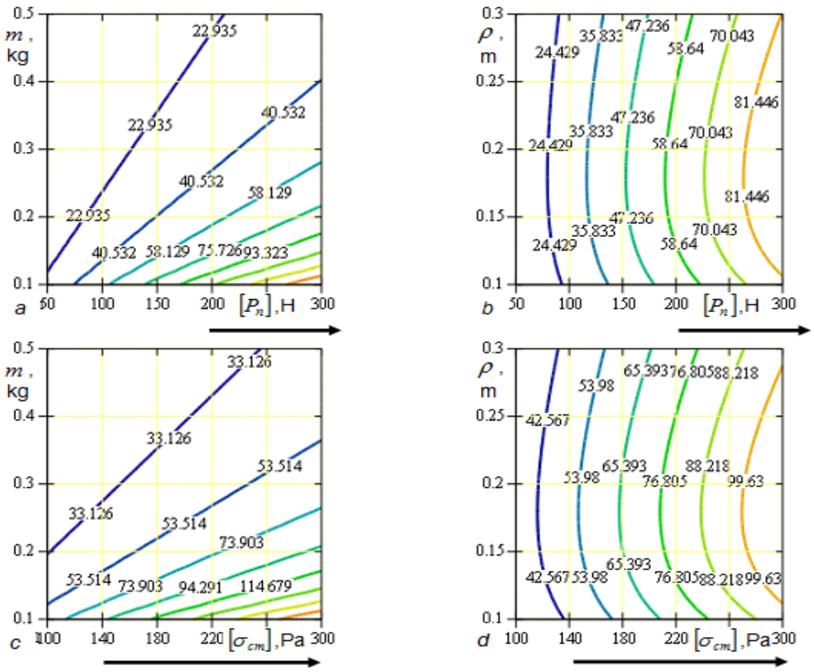

Fig. 6 – Changes dependencies on the critical angular velocity of the digger drive shaft blade

a – $\omega_{o.n}^{kp} = f([P_n], m)$; *b* – $\omega_{o.n}^{kp} = f([P_n], \rho)$; *c* – $\omega_{o.n}^{kp} = f([\sigma_{cm}], m)$; *d* – $\omega_{o.n}^{kp} = f([\sigma_{cm}], \rho)$

CONCLUSIONS

As a result of the technological process of the combined root digger, the following values of its key structural and kinematic parameters were determined: the disc's diameter – $D =$ 0,45 m; blades angular velocity – $\omega_o =$ 60…65 rad/s; the disc attack angle – $\alpha =$ 32-37^0; the axis setting angle of reel – $\beta \cong$ 30^0; cleaning blade weight – $m =$ 0,22…0,25 kg; the reel axles number – 4 pcs.

The method and results obtained in theoretical researches can be used by specialists at design engineering bureaus for development of new or improvement of existing combined cleaning systems of root crop harvesting machinery.

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