Вісник Тернопільського національного технічного університету
Scientific Journal of the Ternopil National Technical University
2018, № 2 (90)
ISSN 2522-4433. Web: visnyk.tntu.edu.ua

UDC 631.356.24

DIGGING OF CHICORY ROOT CROPS BY COMBINED DIGGER

Viktor Baranovsky; Oleksandr Skalskyi

Ternopil Ivan Puluj National Technical University, Ternopil, Ukraine

Summary. *The production of rooted chicory crop is one of the traditional branches of the agro-industrial complex of Ukraine. Rooted chicory is used in the pharmaceutical, coffee, alcohol and confectionery industries. The main reason for the decline in chicory production is the imperfection of the technique for its harvesting and the non-compliance of the quality indices of its operation with agrotechnical requirements. Mechanized harvesting by outdated complexes of root cropping machines results in significant loss of chicory root crops, which can be 45...60% depending on soil and climatic conditions of harvesting. An important factor for the effectiveness of the development of operating devices for the digging of chicory root crops is to take into account their agrobiological and physico-mechanical properties. They sufficiently correct the mechanical and technological processes and phenomena that are characteristic of the operating processes of complex dynamic systems, "root crop-operating device-soil environment". Based on the conducted modelling of the technological process, analytical dependencies are developed to determine the power of chicory root crops digging by combined operating device. The developed models take into account the rheological properties of the soil and root-plant environment and the type of dynamic load of the operating device. The results of the investigations are the next step in developing of methodology for substantiating the parameters of the digger operating bodies.*

Key words*: concave disc, ripper, soil, dynamic system, elastic medium, coefficient of friction, dumping strength.*

Received 29.03.2018

Statement of the problem. Formulation of the problem. The main reason for the decline in chicory root production is the imperfection of the technique for its harvesting and the non-compliance of the quality indicators of its operation with agrotechnical requirements. The rooted chicory is used in the pharmaceutical, coffee, alcohol and confectionery industries, and their timely harvesting in optimal agrotechnical terms with minimal losses and labor costs is one of the important modern problems of the development of harvesting machines [1].

The development of the improved diggers providing acceptable damage and completeness of rooted chicory harvesting in accordance with agrotechnical requirements, is an important scientific problem. The key factor of improving the efficiency of rooted chicory diggers development is to take into account their agrobiological characteristics and mechanical properties, which substantially correct the mechanical and technological processes and phenomena that are characteristic of the complex dynamic system "root crop-operating device-elastic soil environment" [2].

The concept development and the algorithm design for modern combined diggers construction is possible on the basis of further analysis of technological processes and of operating device structure functioning for the rooted chicory crop diggers. It can be achieved through in-depth identification of current functional processes and operating devices of combined diggers [3].

Analysis of the available investigations and publications. Analysis of the current state of functioning of the combined diggers of root harvesting machines [4 – 6] showed that there are significant opportunities for the scientific hypotheses promotion and further scientific investigations aimed at the development, research and introduction into agrarian production of energy-saving, high-tech combined diggers, providing efficient performance of related functional operations, both digging and simultaneously removing the vine remains from the root crop heads.

Corresponding author: Viktor Baranovsky; e-mail: baranovskyvm@ukr.net

The results of analytical investigations of the development of the mathematical model for calculating the pulling force in case when the root crops are digged from the soil without the previous digging down are given in paper [7]. At the same time in order to carry out the investigation, the formalization (modeling) of the rooted chicory forms, density and soil moisture are presented, the scheme for determination of the conic root digging force is given. The absence of analytical models of the process of functioning of the related operating devices of combined diggers performing digging operations with the simultaneous destruction of the soil environment, or previous partial destruction of the root crop links with elastic soil environment and the consideration of its rheological characteristics and properties caused the given scientific investigations.

Statement of the task. Setting objectives. Mechanized harvesting by existing complexes of root harvesting machines resuls in significant loss of chicory roots, which can amount to 45...60% and unsatisfactory quality indicators of root crop removal from impurities (12...18%), depending on the root crop yield, soil and climatic conditions of harvesting, the design of the digging operating device, its structural-kinematic parameters and modes of operation, etc. [7]. The use of existing technical equipment designed to the chicory root crop digging and the use of manual labor in certain harvesting technological processes typical for collective farms, significantly increases the use of energy resources and sufficiently reduces the profitability of the management environment. The use of modern self-propelled combines produced by foreign firms in small chicory crop areas is unprofitable because of the considerable purchase value of such machines – 650...800 thousand UAH hrv. per unit [8].

In order to improve the efficiency of chicory root crop digging, which are rooted at a considerable depth (not less than 2/3 of the total root crop length [9]), on the basis of our invention we offer the combined digger [10, 11] providing significant reduce in damage and loss of chicory root crops Fig. 1.

The combined root crop digger consists of the set to an angle α (Fig. 1a, b) of the roots row axis two contiguous concave disks 1 above which, perpendicular to the roots rows, the hollow horizontal guide tube 5 is installed. Inside the hollow pipe, the bearings 6 are installed on which the drive shaft 7 is put on. On the end edges 8 and 9 of the drive shaft, separate drums 10 and 11 are mounted, which are made in the form of radial flanges 12 mounted on the drive shaft. Between the flanges of each of the drums, along theit generatrixes, the axes 13, 14 are fixed in series and parallel. The flat elastic elements 15 are located on axis. Two supporting plates 17 are fixed radially to the outer lower part 16 of the hollow tube. The horizontal pin 18 is mounted in the supporting plates. The rotary riser 19 with mounted underground lifter 20 is put on the pin. The travel depth of the underground lifting device 20 is greater than the travel depth of the concave disks 1. The direction of the drive shaft 5 rotation is identical with the direction of movementV_k of the digger. The rotary riser of the underground lifter is produced by spring loading due to the spring 21 (Fig. 1a). The rotation of the riser on the finger is limited to the stop 24 fixed on the supporting plates.

Between the upper 21 (Fig. 1b) lateral part of the rotary riser 19 and the inner part of the side wall 22, the damper for the riser made in the form of springs 23 and 24, or plate S-shaped springis located. In this case, one end of the spring is fixed to the top of the rotary riser, and the second – to the inner side of the side wall.

While the combined digger is moving, the underground lifter 20 stretches the spring 21 and is deviated in the opposite direction on the pin 18 to the stop 24 due to the resistance of the soil medium. The simultaneous translational displacement of the underground lifter in the soil medium and the reverse compression of the spring produce wave-generating and opposite forces whose action result in the occurrence of forced vibrations around the root crop soil environment causing intense destruction of chicory root crop connection with the soil at the rooting depth, i.e. the initial process intensification of underground lifting process and partial root crop digging take place. Simultaneously with the initial root crop digging by underground lifting device two related operations are performed – final digging of root crops by concave discs 1 due to their free rotation on their axts 2 in the soil environment and cleaning of the root heads from vine remains from two related rows by rotating drums 10 and 11 of the drive shaft 7 and the interaction of cleaning elastic elements 15 with root heads.

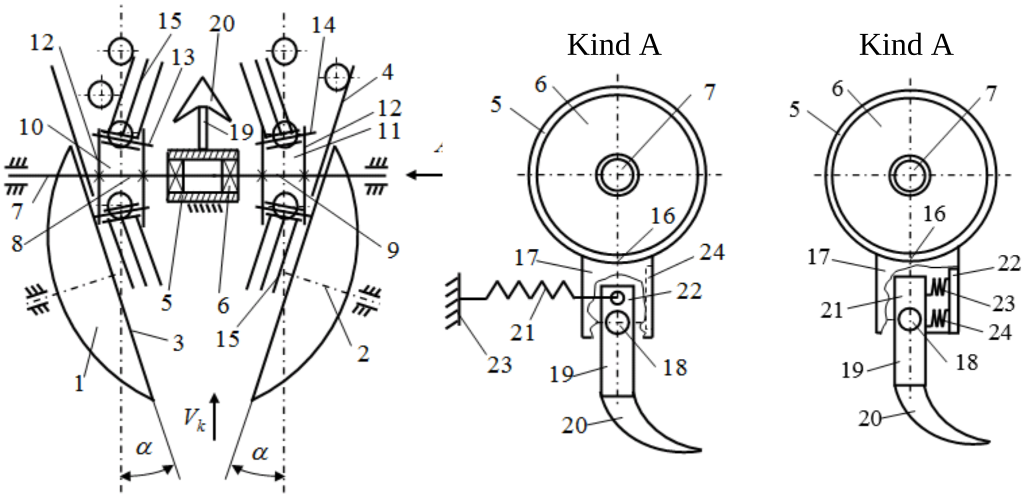

Figure 1. The constructive scheme of the combined rooters digger:
a, b: 1 – concave disk; 2 – axis of rotation; 3 – working edge of the disk; 4 – root of the strap; 5 – horizontal pipe; 6 – bearings; 7 – drive shaft; 8, 9 – end edge of drive shaft; 10, 11 – drum; 12 – radial flange; 13, 14 – axis; 15 – flat elastic element; 16 –outer lower part of the pipe; 17 – support plate; 18 – pin; 19 – rotary riser; 20 – underground lifting device; a: 21 – spring; 22 – upper part of the riser; 23 – frame; 24 – stop; b: 21 – upper part of the riser; 22 – inner part of the side wall of the supporting plate; 23, 24 – spring

To solve the problem of the rational parameters optimization for the combined digger operating devices providing required damage indexes and completeness of root crop digging, it is necessary to develop the mathematical model characterizing the resulting lifting force is required for the root crop digging from the soil provided the simultaneous previous destruction of the root crop connection with the soil environment.

To analyze the chicory root digging process taking into account the properties of the soil environment we formalize the object of investigation in the form of complex dynamic system "root crop-underground lifter-concave disk-soil environment".

In such a case:

- we simulate rooted chicory in the form of three-dimensional spatial body of corrugated tapered and cylindrical shape;

- considering the sufficient chicory rooting depth in the soil as continuous medium with specific soil density depending on the layered rooting depth in the soil;

- we assume that the layered soil mixture before the biggining of the root crop is the barotropic medium where the internal connections between the density ρ_c and the internal pressure P_c of the soil environment in general form according to [11] is characterized by the dependence $\rho = \rho_0(P_c)$ and the internal connections are described by equations:

$$P_c = K_c \rho_c^{\gamma_\rho}, \tag{1}$$

where P_c – is the internal pressure of the soil, Pa; K_c, γ_ρ – are the empirical coefficients determined experimentally; ρ_c – is the density of soil environment, g/cm^3;

- the initial coordinate dependence of the change in soil density ρ_{ic} on deph h_{ic} around the rootcrop soil environment, or the layred depth $h_{i\rho}$ of rooting in solid soil environment where $h_{ic} = h_{i\rho} = z_i$, according to [11], changes by exponential law:

$$\rho_0(z_0; w_0) = f_{\rho_0}(z_0; w_0) = \rho_0(w_0) exp(z_0\theta_0) = \rho_0(w_0) e^{z_0\theta_0}, \quad (2)$$

where $\rho_0(z_0)$ – is the dependence of soil density on the soil moisture at the initial depth z_0 or rooting in the soil amniotic environment;

- the interaction between the soil and root crop in the soil environment is characterized by static frictional force F_m;

- the weight force of the root crop P_k is applied at the point of the gravity center.

Statement of the main material. Taking into account that rooted chicory is one of the longest in terms its length and brittle in comparison with other ones, their required digging from the soil without previous digging down or the destruction of connections with the soil environment is practically impossible [9].

The digging process of chicory root crops by combined digger can be considered in two main aspects:

- the first simplified case, when the underground lifter only destryes the layered connections of root crops with the amniotic soil environment;

- the second complex case, when the underground lifter not only destroys the layred connections of root crops with the amniotic soil environment, but also performs the previous root crop pushing from the soil.

In order to eliminate the damage and losses of the root crops during their digging, in the first case, the condition when the root of the body is not broken or ruptured should be provided, that is, the external single force applied to the body of the root crop by the action of the concave disk (lateral or transverse bending force F_{Vc} acting on the elementary area dS_k of the root crop body, the longitudinal force F_{Vc} directed towards the movement of the digger with the speed of its movement V_k and the vertical stretching force F_{zc}) should not be greater than the external single force, respectively, transverse permissible force $[F_{nc}]$, longitudinal permissible force $[F_{Vc}]$ and vertical permissible force $[F_{zc}]$.

Hence, relatively, the sum of all forces acting on the root crop body or the resulting force of the chicory root crop digging $\sum_{i=1}^{n} F_{rc}$ by concave discs should also not be greater than the permissible digging force $\sum_{i=1}^{n}[F_{rc}]$, under which the conditions eliminating the possibility of breakage and rupture of the root crop body or its damage are created.

Thus, the vector form for recording the dynamic condition of the chicory root crops digging without breaking and rupture of the body valid for root crops of arbitrary shape and different soil models is as follows:

$$\sum_{i-1}^{n} \vec{F}_{rc} = \vec{F}_{nc} + \vec{F}_{Vc} + \vec{F}_{zc} + \vec{F}_m + \vec{P}_k \le \sum_{i-1}^{n} [\vec{F}_{rc}]. \quad (3)$$

For the cylindrical smooth surface, the elementary area dS according to [12] is determined by the formula:

$$dS = \frac{\pi D_k \sqrt{h_\rho^2 + 0{,}25 D_k^2}}{h_\rho}\left(1 - \frac{z}{h_\rho}\right)dz\,, \tag{4}$$

where dS – is – the elementary area of the root crop body with cylindrical shape, m^2; D_k – is the diameter of the root crop head, m; h_ρ – is the rooting depth in soil, m; z – is the vertical center coordinate of the elementary platform, m. where – the elementary area of the root crop body with cylindrical shape, m^2; – the diameter of the root crop head, m; – Depth of bedding of root crops in soil, m; – vertical center coordinate of the elementary platform, m.

Then the intensity of the specific side load $q(z)$on the body of the root crop during digging equals:

$$q(z) = \beta\left(1 - \frac{z}{h_\rho}\right)e^{\alpha\gamma z}\,, \tag{5}$$

in such a case the depth of influence β (the point of breaking of the soil "boiling layer", which occurs as the result of the interaction of the operating device with the soil environment and directly with the root crop) is

$$\beta = \frac{\pi D_k \rho_o^\gamma \sqrt{h_\rho^2 + 0{,}25 D_k^2}}{h_\rho}\,. \tag{6}$$

If the static friction coefficient between the soil and the root crop is defined as μ_o, then the force of the root crop friction F_m on the soil is determined by the formula:

$$F_m = \mu_o \cos(\psi_k / 2)\int_0^{h_\rho} q(z)dz\,. \tag{7}$$

Substituting expressions from (5), (6) into formula (7), we get:

$$F_m = \mu_o \cos(\psi_k / 2)\int_0^{h_\rho} \frac{\pi D_k A}{h_\rho}\rho_o^\gamma \sqrt{h_\rho^2 + 0{,}25 D_k^2}\left(1 - \frac{z}{h_\rho}\right)e^{\alpha\gamma z}dz\,. \tag{8}$$

Solving the integral expression (9) we get the finite dependence for determining the root crop friction force F_m over the soil occuring in the process chicory root crops digging:

$$\begin{aligned} F_m &= \mu_o \cos(\psi_k / 2)\frac{\pi D_k A}{h_\rho}\rho_o^\gamma \sqrt{h_\rho^2 + 0{,}25 D_k^2}\left(1 - \frac{z}{h_\rho}\right)e^{\alpha\gamma z}\Big|_0^{h_\rho} = \\ &= \frac{\pi\mu_o D_k A\rho_o^\gamma \sqrt{h_\rho^2 + 0{,}25 D_k^2}\cos(\psi_k / 2)}{h_\rho^2\alpha^2\gamma^2}\left(e^{h_\rho\alpha\gamma} - h_\rho\alpha\gamma - 1\right) \end{aligned}. \tag{9}$$

The partial case of expression (9) is the case of the availability of homogeneous soil medium in which coefficients product $\alpha\gamma$ goes to infinity, i.e. $\alpha\gamma \to 0$.

Then the specific lateral loading on the root body and the friction force of the root on the soil are determined by the formulas:

$$q = \beta\left(1 - \frac{z}{h_\rho}\right); \; F_m = 0{,}5\pi A\mu_0 h_\rho D_k \rho_0^\gamma \cos(\psi_k / 2). \qquad (10)$$

The extremums of the functions equal to q_{0i}, are in points z_{0i} and depend on the depth of influence β (break points of the soil "boiling layer" resulting from the interaction of the operating device with the soil environment and directly with the root crop itself).

At the same time they are:

$$z_{0i} = \beta\left(1 - \frac{z}{h_\rho}\right); \; q_{0i} = \frac{\beta}{\alpha\gamma} e^{\alpha\gamma h_\rho - 1}. \qquad (11)$$

Assuming that the root body hardness slightly depends on the ordinate, then it can be stated that the place of the most probable rupture of the root crop is determined by the condition $max[l_k(z)q(z)]$, where $l_k(z)$ – is the length of the line on the cone in the plane $z = const$.

Then according to (5) we have:

$$z_P = h_\rho - 0{,}5\alpha\gamma. \qquad (12)$$

Let us consider the case with the corrugated surface of the root crop. This can be limited to a corrugated cylinder, since the wave on the surface of the conic root crops makes a slight error in the calculation of the pulling force.

The derivative of the cylinder can be approximated by the dependence:

$$y = R_k(1 + \lambda \sin \Omega x); \; \lambda = \frac{h}{R_k}. \qquad (13)$$

Here h, Ω – relatively, the amplitude and frequency of corrugations, which can be determined by harmonic analysis. For this case:

$$q(z) = \pi A\rho_0^\gamma D_k \sqrt{1 + h^2\Omega^2 z}\,(1 + \lambda \sin \Omega z)e^{\alpha\gamma z}. \qquad (14)$$

The vertical force of root crops pulling out from soil is equal to:

$$F_{zc} = P_k + \pi A\rho_0^\gamma D_k\left[\frac{1}{\alpha\gamma}\left(e^{\alpha\gamma L_k} - 1\right)\right] + \\ + \frac{\lambda}{\alpha^2\gamma^2\Omega^2} e^{\alpha\gamma L_k}\left(\alpha\gamma \sin \Omega L_k - \cos \Omega L_k\right) + \frac{\lambda\Omega}{\alpha^2\gamma^2 + \Omega^2}. \qquad (15)$$

In the case where the results of the harmonic analysis give more than one harmonics, then the result of the dependency analysis (13) – (15) is considerably more complicated:

$$F_{zc_i} = Q + \pi A \rho_0^{\gamma} D_k \left[\frac{1}{\alpha\gamma}\left(e^{\alpha\gamma L_k} - 1\right) \right] + \\ + \sum_{i=1}^{n} \left\{ \frac{\lambda k}{\alpha^2\gamma^2 + \Omega^2 k} e^{\alpha\gamma L_k} \left(\alpha\gamma \sin(\Omega k_i L_k) - \Omega k \cos(\Omega k_i L_k) \right) + \frac{\lambda k_i \Omega}{\alpha^2\gamma^2 + \Omega^2 k_i} \right\}. \quad (16)$$

The obtained mathematical model (16) characterizes the change in the chicory root crop digging force F_{zc}, depending on the parameters of the process and properties of the soil environment for non-vibrational operating devices.

For vibrational operating devices, we assume that the vibrating operating devices are working at a depth $b \le h_\rho$. Their influence on the process of the operating device interaction with the soil environment is to destroy the connection of the soil with the root crop (i.e. change the static friction coefficient to the dynamic friction coefficient) and interlayering of the coordinate dependence of the soil density due to the formation of the "boiling" layer".

Let us introduce the average density of the soil environment ρ_c at the depth of the operating body, in this case:

$$\rho_c = \frac{1}{b}\int_0^b \rho(z)dz = \frac{\rho_0}{\alpha b}\left(e^{\alpha b} - 1\right), \quad (17)$$

and for the conical smooth surface of the root crop body, the intensity of the lateral loading $q(z)$ has the functional view:

$$q(z) = \begin{cases} \dfrac{\pi D_k A}{h_\rho} \rho_c^{\gamma} \sqrt{h_\rho^2 + 0{,}25 D_k^2}\left(1 - \dfrac{z}{h_\rho}\right); & 0 \le z \le b; \\ \dfrac{\pi D_k A}{h_\rho} \rho_c^{\gamma} e^{\alpha\gamma b} \sqrt{h_\rho^2 + 0{,}25 D_k^2}\left(1 - \dfrac{z}{h_\rho}\right); & b \le z \le h_\rho \end{cases}. \quad (18)$$

Then the force of the chicory root crops digging by vibrational operating device is determined by the formula:

$$F_z = Q + \frac{\pi A \rho_0^{\gamma} D_k \mu_o}{\alpha h_\rho} \left[\begin{array}{l} \dfrac{\left(e^{\alpha b} - 1\right)^{\gamma}\left(2h_\rho - b\right)}{2} + \\ + e^{2\alpha\gamma b}\left(e^{\alpha\gamma\left(h_\rho - b\right)} - 1\right)\left(1 + \dfrac{1}{\alpha\gamma h_\rho}\right) - \dfrac{1}{\gamma^2}\left(e^{\alpha\gamma\left(h_\rho - b\right)} - \dfrac{b}{h_\rho}\right) \end{array} \right]. \quad (19)$$

It is defined that the use of vibrational operating bodies causes the density discontinuity of the soil medium at the point $z = b$, in this case:

$$\Delta\rho = \frac{\rho_0}{\alpha b}\left[(\alpha b - 1)e^{\alpha b} - 1\right]. \quad (20)$$

Thus, as a result of theoretical investigations of the chicory root crops digging process, the mathematical models characterizing the root crops digging force under the condition of root-crop undamage by non-vibration operating devices for root crops with the corrugated surface (16) and for vibrational operating devices pf of the conical surface of root crops (19) process parameters and soil properties.

Conclusions. The obtained dependences (16) and (19) are theoretical models allowing to determine the required forces at the stage of the operating devices design and development for combined diggers:

- for digging the chicory root crops in the general case;

- maximum acceptable forces for the brittle chicory root crop digging provided that they are not damaged, or provided that their damage is minimized.

In future, the results of the investigations will be used in developing the methods and methodology for explanation of the rational parameters and operating modes for the operating devices of root crop diggers.

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УДК 631.356.24

ВИКОПУВАННЯ КОРЕНЕПЛОДІВ ЦИКОРІЮ КОМБІНОВАНИМ КОПАЧЕМ

Віктор Барановський; Олександр Скальський

Тернопільський національний технічний університет імені Івана Пулюя, Тернопіль, Україна

Резюме. *Виробництво коренеплодів цикорію є однією з традиційних галузей агропромислового комплексу України. Корені цикорію використовують у фармацевтичній, кавовій, спиртовій та кондитерській галузях промисловості. Основною причиною зниження виробництва цикорію є недосконалість техніки для його збирання та невідповідність показників якості її роботи агротехнічним вимогам. Механізоване збирання застарілими комплексами коренезбиральних машин призводить до значних втрат коренеплодів цикорію, які можуть становити 45…60 % залежно від грунтових і кліматичних умов збирання. Важливою передумовою ефективності розроблення робочих органів для викопування коренеплодів цикорію та обгрунтування їх раціональних параметрів і режимів роботи є врахування їх агробіологічних і фізико-механічних властивостей, а також фізико-механічних характеристик навколоплідного грунтового середовища. Вони суттєво коригують механіко-технологічні процеси та явища, характерні для робочих процесів складних динамічних систем «коренеплід – робочий орган – грунтове середовище». На основі проведеного теоретичного моделювання технологічного процесу функціонування динамічної системи розроблено аналітичні залежності для визначення сили викопування коренеплодів цикорію комбінованим робочим органом у загальному випадку та максимально допустимі зусилля викопування крихких коренеплодів цикорію за умови їх не пошкодження чи за умови мінімізації їх пошкоджень. Розроблені моделі враховують реологічні властивості грунтово-коренеплідного середовища та виду динамічного навантаження робочого органу. Результати досліджень є подальшим кроком у розробленні методології обгрунтування параметрів робочих органів і режимів роботи копачів коренеплодів.*

Ключові слова: *сферичний диск, розрихлювач, грунт, динамічна система, пружне середовище, коефіцієнт тертя, сила викопування.*

Отримано 29.03.2018