UDC 631.356.2
DOI: 10.37128/2520-6168-2025-2-16

STUDY OF THE PROCESS OF CONTACT INTERACTION THE CLEANING BLADE WITH THE HEAD OF CHICORY ROOT CROPS

Maksym HADAICHUK, Postgraduate Student
Vinnytsia National Agrarian University

ГАДАЙЧУК Максим Юрійович, аспірант
Вінницький національний аграрний університет

For mechanized harvesting of chicory roots, root harvesters are currently used, in which the root digging module is built on the basis of a single-disk spherical digger installed at an angle of attack to the direction of movement and a cultivator placed behind it and a horizontal drive single-shaft cleaner of the remains of the top from the root heads above it. The flexible cleaning blades, which are placed on the rotor of the single-shaft cleaner during the cleaning of the remains of the top, lose their initial rigidity, which reduces the efficiency of the root harvesting machine and the quality of the raw material from chicory roots for its processing.

The purpose of the work is to increase the technological efficiency of the chicory root digging module by developing a mathematical model of the contact interaction of the cleaning blade with the root head and optimizing the rational parameters of the single-shaft cleaner.

Based on the analysis of the technological process of the single-shaft cleaner, an analytical mathematical model was developed that functionally describes the contact interaction of the cleaning flexible blade with the root head or with the tops on it. It was established that when designing blade cleaners for tops from root heads, it is necessary to take into account the relationship between permissible deformations and the main parameters of the cleaning flexible blades - the rotation frequency of the single-shaft cleaner, the length, width and thickness of the blade, the maximum permissible number of blades in one section, the number of sections on the rotor of the single-shaft cleaner.

The constructed nomogram allows you to determine the maximum permissible thickness and minimum permissible length of the blade depending on its operating conditions. The results obtained are a further step in improving the methodology for optimizing the parameters of the working bodies of combined modules for digging chicory roots.

Key words: *root crop, chicory, top residues, cleaner rotor, cleaning blade, force, deformation, model, displacement.*

Eq. 27. Fig. 4. Ref. 22.

1. Problem formulation

Existing technical devices and means for harvesting chicory roots by mechanized means do not satisfy agrotechnical requirements for root harvesting machines in the context of compliance with the main quality indicators - losses and damage to roots during their digging [1, 2]. In addition, during the harvesting of the main mass of tops and trimming the tops from the heads of root crops with different types of top cutters, a significant part of the roots falls out or breaks from the soil due to the dynamic interaction of the cutter copier with the root crop head [3, 4].

Obtaining the required quality of raw materials for processing from chicory roots is ensured by additional post-harvest preparation of the harvested roots to the required condition of the processed product and requires additional costs, which reduces the profitability of the processing industry [5].

Reducing the content of tip residues in raw root crops from 0.5 to 1.5% reduces the total costs of their processing by 10..15% and increases the yield of the final product of higher quality by an average of 10…20% [6]. The use of cleaning flexible blades as part of a single-shaft blade cleaner [7], which is designed to clean root crop heads from tip residues, partially solves this problem, which leads to an increase in the quality of root harvesting machines [8]. However, one of the main disadvantages in the process of cleaning flexible blades during their contact interaction with tip residues and chicory root heads is a fairly rapid loss of the initial stiffness of the flexible blades, which leads to a significant reduction in their service life [9, 10].

Reducing the rigidity of the material structure of the cleaning flexible blades does not provide the necessary quality indicators for the separation of the tops from the heads of chicory roots in accordance with agrotechnical requirements [11, 12].

A qualitative solution to the scientific and technical problem of increasing the service life of the cleaning flexible blades of root head cleaners and, ultimately, a significant reduction in the amount of plant impurities in the collected head is possible by studying the process of contact interaction of the cleaning elastic blades with the root head and optimizing their rational parameters.

2. Analysis of recent research and publications

The main results that characterize the analysis of the contact interaction of elastic elements with the surface of physical bodies or the remains of the tip on the heads of root crops are described in scientific works [13-17].

They set out general aspects that describe the kinematic processes that regulate the main provisions of the directions and results of the research on the issue of coordination of the operating speed of the cleaning devices and the kinematic and structural parameters of the elastic elements, or the manufacturability of the harvesting unit.

The analysis of the processes of dynamic interaction of cleaning flexible blades with the remains of the tip on the heads of root crops, taking into account the relationships of permissible deformations and the main parameters of the blades, is set out insufficiently and not in full, which does not allow for the effective establishment of rational parameters and operating modes of single-shaft cleaners.

3. The purpose of the article

The purpose of the research is to increase the technological efficiency of the chicory root digging module by developing a mathematical model of the contact interaction of the cleaning blade with the root head and optimizing the rational parameters of the single-shaft cleaner.

4. Results and discussion

To analyze the process of contact interaction of the cleaning flexible blade 7 (Fig. 1) of the driven single-shaft cleaner 4 of the tip residues of the combined chicory root digger [18, 19], a calculation scheme was drawn up, which is shown in (Fig. 2).

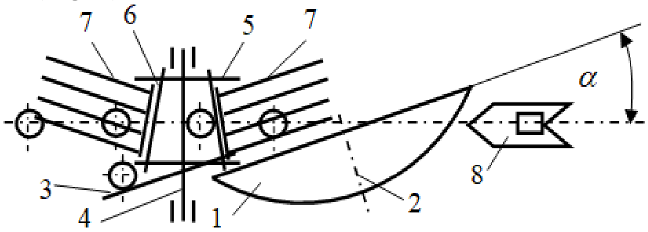

Fig. 1. Structural diagram of a combined single-disk chicory root digger:
1 – spherical disk; 2 – axis of rotation of the spherical disk; 3 – root guide; 4 – single-shaft cleaner of the remains of the top from the heads of root crops; 5 – flange; 6 – axis; 7 – cleaning flexible blade

The single-shaft cleaner of the remains of the tops from the heads of root crops is a frame 1 (Fig. 2) on which a horizontal shaft with a drum 2 is installed. Adjacent flanges 3 are installed on the drum, between which axes 4 are fixed. Flexible cleaning blades 5 are hingedly installed on the axes, rotating with an angular velocity ω_b [8]. During rotation, the cleaning flexible blades 5 interact with the root head 6, which leads to the removal of the tops from it. In the first case, to develop a mathematical model that functionally describes the process of contact interaction of the hinged cleaning flexible blade 5 (Fig. 2) with the root head 6 or the tops on it, we will consider the blade as a thin flexible (elastic) rod that is under the action of force F_b, which arises as a result of the impact from the side of the head or the remains of the tip on it. In this case, the cleaning flexible blade bends to a certain spatial position, and the magnitude of the bend will depend on the magnitude of the force F_b.

The differential equation of the blade elastic line has the form [19]:

$$EI\frac{d\theta}{dS_b} = -F_b X, \qquad (1)$$

where E – modulus of elasticity of the blade material, N/m^2; I – moment of inertia of the blade section, kg m^2; θ – angle between the tangent to the elastic line and the axis OY, degree.; S_b – curvilinear abscissa from the instantaneous point B to the free end of the blade, m; $d\theta/dS_b$ – curvature of the centerline of a curved blade at a point B.

At the same time, we have that$dX/dS_b = \sin\theta$.

Determine the radius of curvature R_b – section of the curved axis of the blade between two adjacent sections. It will be smallest in the section of the greatest bending moment at point A, i.e.:

$$R_b \frac{dS_b}{d\theta} = \frac{-EI}{F_b X}. \tag{2}$$

Let us denote the relation $F_b / EI = k$.

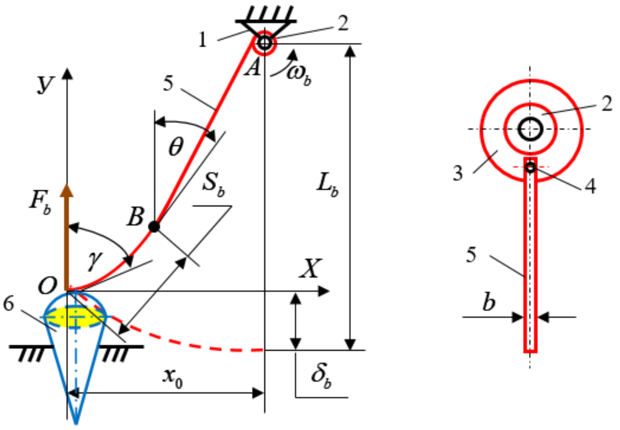

Fig. 2. Scheme for calculating the contact interaction process flexible cleaning shovel with root head (shovel bend): 1 – frame, 2 – drum; 3 – flange; 4 – axle; 5 – flexible blade; 6 – root crop

Then according to (1) and (2) we have:

$$R_b = \frac{1}{kX} \qquad X = -\frac{d\theta}{kdS_b}. \tag{3}$$

Let's substitute into the expression $dx / dS_b = \sin\theta$ value X from dependence (3), we obtain:

$$-k\sin\theta = \frac{d^2\theta}{dS_b^2}. \tag{4}$$

Assuming that the angle at the free end of the blade is θ equal to the angle γ, or $\theta = \gamma$.

After differentiating equation (4), we have:

$$2k\left(\cos\theta - \cos\gamma\right) = \left(\frac{d\theta}{dS_b}\right)^2. \tag{5}$$

We integrate the differential equation (5) by the method of separation of variables. In doing so, we determine the arc length of the curved cleaning blade Sb, i.e.:

$$S_b = \frac{1}{2\sqrt{k}} \int_0^{\gamma} \frac{d\theta}{\sqrt{\sin^2(0.5\gamma) - \sin^2(0.5\theta)}}. \tag{6}$$

Let us introduce the notation sin (0.5γ) = Φ.

We will also introduce a new variable, which we will denote by the symbol and which is related to the angle θ by the equation:

$$\sin(0.5\theta) = \Phi\sin\nu = \sin(0.5\gamma)\sin\nu. \tag{7}$$

Having solved the integral expression (6) within the limits of integration from 0 to $\pi/2$ Taking into account dependence (7), we obtain the equation for determining the length of the cleaning flexible blade L_b :

$$L_b = \frac{1}{2\sqrt{k}} \int_0^{\pi/2} \frac{d\nu}{\sqrt{1 - \Phi^2 \sin^2\nu}} = \frac{1}{\sqrt{k}}\, p\left(\Phi^2\right), \tag{8}$$

where $p\left(\Phi^2\right)$ – the complete elliptic Legendre integral of the first kind, which is written in normal form [20].

Having written down that $dx = \sin\theta dS_b$ and solving equation (5) with respect to *X* taking into account expression (8), we obtain the dependence for determining the horizontal displacement x_o end of the cleaning flexible blade:

$$x_0 = \frac{2\Phi}{\sqrt{k}}, \qquad (9)$$

or according to (3) we determine the radius of curvature R_b the area of the curved axis of the blade between two adjacent sections, i.e.:

$$R_b = \frac{1}{2\Phi\sqrt{k}}. \qquad (10)$$

To find the sine of half the angle γ, which is denoted by the symbol Φ, we first calculate the deflection of the cleaning flexible blade in the vertical plane or vertical direction of the OU.

From the equation of the elastic curve and taking into account that $dY / dS_b = \cos\theta$, we will get:

$$Y = -\int_0^{\gamma} \cos\theta dS_b + C. \qquad (11)$$

The integration constant C is determined from the boundary conditions at the tip of the blade: $C = L_b - \delta$, where δ – vertical deformation of the blade, m (Fig. 2). Taking into account expression (8) and the integral notation (11) and the previously adopted notations, we obtain:

$$Y = L_b - \delta - \int_0^{\gamma} \frac{\cos\theta d\theta}{\sqrt{2k\left(\cos\theta - \cos\gamma\right)}} = L_b - \delta - \frac{2}{\sqrt{k}} \int_0^{\pi/2} \sqrt{1 - \Phi^2 \sin^2 \nu d\nu} - \int_0^{\pi/2} \frac{d\nu}{\sqrt{1 - 2\Phi^2 \sin^2 \nu}}. \qquad (12)$$

In the final case, after the final solution of the integral expression (12), we obtain:

$$Y = L_b - \delta - \frac{1}{\sqrt{k}}\left[2q\left(\Phi^2\right) - p\left(\Phi^2\right)\right], \qquad (13)$$

where $q\left(\Phi^2\right)$ – the complete elliptic Legendre integral of the second kind, which is written in normal form [20]. At point *O*, the value of *Y* is zero, i.e. $Yo = 0$. Then equation (13) is reduced to the form:

$$L_b - \delta = \frac{1}{\sqrt{k}}\left[2q\left(\Phi^2\right) - p\left(\Phi^2\right)\right]. \qquad (14)$$

In the following, we will define $\sqrt{k}$ from the equation (8):

$$\sqrt{k} = \frac{p\left(\Phi^2\right)}{L_b}, \qquad (15)$$

and substitute this value into dependences (10) and (14).
In this case, we will obtain a system of equations:

$$\begin{cases} \delta = 2L_b \dfrac{p\left(\Phi^2\right) - q\left(\Phi^2\right)}{p\left(\Phi^2\right)}; \\ R = \dfrac{1}{2\Phi p\left(\Phi^2\right)}; R_{\min} \geq 15b \end{cases}, \qquad (16)$$

where for rubberized blades according to [21] the inequality is valid $R_{\min} / b \geq 15$, b – blade thickness, m.

Fig. 3 shows the dependence of the change in vertical deformation δ flexible cleaning blade depending on its working length L_b as a function $L_b = f_L(\delta)$ and which is constructed according to the system of equations (16).

The constructed graphic model (Fig. 3) regulates the functional relationship of the design parameters (working length L_b and thickness *b*) and vertical deformation δ cleaning flexible blade and allows you to determine their maximum permissible values.

For example, for the first time, which will ensure effective and long-term separation of the tip residues from the heads of chicory roots, the thickness of the blade should not be more than 0.35 cm, Fig. 3.

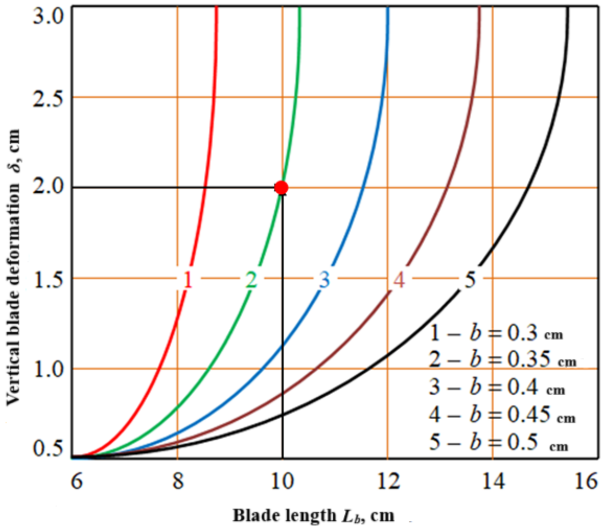

***Fig. 3. Dependence of the change in vertical deformation cleaning flexible blade as a function** $L_b = f_L(\delta)$*

In the second case, we assume that the cleaning flexible blade 5 (Fig. 2) is fixed cantilever (rigidly) to the drum 2 of the shaft, which, during its rotation, experiences resistance from the air environment. For dynamic analysis, we consider the cleaning flexible blade as an elastic line 1, Fig. 4.

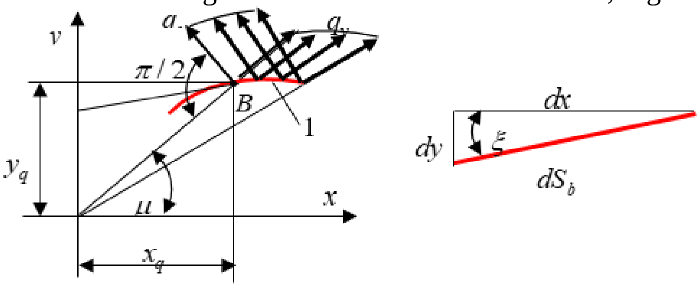

Fig. 4. Scheme of the action of the distributed load on the cleaning flexible blade:
1 – a segment of a flexible cleaning blade (elastic blade line)

For plane bending and existing displacements, the differential equation of equilibrium of the elastic line has the form:

$$\frac{d^2\xi}{dS_b} = \frac{1}{H_b}\frac{dM_b}{dS_b} \qquad (17)$$

where M_b – internal bending moment in this cross section, kg m; H_b – stiffness of the blade cross section during bending, N m; ξ – angle of inclination of the tangent to the elastic line, rad.

For this loading scheme of the flexible blade, the internal bending moment M_b at any point $Q(x_q; y_q)$ arises from distributed centrifugal loads q_v and air resistance q_o, which act on the length of the arc S_b from the free end of the blade to the current point.

In this case, the internal bending moment M_b in this cross section is determined by the formula:

$$\begin{aligned} M_b &= \int_0^{S_b}(q_v\cos\mu - q_o\sin\mu)(y-y_q)\,dS_b - \int_0^{S_b}(q_v\sin\mu + q_o\cos\mu)(x-x_q)\,dS_b = \\ &= \int_0^{S_b}\left[q_v(y\cos\mu - x\sin\mu) - q_o(y\sin\mu + x\cos\mu)\right]dS_b - \\ &- y_q\int_0^{S_b} q_v(y\cos\mu - x\sin\mu)\,dS_b + x_q\int_0^{S_b} q_v(\sin\mu + q_o\cos\mu)\,dS_b \end{aligned} \qquad (18)$$

Coordinates x_q and y_q points Q in this case play the role of constant values, therefore in the following the subscript q In this case, the derivative of the internal bending moment M_b will be written as:

$$\frac{dM_b}{dS_b}=\frac{dx}{dS_b}\int_0^{S_b}\left(q_v\sin\mu+q_o\cos\mu\right)dS_b-\frac{dy}{dS_b}\int_0^{S_b}\left(q_v\cos\mu-q_o\sin\mu\right)dS_b \quad (19)$$

Then the differential equation (17) can be written as:

$$\frac{d^2\xi}{dS_b}=\frac{1}{H_b}\frac{dx}{dS_b^2}\int_0^{S_b}\left(q_v\sin\mu+q_o\cos\mu\right)dS_b-\frac{dy}{dS_b}\int_0^{S_b}\left(q_v\cos\mu-q_o\sin\mu\right)dS_b \quad (20)$$

In this case, according to Fig. 4, we have: $tg\mu=y/x$; $\sin\mu=y/x$; $\cos\mu=x/\sqrt{x^2+y^2}$;

$$tg\varphi=dy/dx=y'\;;\; dS_b=\sqrt{(dx)^2+(dy)^2}\;;\;\cos\xi=dx/dS_b=\frac{dx}{\sqrt{(dx)^2+(dy)^2}}=\frac{1}{\sqrt{1+(y')^2}}\;;$$

$$\sin\xi=dy/dS_b=\frac{dy}{\sqrt{(dx)^2+(dy)^2}}=\frac{y'}{\sqrt{1+(y')^2}}.$$

In addition, according to [22], the distributed centrifugal load q_v and air resistance load q_o is determined by the formula:

$$q_v=S_r\rho_b\omega_b^2\sqrt{x^2+y^2}, \quad (21)$$

$$q_o=\frac{k_o b\rho_n\omega_o^2\left(x+yy'\right)\sqrt{x^2+y^2}}{2\sqrt{1+(y')^2}}, \quad (22)$$

where F_r – blade cross-sectional area, m^2; ρ_b – specific weight of the blade, kg/m^3; ω_b – blade angular velocity, rad/s; k_o = 0.45 – coefficient of aerodynamic air resistance, the value of which is assumed to be constant along the entire length of the cleaning flexible blade, m^2; ρ_n – specific air density, kg/m^3.

Taking into account equations (21) and (22), the differential equation (20) will take the form:

$$\frac{d^2\xi}{dS_b^2}=\frac{F_r\rho_b\omega_b^2}{H_b\sqrt{1+(y')^2}}\left(y'\int_{x_k}^{x}x\sqrt{1+(y')^2}dx-y\int_{x_k}^{x_b}y\sqrt{1+(y')^2}dx\right)+\frac{k_o b\rho_n\omega_b^2}{2H_b\sqrt{1+(y')^2}}\left(y'\int_{x_k}^{x}y\left(x+yy'\right)dx+\int_{x_k}^{x_b}x\left(x+yy'\right)dx\right) \quad (23)$$

$$\frac{d^2\xi}{dS_b^2}=\frac{\omega_b^2}{H_b\sqrt{1+(y')^2}}\left[\begin{aligned}&F_r\rho_b\left(y'\int_{x_k}^{x}x\sqrt{1+(y')^2}dx-y\int_{x_k}^{x_b}y\sqrt{1+(y')^2}dx\right)+\\&0.5k_o b\rho_n\left(y'\int_{x_k}^{x}y\left(x+yy'\right)dx+\int_{x_k}^{x_b}x\left(x+yy'\right)dx\right)\end{aligned}\right] \quad (24)$$

Taking into account that $\xi=arctg\left(y'\right)$ the differential equation for the curvature of the longitudinal axis of the blade can be written as:

$$\frac{d\xi}{dS_b}=\frac{d\xi}{dx}\frac{1}{\sqrt{1+(y')^2}}=\frac{d}{dx}\frac{\left[arctg\left(y'\right)\right]}{\sqrt{1+(y')^2}}=\frac{y''}{\sqrt[3]{1+(y')^2}}. \quad (25)$$

Then the second derivative of the differential expression (25) is equal to:

$$\frac{d^2\xi}{dS_b^2}=\frac{d}{dx}\left(\frac{y''}{\sqrt[3]{1+(y')^2}}\right)\frac{1}{\sqrt{1+(y')^2}}=\frac{y'''\left[1+(y')^2\right]-3y'\left(y''\right)^2}{\sqrt[3]{1+(y')^2}}. \quad (26)$$

or taking into account entries (24) and (26) we obtain the final dependence, or the integral-differential equation of the elastic line of the cleaning flexible blade of a single-shaft cleaner of the remains of the tops from the heads of root crops:

$$\frac{y'''\left[1+(y')^2\right]-3y'(y'')^2}{\sqrt[3]{1+(y')^2}}=\int_{x_k}^{x}\left[\Theta_1 x(x+yy')+\Theta y\sqrt{1+(y')^2}\right]dx+y'\int_{x_k}^{x}\left[\Theta_1 y(x+yy')-\Theta x\sqrt{1+(y')^2}\right]dx \quad (27)$$

where $F_r = b\delta$; $H_b = EI$; $\Theta=\frac{F_r\rho_b\omega_b^2}{H_b}=\frac{b\delta\rho_b\omega_b^2}{EI}$ $\Theta_1=\frac{k_o\rho_n\omega_b^2}{2EI}$.

Numerical solution of equation (27) by the Runge-Kut method in a software environment for a personal computer under given initial conditions and boundaries of the solution search interval [x_k , x_k] at different values of blade angular velocity ω_b allows you to establish or determine the rational profile of the elastic line of the cleaning flexible blade.

5. Conclusion

Analytical models have been developed that functionally describe the process of contact interaction of a hinged cleaning flexible blade with the root crop head or with the tops remaining on it, and also determine the profile of the elastic line of a cantilevered cleaning flexible blade.

It has been established that when designing blade cleaners for tops remaining from root crop heads, it is necessary to take into account the relationship of permissible deformations with the main parameters of cleaning flexible blades - the rotation frequency of a single-shaft cleaner or the rotation frequency of a cleaning flexible blade, the length, width and thickness of the blade, the maximum permissible number of blades in one section, the number of sections on the rotor of a single-shaft cleaner.

The constructed nomogram allows you to determine the maximum permissible thickness and minimum permissible length of the blade depending on its operating conditions.

The results obtained are a further step in improving the methodology for optimizing technological parameters and structural and kinematic parameters of the working bodies of combined modules for digging chicory roots.

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ДОСЛІДЖЕННЯ ПРОЦЕСУ КОНТАКТНОЇ ВЗАЄМОДІЇ ОЧИСНОЇ ЛОПАТІ З ГОЛОВКОЮ КОРЕНЕПЛОДІВ ЦИКОРІЮ

Для механізованого збирання коренів цикорію наразі використовуються коренезбиральні машини, у яких модуль викопування коренів побудований на основі однодискового сферичного копача, встановленого під кутом атаки до напрямку руху, а позаду нього розташовано культиватор і горизонтальний одновальний очисник залишків гички з головок коренеплодів. Під час очищення залишків гички гнучкі лопаті, закріплені на роторі одновального очисника, втрачають початкову жорсткість, що знижує ефективність роботи коренезбиральної машини та якість сировини коренів цикорію для подальшої переробки.

Метою роботи є підвищення технологічної ефективності модуля викопування коренів цикорію шляхом розроблення математичної моделі контактної взаємодії очисної лопаті з головкою коренеплоду та оптимізації раціональних параметрів одновального очисника.

На основі аналізу технологічного процесу роботи одновального очисника розроблено аналітичну математичну модель, що функціонально описує процес контактної взаємодії гнучкої очисної лопаті з головкою коренеплоду або з гичкою, яка на ній залишається. Встановлено, що під час проєктування лопатевих очисників для видалення гички з головок коренеплодів необхідно враховувати взаємозв'язок між допустимими деформаціями та основними параметрами гнучких очисних лопатей – частотою обертання одновального очисника, довжиною, шириною та товщиною лопаті, максимально допустимою кількістю лопатей у секції, а також кількістю секцій на роторі очисника.

Побудована номограма дає змогу визначити максимальну допустиму товщину та мінімальну допустиму довжину лопаті залежно від умов її роботи. Отримані результати є подальшим кроком у вдосконаленні методики оптимізації параметрів робочих органів комбінованих модулів для викопування коренів цикорію.

Ключові слова: *коренеплід, цикорій, залишки гички, ротор очисника, очисна лопать, сила, деформація, модель, переміщення.*

Ф. 27. Рис. 4. Літ. 22.

INFORMATION ABOUT THE AUTHORS

Maksym HADAICHUK – Postgraduate Student of the Department of Agroengineering and Technical Service of Vinnytsia National Agrarian University (Soniachna Str., 3, Vinnytsia, 21008, Ukraine, e-mail: max3novmac@gmail.com, https://orcid.org/0009-0008-8967-8171).

ГАДАЙЧУК Максим Юрійович – аспірант кафедри агроінженерії та технічного сервісу Вінницького національного аграрного університету (ВНАУ, вул. Сонячна, 3, м. Вінниця, Україна, 21008, e-mail: max3novmac@gmail.com, https://orcid.org/0009-0008-8967-8171).