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Theoretical research of force interaction of a flexible cleaning blade with a beet root head

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Abstract. The most common technology of removing the sugar beet haulm in the world is a continuous cut of the entire mass of the green haulm with further additional removal of the upper parts of the sugar beet heads, which is carried out without extracting the roots from the ground. This is the scheme according to which most top harvesting machines, manufactured in the world, now operate. However, we have found in our studies that, due to additional cutting off the upper parts of the root crop heads, up to 10% of the sugar-bearing mass is lost. Besides, there is an urgent need for immediate processing of the sugar beet root crops, as losses of the sugar juice occur, and bacteria enter inside of the root crop through the cut-off part, causing rotting. Therefore, a more favourable operation for harvesting root crop tops is not cutting off their heads but cleaning them from the residues of the foliage. In addition, the operation of cleaning the sugar beet roots from the residues of the foliage is subject to rather high requirements due to the absence of the green and dry residues on the heads of the roots, as well as the losses and damage of the root crops themselves. The purpose of this investigation is to develop a theory of the force interaction of the flexible cleaning blade with the sugar beet head in the process of its cleaning when the blade is mounted on the vertical driving shaft. The methods used of the investigation are those of modelling, higher mathematics and theoretical mechanics, as well as programming and numerical calculations on the computer. As a result of the research, an equivalent scheme was developed and a mathematical model was constructed describing the force interaction of the flexible cleaning blade with the surface of the sugar beet root.

Keywords: sugar beet, haulm, cleaning blade, impact.

INTRODUCTION

Sugar beet is the most important source of sugar. In Europe its plantations occupy more than 6 million hectares, which accounts for 70% of the world's plantations of this crop. The largest areas of this crop are located in Russia, France, Germany, Ukraine and Poland. In addition to the sugar-containing roots, the yield of sugar beet includes haulm which is a good animal fodder or a raw material for generation alternative energy from the bio-raw materials (Eichhorn, H. 1999; Pogorely & Tatjanko, 2004; Bentini et al., 2005).

Sugar beet harvesting is a complex and expensive process which largely determines the profitability of the sugar beet production (Helemendik, 1996; Gruber, 2005). Separation of the haulm from the root is an important process with regard to obtaining a high-quality material for its processing into sugar, reducing losses and production of high-quality fodder.

Most machines for harvesting sugar beet work according to a scheme when at first complete cutting of the entire mass of the green haulm is carried out without extraction of the roots from the ground, with additional separation of the upper parts of the root crop heads from the residues. However, due to additional separation of the upper parts of the root crop heads, up to 10% of the sugar-bearing mass is lost (Bulgakov et al., 2016). In addition, there arises an urgent need for immediate processing of sugar beet roots because losses of sugar juice occur, and bacteria enter the inside of the root crop through the cut-off part, which worsens the preservation of the material. In view of this, it is more efficient not to cut the root crop heads but to clean them from the residues of the haulm. In this case the operation of cleaning the sugar beet roots from the haulm residues is subject to sufficiently strict requirements which provide that there should not be any green and dry residues on the root crop heads, as well as losses and damage to the root crops themselves.

To implement the process of stripping the haulm residues from the sugar beet heads from which the main massive of the haulm has been previously removed and collected without extraction of the roots from the ground, we developed a series of new root head cleaners (Vasilenko, 1996; Pagorely & Tatjanko, 2004; Bulgakov et al., 2017). A distinctive feature of these cleaners of the root crop heads from the haulm residues is a vertical drive shaft, on the console end of which there are cleaning elements placed in the form of several flexible blades, directed downwards towards the heads of the root crops. This cleaner moves along the rows of the sugar beet plantations, as a result of which the console ends of the flexible cleaning blades, performing a rotational and simultaneously a forward movement, strike the heads of the root crops, stripping (knocking off) the haulm residues from them and without inflicting damage to the spherical surfaces of the root crops heads. Consequently, this cleaner is intended for cleaning only one row of root crops. In the case of a multi-row embodiment an identical cleaner should be installed on each beet root row.

Although there are many scientific studies devoted to the separation of the sugar beet haulm (Helemendik,1996; Zhang et al., 2013; Bulgakov et al., 2016; Bulgakov et al., 2018; Bulgakov et al., 2019), yet the interaction force of the flexible cleaning blade with the surface of the sugar beet head has been little disclosed.

The purpose of the work is theoretical research of the interaction of the flexible cleaning blade with the sugar beet head and determination of optimal geometrical parameters of the blades.

MATERIALS AND METHODS

Fig. 1 presents a design and technological scheme of one of the layout variants of a cleaner of this type with a vertical drive shaft carrying flexible cleaning blades, and in Fig. 2 an experimental installation in operation. The cleaner consists of a frame 1 on which a vertical drive shaft 2 is mounted on the lower end of which a disk 3 of a pre-set diameter is fixed. On the outer generatrix of the disk 3, with a pre-set step along the circumference, there are fixed spherical joints 4 of the disk, in which double-arm levers 5 are installed, at the lower short ends of which, on axes 6, there are installed flexible cleaning blades 7 with cantilever ends pointing down. The upper ends of the double-arm levers 5 also have spherical joints 8 of the levers, which, through the pairs of screws 9, by means of kinematic mechanisms 10 are connected with the drive shaft 2. Using the pairs of screws 9, it is possible to prechange and fix the length of the kinematic mechanisms 10, which provides a possibility to pre-install flexible cleaning blades 7 with different angles of their arrangement in a vertical plane. The flexible cleaning blades 7, in their turn, can rotate around the axles 6 and deviate during operation in a radial direction with respect to the drive shaft 2.

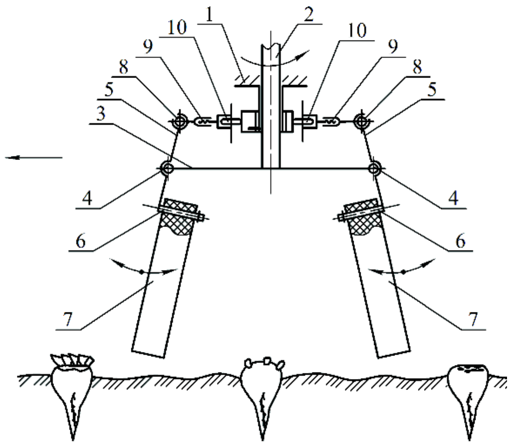

Figure 1. A design and technological scheme of the new cleaner of the root crop heads without extraction from the ground, with a vertical drive shaft (Bulgakov et al., 2018): 1 – the frame; 2 – the vertical drive shaft; 3 – the disk; 4 – the spherical joints of the disk; 5 – the double-arm levers; 6 – the axles; 7 – the flexible cleaning blades; 8 – the spherical joints of the levers; 9 – the pairs of screws; 10 – the kinematic mechanisms.

The technological process of cleaning the root crop heads from the haulm residues without extraction from the ground by a cleaner of this type proceeds in this way. The vertical drive shaft 2, extending in cantilever on the frame 1, moves in a forward direction along a row of the sugar beet roots from which the main mass of the haulm has already been removed. Due to the rotation of the shaft 2 at a pre-set angular speed ω, the flexible cleaning blades 7, under the action of the centrifugal forces, deviate from the vertical position at a certain angle, as a result of which they create the so-called 'cleaning cone' (the top of which is on the axis of the drive shaft 2, the base is directed downwards, and the generatrix surface is composed of the end surfaces of the cleaning blades 7), which ensures the necessary width of the cleaning zone. The cleaning working tool, i.e. the vertical drive shaft 2, together with the cleaning Blades 7, installed at a predetermined height above the soil surface (with a

Figure 2. An experimental installation – a cleaner of the root crop heads from the haulm residues.

significant amount of residues on the heads of the root crops and with other plant residues in the row; this height should be as small as possible), moves in a forward direction along the row of the root crops and, due to the rotation of the drive shaft 2, its flexible cleaning blades 7 perform strikes at the front part of the root crop heads. Bending further, they move with their plane already along the upper surfaces of the root crop heads and cover also the rear part of the head; thus stripping the existing residues from the entire surface of the root crop heads.

The research was conducted applying the methods of theoretical mechanics, higher mathematics, the elasticity theory, as well as the methods of compiling and solving differential equations of the movement on the PC. The main design parameters of the new working tool for cleaning the sugar beet heads from the haulm residues are the width and the length of the blade, under the action of which the stalks of the haulm, remaining on the spherical surface of the sugar beet heads, are separated after the main massive of the haulm has been cut off without extraction of the roots from the ground.

Let us construct an equivalent scheme of the contact interaction of the flexible cleaning blade with the sugar beet head (Fig. 3). First of all, let us present the body of the root crop head in the form of a truncated cone, the shape that the sugar beet heads assume in most cases after complete cutting of the main massive of the haulm without extraction of the roots from the ground, their collection and transportation from the field. Let us suppose that the sugar beet root lies motionless in the soil (actually fixed in it) after cutting off the upper part of the haulm; therefore its head also remains motionless.

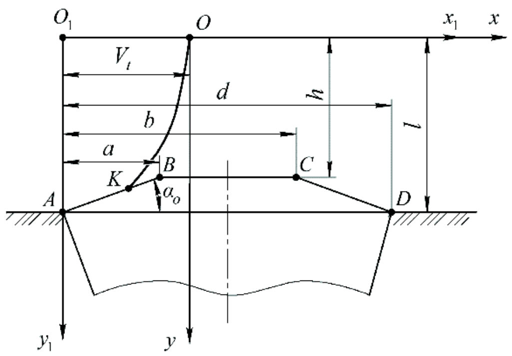

Figure 3. An equivalent scheme of a contact interaction of the flexible cleaning blade with the head of the beet root.

Let us connect the surface of the head of the root crop with a fixed (absolute) Cartesian coordinate system $x_1O_1y_1$. We place the origin of this coordinate system (point O_1) so that the horizontal axis O_1x_1 of this coordinate system passed through point O of attachment of the flexible blade to the cleaning tool and is directed towards the forward movement of the cleaner. It should be noted at once that, despite the fact that the cleaning blades are set to pivot on the axes, when driving upon the head of the root crop, moving along the surface of the head, and from it, the flexible cleaning blade moves forward with its front part, which gives a reason to consider it conditionally fixed on the vertical cleaning drive shaft. In this case axis O_1y_1 of the mentioned coordinate system is directed vertically downwards and passes through the leftmost point A of the root crop head (the truncated cone). In the plane, which is formed by the coordinate system $x_1O_1y_1$, this sugar beet head (the truncated cone) is shown as an equilateral trapezium $ABCD$, the lower base of which has a length greater than the length of the upper base, and the angles between the base and the lateral sides are indicated by α_o (Fig. 3).

The equations of the broken line *ABCD* in the coordinate system $x_1O_1y_1$ will be the following equations of straight lines:

$$y_1 = \begin{cases} l - x_1 \tan\alpha_o, & 0 \le x_1 < a, \\ h, & a \le x_1 < b, \\ h + (x_1 - b)\tan\alpha_o, & b \le x_1 \le d, \end{cases} \tag{1}$$

where α_o is the angle between the lower base of the cone (the lower base *AD* of the trapezium *ABCD*) and the generatrix *AB* of the cone; *a, b, d, h, l* – the parameters characterising the position, size and shape of the surface of the truncated head of the root crop in the coordinate system $x_1O_1y_1$, shown in Fig. 3.

Next, in Fig. 3 we will show a flexible cleaning blade in the form of curve *OK*, where *O* is the point of attachment (fixing) of the blade) to the shaft of the cleaning tool. Point *K* is the end of the cleaning blade, which is also a contact point of the end of the blade with the head of the sugar beet root. In Fig. 3 the contact point *K* is shown in an arbitrary position on the surface of the root crop head, i.e. it is depicted at an arbitrary moment of time *t*.

When the shaft of the cleaning tool rotates, the point *K* of the end of the flexible blade moves in a circle with a certain radius *r*; however, the contact point *K*, because of the forward movement of the cleaner, describes a more complex path on the surface of the root crop head; in the first approximation it describes a certain cycloid. Thus, owing to the simultaneous rotational and forward movements, the cleaning blade, due to the elasticity of the material from which the cleaning blade is made, strips the haulm residues off the head of the root crop.

Let us connect the moving coordinate system *xOy* with the point of attachment *O* of the blade. In addition to this, the origin of the coordinates of this system is at the attachment point *O* of the flexible blade to the vertical shaft of the cleaner, axis *Ox* is directed along axis O_1x_1, axis *Oy* is directed down, parallel to axis O_1y_1.

The coordinates of point *K* at the end of the flexible cleaning blade will be denoted by *x* and *y*. In the coordinate system $x_1O_1y_1$ coordinates x_1, y_1 of point *K* are connected with coordinates *x*, *y* of this point in the coordinate system *xOy* as follows:

$$x_1 = V \cdot t + x, \tag{2}$$

$$y_1 = y \tag{3}$$

where $V = \frac{\pi n}{30} r$ is the linear (circumferential) speed of point *K* of the end of the blade, m s^{-1}; *n* is the number of revolutions of the blade, min^{-1}; *r* is the radius of the circle along which point *K* of the end of the blade moves during the rotation of the cleaning tool, m; *t* is the time of the forward movement of the cleaner, s.

By substituting the values of x_1 and y_1, defined by expressions (2) and (3), into expression (1), we obtain:

$$y = \begin{cases} l - (Vt + x)\tan\alpha_o, & 0 \le (Vt + x) < a, \\ h, & a \le (Vt + x) < b, \\ h + (Vt + x - b)\tan\alpha_o, & b \le (Vt + x) \le d. \end{cases} \tag{4}$$

RESULTS AND DISCUSSION

In order to determine the parameters of the flexible cleaning blade, let us construct an equivalent scheme of forces that act upon a certain selected element in the cleaning blade during its interaction with the head of the beet root (Fig. 4). We will select an element with a length of ds on the uniform cleaning blade at a distance s from the beginning of the blade. During the interaction of the cleaning blade with the sugar beet head from the side of the root crop, a reaction arises from this interaction, which can be decomposed into two components $Q = Q(S)$ and $N = N(S)$, where force $Q(S)$ is directed parallel to axis Ox, and force $N(S)$ is directed parallel to axis Oy. In addition to it, a bending moment $M = M(S)$ arises from the said interaction of the blade with the beet head. These forces, which are shown in Fig. 4, and the bending moment are transmitted to the cleaning blade; and these forces act upon the element with a length of ds, selected in the body of the cleaning blade. From one side force Q acts upon the selected element, from the other side force. $Q_1 = Q + \frac{dQ}{ds} \cdot ds$ In a similar way, from one side force N acts upon the selected element, from the other side force $N_1 = N + \frac{dN}{ds} \cdot ds$ (Fig. 4). Since the selected element is in a state of equilibrium, it is possible to write the equilibrium equations of this element into the projections on axes Ox and Oy:

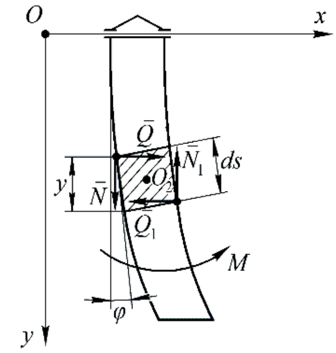

Figure 4. A diagram of forces acting upon an element of the blade during its interaction with the beet root head.

$$\left.\begin{aligned} Q - \left(Q + \frac{dQ}{ds} \cdot ds \right) = 0, \\ N - \left(N + \frac{dN}{ds} \cdot ds \right) = 0, \end{aligned}\right\} \quad (5)$$

or

$$\left.\begin{aligned} -\frac{dQ}{ds} \cdot ds = 0, \\ -\frac{dN}{ds} \cdot ds = 0. \end{aligned}\right\} \quad (6)$$

Since $ds \neq 0$, then from the system of Eq. (6) we obtain:

$$\left.\begin{aligned} \frac{dQ}{ds} = 0, \\ \frac{dN}{ds} = 0. \end{aligned}\right\} \quad (7)$$

From this one can draw a conclusion that forces Q and N are constant values along this blade, starting from $s = 0$ to $s = L$, where L is the length of the blade.

The bending moment in the section of an elastic-viscous rod in accordance with the Focht law (Timoshenko, 1975; Dreizler & Lüdde 2010) is determined by the formula:

$$M = c\left(k + \eta \frac{\partial k}{\partial t}\right), \tag{8}$$

where $c = E \cdot I$ – the bending stiffness of the blade section; E – the elasticity modulus of the material of the blade; I – the inertia moment of the cross section; η – the viscosity coefficient of the blade; k – the curvature of the curved axis of the blade.

The curvature value of the curved axis of the blade is determined by the formula:

$$k = \frac{d\varphi}{ds}. \tag{9}$$

In the first approximation we take $\eta = 0$. Then from expressions (8) and (9) we obtain:

$$M = c\frac{d\varphi}{ds}. \tag{10}$$

Further, from the equilibrium condition of the selected element with respect to its rotation around the transverse axis, which passes through the centre of mass (point O_2) of this element, we can write the following equality of moments of the forces indicated in Fig. 4:

$$dM = Q \cdot dy - N \cdot dx, \tag{11}$$

or

$$dM = Q\cos\varphi \cdot ds - N\sin\varphi \cdot ds, \tag{12}$$

where φ – the angle of rotation of the blade.

Then from expression (12) we obtain:

$$\frac{dM}{ds} = Q\cos\varphi - N\sin\varphi \tag{13}$$

Thus, an equation of the rotation of the element of the cleaning blade relative to the transverse axis, which passes through its centre of mass (point O_2), is obtained.

The surface of the root crop, stripped by the end of the blade, is determined by three linear sections AB, BC and CD (Fig. 5). Stripping of the haulm residues by a flexible cleaning blade starts at point A and ends at point D.

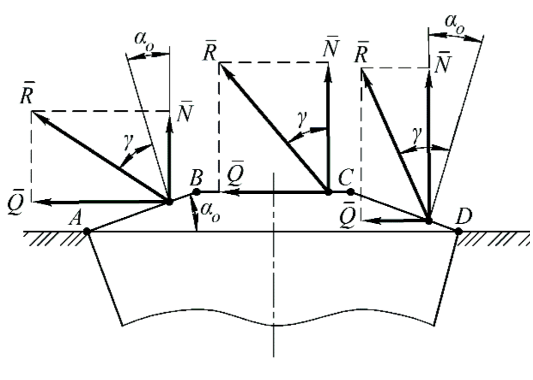

Figure 5. A diagram of the calculated contact areas of the flexible cleaning blade with the surface of the root crop.

The horizontal and the vertical reactions at the end of the blade from the side of the surface of the root crop head in section AB will be equal to:

$$N = R \cdot \cos(\gamma + \alpha_o),$$
$$Q = R \cdot \sin(\gamma + \alpha_o), \tag{14}$$

in section *BC*:

$$N = R \cdot \cos\gamma,$$
$$Q = R \cdot \sin\gamma, \tag{15}$$

in section *CD*:

$$N = R \cdot \cos(\gamma - \alpha_o),$$
$$Q = R \cdot \sin(\gamma - \alpha_o), \tag{16}$$

where γ – the angle of friction.

In general, it is convenient to write thus:

$$N = R \cdot \cos(\gamma + \alpha),$$
$$Q = R \cdot \sin(\gamma + \alpha), \tag{17}$$

where angle α is written in the following way:

$$\alpha = \begin{cases} \alpha_o, & 0 \le (Vt + x) < a, \\ 0, & a \le (Vt + x) < b, \\ -\alpha_o, & b \le (Vt + x) \le d. \end{cases} \tag{18}$$

Let us substitute values *N* and *Q* from (17) into expression (13); we obtain:

$$\frac{dM}{ds} = R\sin(\gamma + \alpha)\cos\varphi - R\cos(\gamma + \alpha)\sin\varphi = -R\sin(\varphi - \gamma - \alpha). \tag{19}$$

After substituting the value of the moment *M* from (10) into expression (19), we obtain:

$$c\frac{d^2\varphi}{ds^2} = -R\sin(\varphi - \gamma - \alpha), \tag{20}$$

or

$$\frac{d^2\varphi}{ds^2} = -p^2 \sin(\varphi - \gamma - \alpha) \tag{21}$$

where $p^2 = \frac{R}{c}$.

Let us multiply each term of the left and the right side of Eq. (21) by $2\frac{d\varphi}{ds}ds = 2d\varphi$. We will have:

$$2\frac{d\varphi}{ds}\frac{d^2\varphi}{ds^2}ds = -2p^2 \cdot \sin(\varphi - \gamma - \alpha)d\varphi \tag{22}$$

Since:

$$2\frac{d\varphi}{ds}\frac{d^2\varphi}{ds^2} = \frac{d}{ds}\left(\frac{d\varphi}{ds}\right)^2, \tag{23}$$

then Eq. (22) will obtain the form:

$$d\left(\frac{d\varphi}{ds}\right)^2 = -2p^2 \cdot \sin(\varphi - \gamma - \alpha)d\varphi \tag{24}$$

We integrate the resulting Eq. (24). We have:

$$\int d\left(\frac{d\varphi}{ds}\right)^2 = 2p^2 \int d\left[\cos(\varphi-\gamma-\alpha)\right] \tag{25}$$

After which we will have:

$$\left(\frac{d\varphi}{ds}\right)^2 = 2p^2 \cdot \cos(\varphi-\gamma-\alpha) + C \tag{26}$$

where C – an arbitrary constant.

We find the arbitrary constant C that enters into expression (26). If we take into account the limiting conditions $M(L) = 0$, then, according to expression (10), we will have:

$$\frac{d\varphi}{ds}(L) = 0 \tag{27}$$

where L – the length of the blade.

Then, using the resulting expression (27), we can write:

$$0 = 2p^2 \cdot \cos(\varphi_1-\gamma-\alpha) + C \tag{28}$$

hence the arbitrary constant C will be equal to:

$$C = -2p^2 \cdot \cos(\varphi_1-\gamma-\alpha) \tag{29}$$

where φ_1 – the angle of rotation of the end of the blade.

Substituting expression (29) into Eq. (26), we will have:

$$\left(\frac{d\varphi}{ds}\right)^2 = 2p^2\left[\cos(\varphi-\gamma-\alpha) - \cos(\varphi_1-\gamma-\alpha)\right] \tag{30}$$

After certain transformations of expression (30) we obtain:

$$ds = \frac{d\varphi}{\sqrt{2}\, p\sqrt{\cos(\varphi-\gamma-\alpha) - \cos(\varphi_1-\gamma-\alpha)}} \tag{31}$$

By integrating Eq. (31) within the range from 0 to L, and from $\varphi = 0$ to $\varphi = \varphi_1$, we will obtain:

$$\int_0^L ds = \frac{1}{\sqrt{2}\cdot p} \cdot \int_0^{\varphi_1} \frac{d\varphi}{\sqrt{\cos(\varphi-\gamma-\alpha) - \cos(\varphi_1-\gamma-\alpha)}} \tag{32}$$

where L – the length of the blade.

Thus, integrating Eq. (32) along the elastic line, we find the desired length L of the flexible cleaning blade:

$$L = \frac{1}{\sqrt{2}\cdot p} \cdot \int_0^{\varphi_1} \frac{d\varphi}{\sqrt{\cos(\varphi-\gamma-\alpha) - \cos(\varphi_1-\gamma-\alpha)}} \tag{33}$$

The resulting expression (33) makes it possible to determine the length of the blade L through an integral that can be calculated using a PC.

However, the length of the blade L, determined by expression (33), is exactly that long flexible cleaning blade which is rational and necessary in order, based on its deformations and the forces applied at the head of the root crop, to ensure a maximum complete contact with the surface of the root crop head without extracting it from the ground, that will ultimately ensure its high quality of cleaning.

Using expression (33), as well as the blade section parameters: width – 0.02 m, length – 0.04 m, the reaction value – $R = 15$ N, we constructed a calculation model for the removal process of the sugar beet haulm in the MatLab system. The value of reaction R is chosen from the destruction condition of the haulm by the cleaning blade on the root crops. The dependencies, shown in Fig. 6, indicate that, with the increase in the length L of the cleaning blade, it is necessary to increase the elasticity modulus E of its material. This is explained by the fact that, as the length of the blade increases, the moment in its elementary sections increases from the components of reaction R; and, in order to overcome it, greater resistance of the material to deformation is needed. To ensure that the range of the protruding heights of root crops above the soil surface up to 0.1 m is copied, the required blade length L must be at least 0.2 m. In addition to the length of the blade, it is necessary to substantiate the value of its maximum deflection angle φ_1. From Fig. 6 it is evident that, with increasing angle φ_1, the maximum length L of the blade decreases, and for $\varphi_1 = 80°–90°$ it does not exceed 0.2 m, but for $\varphi_1 = 60°–70°$, it ranges from 0.12 m to 0.28 m. Since it is difficult to achieve large values of the elasticity modulus E by selecting properties of the material and by reinforcement, one should strive for smaller values of the required elasticity modulus. Therefore, as a rational value for the deflection angle of the cleaning blade, angle $\varphi_1 = 60°$ was selected, at which the permitted values of the elasticity modulus are $E = 3–11$ MPa, and the working length L of the cleaning blade may be selected from a range of 0.2–0.24 m.

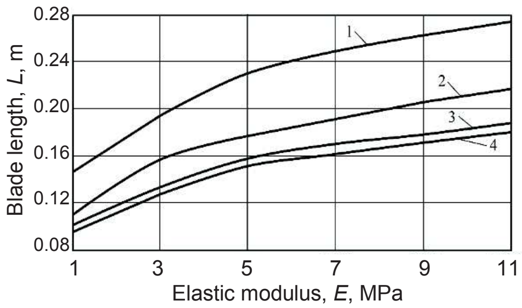

Figure 6. Dependence of length L of the cleaning blade upon its modulus of elasticity E: 1) $\varphi_1 = 60°$; 2) $\varphi_1 = 70°$; 3) $\varphi_1 = 80°$; 4) $\varphi_1 = 90°$.

The design of the sugar beet root crown cleaner with a vertical drive shaft developed by the authors incorporates the possibility of installing cleaning blades of different lengths L and with different physical and mechanical properties of the materials that can be used for their production. Fig. 7 presents one cleaning element, which can hold cleaning blades of different lengths L and with different properties, for example, with different elastic moduli E.

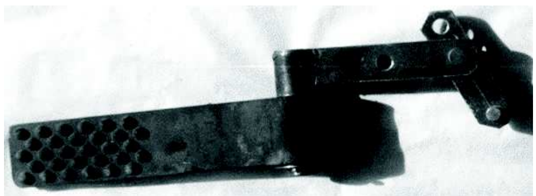

Figure 7. Cleaning element that can hold flexible blades of different lengths and with different elastic moduli (manufactured from different materials: rubber, plastic, cord-reinforced rubber, belts).

The further experimental investigations carried out by the authors have proved that the best quality of the cleaning of sugar beet root crowns from haulm residues according to the criterion of their amount left after the pass of the cleaner is achieved when using a cleaning blade made of bossed rubber (with bosses of hemispherical shape positioned chequer-wise on the blade's cantilever end) and sized as follows: the length is $L = 0.20$ m, the breadth is 0.06 m and the thickness is 0.02 m.

The data obtained during the experimental investigations and processed in the MatLab environment are presented in Fig. 8.

As is seen in the presented graphs, the minimum amount of haulm residues is left on the root crowns, when blades with the length L equal to 0.20–0.21 m are used. And the preferable angular velocity of rotation in this case is 734 rad s^{-1}. Further increase of the blade length L is not advisable, since the continuing increase of the quality of cleaning will at greater lengths be outweighed by the excessive wear and tear of the cantilever ends of the cleaning blades as a result of their possible contacts with the soil surface. That results also in the excessive material consumption.

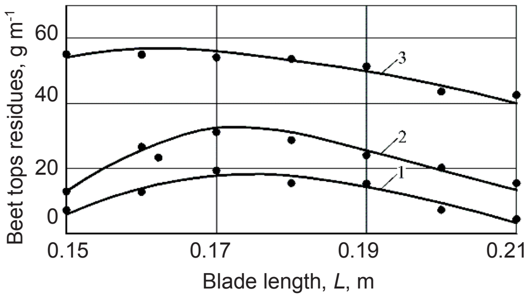

Figure 8. Relation between amount of haulm residues on sugar beet root crowns after their cleaning and cleaning blade length L at different angular velocities of rotation of cleaner's drive shaft: 1–734 rad s^{-1}; 2–540 rad s^{-1}; 3–448 rad s^{-1}.

The data obtained as a result of the experimental investigations lend full support to the completed analytical calculations.

Next, we will define analytically what the width of the flexible cleaning blade should be. The main kinematic parameter of the movement of the cleaning blade is the kinematic condition λ, which is determined by means of the following expression (Grote & Antonsson, 2008):

$$\lambda = \frac{V_b}{V_c} = \frac{\omega R}{V_c} \qquad (34)$$

where V_b – the linear speed of the end of the cleaning blade, m s^{-1}; V_c – the forward speed of the cleaner of the root crop heads, m s^{-1}; ω – the angular speed of rotation of the cleaning blade, rad s^{-1}; R – the radius of the working tool on which the cleaning blades are installed, m. Let us consider conditions when: $\lambda > 1$, $\lambda = 1$ and $\lambda < 1$.

If $\lambda < 1$, that is, $\varphi \cdot R < V_b$, then, as the results of experimental investigations show, the haulm residues will remain after the passage of the cleaner, which does not satisfy the agro technical requirements; therefore this case is excluded. Besides, the speed of the forward movement of the cleaner is so great that there remain areas on the heads of the root crops which the cleaning blades do not touch. Therefore, to achieve high-quality cleaning of the heads of root crops from the haulm residues, it is necessary to observe a condition when $\lambda \geq 1$. Let us consider an extreme case when there is no overlap of the zone of action of the cleaning blades, i.e. $\lambda = 1$, yet there are no above-mentioned areas on the root crop heads that are not captured by the blades. Multiplying the numerator and the denominator of expression (34) by the time t of the interaction of the flexible cleaning blade with the head of the beet root crop, we will obtain:

$$\lambda = \frac{t \cdot \omega \cdot R}{t \cdot V_c} = \frac{\Theta \cdot R}{t \cdot V_c} \qquad (35)$$

In expression (35), the product ($t \cdot \omega$) shows at what angle the cleaning blade will rotate relative to the vertical axis of rotation during the interaction of the blade with the head of the beet root crop. Let us denote the said angle as Θ. Consequently, $\Theta = \omega \cdot t$.

On the other hand, angle Θ will be part of a full revolution (the working period) of the cleaning blade. This angle, as such, will mean through what angle of rotation of the working tool the next cleaning blade comes into action. In this case, when the design of the cleaner has 8 blades, we find that: $\Theta = \frac{360°}{8} = 45°$.

Then the time from the start of the interaction of this cleaning blade with the surface of the head of the beets till the beginning of the interaction of the next blade (on condition that that there is no overlapping of the area of action of the cleaning blades, i.e. $\lambda = 1$) will be:

$$\Delta t = \frac{\Theta}{\omega} \tag{36}$$

On the other hand, it is necessary to observe a condition when the forward movement of the root head cleaner during the time Δt should not exceed the width of the cleaning blade b, i.e. it is necessary that:

$$b = V_c \cdot \Delta t \tag{37}$$

or, taking into account expression (36), we will have:

$$b = V_c \frac{\Theta}{\omega} \cdot \tag{38}$$

From the expression (38) it follows that:

$$\frac{\omega}{V_c} = \frac{\Theta}{b} \tag{39}$$

Having substituted correlation (39) into expression (34), we will have:

$$\lambda = \frac{R\Theta}{b} \cdot \tag{40}$$

Because of the requirement to satisfy the fulfilment of inequality $\lambda \geq 1$, from expression (40) we will have:

$$\frac{R\Theta}{b} \geq 1 \cdot \tag{41}$$

As it is evident from expression (41), the maximum width b_{max} of the cleaning blade should not exceed the value:

$$b_{max} \leq R \cdot \Theta \cdot \tag{42}$$

On the other hand, the minimum width b_{min} of the cleaning blade should exceed the maximum size of the existing haulm residues on the heads of the beet roots. Considering (Bulgakov et al., 2018), we have the following inequality:

$$R \cdot \Theta > b > 0.01 \text{ m}. \tag{43}$$

The width of the working part of the cleaning blade should be within the range from 10.7 cm to 1.0 cm. For practical purposes, we use a 5 cm width of the cleaning blade.

CONCLUSIONS

1. There is obtained a mathematical model of the rotation of any element of the flexible cleaning blade around the transverse axis, which passes through its centre of mass.

2. There is obtained an expression for determination of the rational length of the blade depending on the rigidity of the blade, the angle φ_1 of rotation of the end of the blade, the angle of friction γ, and angle α that characterises the shape of the head of the beet root. A rational length of the cleaning blade will ensure the greatest coverage of the surface of the beet root head which guarantees the quality of its cleaning from the haulm residues during the force interaction. Based on the analysis of the kinematic condition, a rational width of the blade has been determined.

3. Based on the analysis of the kinematic mode λ, when $\lambda \geq 1$, a rational width of the blade was obtained, which should be within a range from 0.107 m to 0.01 m.

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