THEORETICAL INVESTIGATIONS IN CLEANING SUGAR BEET HEADS FROM REMNANTS OF LEAVES BY CLEANING BLADE

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Abstract. Contemporary technologies for removal of sugar beet tops by most top removing machines made in the world suppose initial basic entire cutting of the tops with subsequent final removal of the remaining leaves from the heads of the root crops, which is done without extracting the roots from the ground. This way of cleaning sugar beets from the remnants of tops places sufficiently high demands that suppose exclusive absence of green and dry remnants on the heads of the root crops, as well as losses and damage of the root crop heads themselves. There are theoretical investigations carried out and new analytical expressions obtained for defining the design and kinematic parameters of a flexible cleaner blade, which ensure efficient stripping of the top remnants from the sugar beet heads, as well as for determination of the stripping force.

Keywords: sugar beet, tops, cleaner, cleaning blade, impact.

Introduction

Sugar beet is one of the important agricultural crops in many European countries [1]. The most labour-consuming and costly operation of the sugar beet production technology is its harvesting [2]. In the sugar beet harvesting process the most significant technological operations are digging the root crops out of the soil and removing the uncut leaves (leafstalks). After the initial cutting of the tops by the harvester a part of the leaves remains, which has to be separated from the root crop [3].

There are many scientific works and dissertations devoted to the issues how to remove the remaining uncut leaves (leafstalks) from the sugar beet heads after their basic cutting without extracting the roots from the ground, using the cutting apparatus of the haulm gatherers and cleaners [4-10], etc. They expose the results of theoretical and experimental investigations of the sugar beet head cleaners of various designs: with blades [6; 7; 9; 10], rings [8], sectors [10], drums [7]. However, the most widely used in the world are cleaners of the sugar beet heads with blades due to their simple design and the required quality of operation under comparatively favourable conditions. The designs of the sugar beet leafstalk removers using blades have been investigated by many scientists. However, in most of the above-mentioned scientific works, along with the theoretical substantiation of the design and kinematic parameters, there are not sufficiently exactly and completely considered the stripping forces created by the cleaners, the size characteristics of the root crops, the direction and module of the operating speed of the progressive motion of the cleaner; as insufficiently substantiated in some research works is the mass of the elastic blades (beaters), etc. In spite of the fact that in many aspects the technological processes of sugar and fodder beet harvesting are similar, removing the remaining uncut leaves (leafstalks) from the heads of the fodder beets without extracting the roots from the ground is practically not studied at all; in some works it is motivated partly and only in an experimental manner [8; 10-12].

It should also be underlined that the information given in literature concerns theoretical and experimental investigations only of particular types and designs of the cleaners of the root crop heads from the remaining leaves with all the assumptions and simplifications made by their authors, and therefore their application for subsequent studies of new cleaner types is highly complicated.

The aim of this investigation is to develop the most complete theory of interaction between a flexible cleaning blade and the head of sugar beet without extracting the root from the ground in the process of its cleaning from the remaining leaves when the flexible blade is installed on the horizontal driving shaft of the cleaner.

Since the size of the publication is limited, then, in correspondence with the assigned task, only the new investigations are reflected here in the general theory of interaction of an elastic cleaning blade with the head of the sugar beet root. The authors intend to show a comparison of the obtained theoretical dependencies with the experimental data in other articles, using concrete design solutions as an example.

Methods of research

The analytical research has been carried out using mathematical simulation on the basis of a theorem about the change of kinetic energy of a mechanical system, a theorem about the change of the moment of the quantity of motion, a theorem of impact forces, generation and closed-form solution of differential equations of motion.

Let us form an equivalent scheme of the operation of the simplest blade cleaner of the sugar beet heads (i.e., we will discuss the interaction process only of a single flexible cleaning blade with the head of the sugar beet placed in the soil the head of which projects to a certain height above the surface level of the soil and which contains on its generatrix uncut remnants of leaves (leafstalks) (Fig. 1). We will study this interaction process of the flexible cleaning blade with the head of the sugar beet root in a longitudinal vertical plane. The axis of the horizontal driving shaft (point O on the equivalent scheme) of the cleaner is perpendicular to the longitudinal vertical plane, the blade AM is pivotally suspended on the axis A at a distance from the centre of the shaft equal to the radius of rotation r. The end of the blade describes a circumference with the radius ρ rotating at a constant angular velocity ω in a longitudinal vertical plane. The axis of the horizontal driving shaft (point O) is moving above the surface level of the soil at a constant height H. The rotation axis O is moving progressively at a constant velocity $\overline{V}_0$. Let us link with the axis of the horizontal driving shaft (point O) the Cartesian orthogonal coordinate system xOz the horizontal axis Ox of which coincides with the direction of the progressive movement of the cleaner and the axis Oz is directed upwards. The length of the blade is equal to $2l$. Point M is the impact point of the flexible blade upon the head of the root crop.

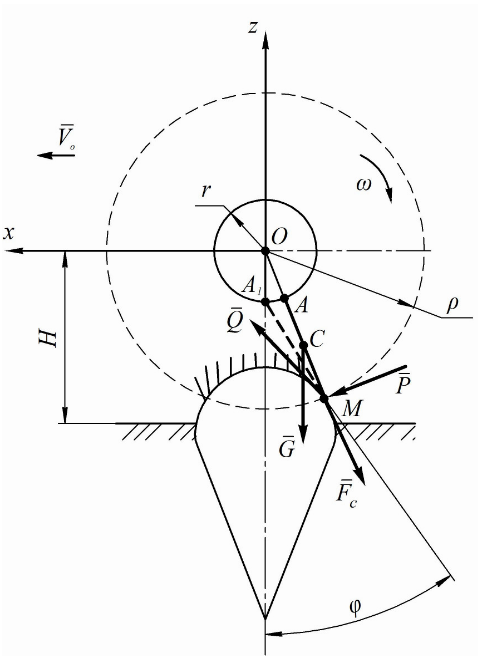

Fig. 1. **Equivalent scheme of interaction of the flexible cleaning blade with the beet head**

The initial impact velocity of the flexible blade against the head of the root crop will be composed of the relative velocity $\overline{V}_r$ of the beater rotating around the point O and the transfer velocity $\overline{V}_o$ of the point O moving progressively. Besides, there may be two possible variants. The first variant, when the direction of rotation of the blade takes place in the direction of the movement of the cleaner (Fig. 1); then the vectors of the relative velocity $\overline{V}_r$ of the blade and the transfer velocity $\overline{V}_o$ are added, $\overline{V} = \overline{V}_o + \overline{V}_r$. The second variant, when the direction of rotation of the blade takes place in the direction opposite to the movement of the cleaner of the root crop heads; then the impact velocity is determined by subtracting these vectors, $\overline{V} = \overline{V}_r - \overline{V}_o$.

We will show in the equivalent scheme forces acting during the collision of the flexible cleaning blade and the head of the root crop. Let us assume that at the point M the force $\overline{P}$ is applied – the impact force of the blade directed perpendicular to the blade AM itself at the very beginning of its collision with the sugar beet head. During the free rotation of the blade AM around the axis (point O)

at the angular velocity ω a centripetal force $\overline{F}_c$ arises which will be equal to $\overline{F}_c = m\rho\omega^2$ and will be directed along the blade *AM* putting the blade in one straight line with the radius *r* and pivot *A*. At the impact of the blade against the sugar beet head, at the meeting stage, the gravity force $\overline{G}$ of the blade also acts upon it, which will be equal to: $G = mg$ and will be concentrated in the centre of masses (point *C*) of the blade at a distance $r + l$ from the axis of rotation, and directed parallel to the vertical axis *Oz*.

When building the equivalent scheme of the blade cleaner, we made the following assumptions:

1. the cleaner blade *AM* is homogeneous along its entire length;
2. at the contact of the cleaning blade with the sugar beet root interaction of forces occurs only at the point *M* of contact with the root crop head;
3. the allowed impact force $\overline{P}$ of the cleaning blade against the root crop does not exceed the allowed force for the knocking (twisting) of the root crop out of the soil, i.e. $P \leq [P]$, where $[P]$ is the allowed force for knocking the sugar beet root out of the soil;
4. the air resistance during the rotation of the blade is not taken into account.

To continue a detailed analytical investigation, we will conditionally divide the technological process of cleaning the sugar beet heads from the remaining leaves into two stages:

1. a stage of meeting of the cleaning blade with the sugar beet head;
2. the working stage of cleaning the head of the sugar beet root from the leaves (leafstalks).

Results and discussion

Since the flexible blade *AM* is progressively moving together with its axis of rotation (point *O*) at velocity $\overline{V}_o$ and is rotating at the same time around the same axis at angular velocity ω, its kinetic energy *T* will be equal to:

$$T = \frac{mV_o^2}{2} + \frac{I_o\omega^2}{2}, \qquad (1)$$

where I_o – inertia moment of the blade in relation to the axis of rotation (point *O*),
m – mass of the blade.

According to Steiner's theorem the inertia moment I_o of the blade will be equal to:

$$I_o = I_c + m(r+l)^2, \qquad (2)$$

where I_c – inertia moment of the blade *AM* in relation to the axis of rotation passing through the centre of masses (point *C*) of the blade, parallel to the rotation axis of the blade;
$r + l$ – distance from the centre of masses of the blade to its axis of rotation.

Substituting expression (2) into (1), we obtain an expression for the computation of the kinetic energy of the blade before the start of its impact contact with the head of the sugar beet root:

$$T = \frac{mV_o^2}{2} + \left[I_c + m(r+l)^2\right]\frac{\omega^2}{2}. \qquad (3)$$

However, at the starting moment of the impact contact point *A* of the pivotal suspension of the blade *AM* to the shaft continues rotation around the rotation axis of the driving shaft at angular velocity ω but the contact point *M* of the blade with the head of the root crop starts slowing down its rotation as a result of the same contact. Therefore, the blade starts turning in the opposite direction around the point *A*, sliding simultaneously with its lower end along the surface of the head of the root crop thus executing the stripping process of the remaining leaves from the sugar beet head.

It is evident that, if before the impact contact with the head of the sugar beet root starts, the blade *AM* is situated in one straight line with the radius *r* of the driving shaft, connecting point *O* of the axis of the shaft with the point *A* of the blade suspension and turning for an arbitrary interval of time *t* by the angle ωt, then after the contact with the root crop head it starts turning by the angle $\omega t - \varphi$, where φ is the deviation angle of the blade from the position in which this point would have been at free rotation around the point O. Therefore, in this case the blade AM will have an angular velocity, equal to $\omega - \dot{\varphi}$, but the kinetic energy T of the blade will be equal to:

$$T = \frac{m \cdot V_o^2}{2} + \left[I_c + m(r+l)^2 \right] \cdot \frac{(\omega - \dot{\varphi})^2}{2}. \tag{4}$$

Comparison of expressions (3) and (4) shows that a part of the kinetic energy defined as dependency (3) transforms into the impact energy and the useful work of stripping the leaves from the head of the root crop.

It is well known that the time derivative from the kinetic energy of the material system is equal to the summary power of all the external and internal forces applied to the system [9]. In particular, for absolutely solid bodies the sum of the operations, consequently, the summary power of all the internal forces, is equal to zero. Therefore, assuming in this case that the lateral part of the root crop head is an absolutely solid body, we obtain the following equality of the power balance of the active forces acting upon the root crop at the impact contact and the consumed kinetic energy:

$$\frac{dT}{dt} = N, \tag{5}$$

where N – summary power of the active forces acting upon the root crop at the moment of time t.

When the theorem about the change of kinetic energy of a mechanical system is applied, reactions of connections without friction should not be taken into account because their work will be equal to zero. As the contact spot of the blade with the root crop head is sufficiently small in comparison with the length of the path (the circumference of a radius, equal to $r + 2l$), which is passed by the lower end of the blade during one revolution around the axis of rotation, one can consider that on this spot the end of the blade AM is moving progressively at a velocity equal to $\overline{V} = \overline{V}_o + \overline{V}_r$. In addition, since the contact occurs in the lower part of this circumference (near the soil surface), we can assume at the first approximation that the vectors $\overline{V}_o$ and $\overline{V}_r$ are parallel; and therefore the geometrical sum of these vectors can be replaced by the algebraic sum, that is $V = V_o + V_r$.

The relative velocity $\overline{V}_r$ of the end of the blade AM before the start of the impact contact will be equal by value to $\overline{V}_r = \omega(r + 2l)$, but in the period of the contact it will be equal to $V_r = (\omega - \dot{\varphi})(r + 2l)$, where $r + 2l$ – the distance from the contact point M to the rotation axis O of the driving shaft.

Consequently, in the first case:

$$V = V_o + \omega(r + 2l), \tag{6}$$

but in the second:

$$V = V_o + (\omega - \dot{\varphi})(r + 2l). \tag{7}$$

The gravity force $\overline{G}$ of the blade AM is small in comparison with the impact force $\overline{P}$ at the start of the contact of the blade with the head of the root crop, and small in comparison with the stripping force $\overline{Q}$ of the leaves (leafstalks) remaining on the head of the root crop in the period of contact; and, therefore, in the equation of the balance of the summary power and energy it can be ignored.

Consequently, at the start of the contact we have equation $N = PV$, or $N = P[V_o + \omega(r + 2l)]$, but in the period of the contact itself – equation $N = P[V_o + (\omega - \dot{\varphi})(r + 2l)]$.

Taking into account this equation of balance, equation (5) will have the following form:

$$\frac{dT}{dt} = P\left[V_o + \omega(r + 2l)\right]. \tag{8}$$

By differentiating expression (4) in time t we will obtain:

$$\frac{dT}{dt} = \left[I_c + m(r+l)^2 \right](\omega - \dot{\varphi})\ddot{\varphi}. \tag{9}$$

By equating the right side parts of expressions (8) and (9) we will have:

$$\left[I_c + m(r+l)^2\right](\omega - \dot{\varphi})\ddot{\varphi} = P\left[V_o + \omega(r+2l)\right]. \quad (10)$$

Now, let the force [P] be the allowed impact force for kicking the sugar beet root out of the soil by collision of the flexible blade with the head of the root crop. Replacing in expression (10) the impact force P by the allowed impact force $[P]$, we obtain a differential equation of a turn of the blade around the point A on condition the beet root is not kicked out of the soil at the start of the impact contact, that is, during a very small interval of time t, more exactly, the time of the impact contact. The angular movement of the blade after the impact will be described by the following differential equation:

$$\left[I_c + m(r+l)^2\right](\omega - \dot{\varphi})\,\ddot{\varphi} = Q\left[V_o + (\omega - \dot{\varphi})\,(r+2l)\right] \quad (11)$$

where Q – stripping force of the remaining leaves from the sugar beet head.

Differential equation (10) can be replaced by a difference equation using a theorem about the change of the moment of the quantity of motion of a mechanical system during the collision:

$$I_A\,\omega_1 - I_A\,\omega_o = M_A(S)\,, \quad (12)$$

where I_A – inertia moment of the blade in relation to point A;
ω_o – angular velocity of the blade in relation to point A before the impact;
ω_1 – angular velocity of the blade in relation to point A after the impact;
$M_A(S)$ – moment of impulse of the impact force in relation to point A.

Here the impulse of the impact S will be equal to:

$$S = \int_0^{\tau} P dt \quad (13)$$

but the moment of this impulse of the impact will have such a value:

$$M_A(S) = 2l\int_0^{\tau} P dt \quad (14)$$

where P – force of the impact;
$2l$ – length of the blade;
τ – duration of the impact.

As the blade did not turn in relation to the point A before the impact contact, therefore $\omega_o = 0$.

Then from expressions (12) and (14) at $\omega_o = 0$ we find the angular velocity ω_1 of the blade in its angular movement in relation to the point A after the impact:

$$\omega_1 = \frac{2l\int_0^{\tau} P\,dt}{I_A} \quad (15)$$

If we replace the force P by the force $[P]$, we will obtain:

$$\omega_1 = \frac{2l\int_0^{\tau} [P]\,dt}{I_A} \quad (16)$$

but, considering that $[P]$ = const, we will have:

$$\omega_1 = \frac{2[P]\,l\,\tau}{I_A} \quad (17)$$

where $I_A = I_c + ml^2$.

In such a way the angular velocity ω_1 of the blade is determined in relation to the point *A* after the impact on condition that beet root is not kicked out of the soil. The angular velocity of the blade in the rotational movement in relation to the point *O* after the impact will be equal to $\omega - \omega_1$. We assume in equation (11), at the first approximation, that $\dot{\varphi} = \omega_1$. Such an assumption can be done due to the short duration of the contact of the blade with the root crop head. Then equation (11) will become considerably simpler and will have the appearance:

$$\left[I_c + m(r+l)^2\right](\omega - \omega_1)\,\ddot{\varphi} = Q\left[V_o + (\omega - \omega_1)\,(r+2l)\right] \tag{18}$$

From equation (18) we find the angular acceleration $\ddot{\varphi}$ of the blade which will be equal to:

$$\ddot{\varphi} = \frac{Q\left[V_o + (\omega - \omega_1)\,(r+2l)\right]}{\left[I_c + m(r+l)^2\right](\omega - \omega_1)} \tag{19}$$

After the first integration of expression (19) we obtain:

$$\dot{\varphi} = \frac{Q\left[V_o + (\omega - \omega_1)(r+2l)\right]t}{\left[I_c + m(r+l)^2\right](\omega - \omega_1)} + C_1 \tag{20}$$

After the second integration of expression (19) we obtain the law of the angular post-impact movement of the blade along the head of the sugar beet at which stripping of the remaining leaves from the head takes place:

$$\varphi = \frac{Q\left[V_o + (\omega - \omega_1)\,(r+2l)\right]t^2}{2\left[I_c + m(r+l)^2\right](\omega - \omega_1)} + C_1 t + C_2 \tag{21}$$

The arbitrary constants C_1 and C_2 are found from the following initial conditions: at $t = 0$: $\dot{\varphi} = \omega_1$, $\varphi = 0$. And then we obtain $C_1 = \omega_1$, $C_2 = 0$.

Then expression (21) will assume the following form:

$$\varphi = \frac{Q\left[V_o + (\omega - \omega_1)\,(r+2l)\right]t^2}{2\left[I_c + m(r+l)^2\right](\omega - \omega_1)} + \omega_1 t \tag{22}$$

As pointed out in [13; 14], the cross-section of the uncut remnants of the leafstalks is generally close to a triangular form, having at its base a cavity also of a triangular form (Fig.2). The stripping force *Q* of the remaining leaves from the sugar beet head will be analytically determined in the following way. We will assume that the stripping process of the remnants of the leaves occurs at the exit of the remnants from the head of the root crop, i.e. through the triangular cavity at the expense of the deformation of the immediate shift. Evidently, the stripping process will be possible on this condition:

$$\frac{Q}{nF} \geq [\tau] \tag{23}$$

where Q – stripping force;
$[\tau]$ – allowed tangential stresses of the shift for the uncut remnants of the leafstalks;
F – cross-section area of one leafstalk;
n – number of the leafstalks which are simultaneously stripped from the spherical surface of the root crop head.

Now let us compute the stripping force Q , necessary for stripping of the uncut remnants of the leafstalks from the head of the root crop. From condition (23) we obtain:

$$Q \geq nF[\tau] \tag{24}$$

As evident from Figure 2, the cross-section area of the uncut remnants of the sugar beet leafstalks will be equal to:

$$F = ah - a_o h_o \tag{25}$$

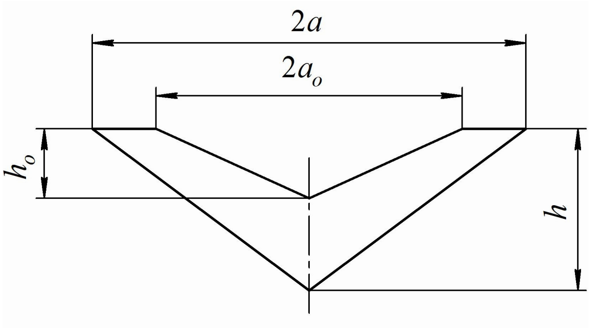

Fig. 2. **Scheme of the cross-section of the contact place of the leaves with the root crop**

Taking into account expressions (24) and (25), we find the stripping force Q:

$$Q \geq \left(ah - a_o h_o\right) n \left[\tau\right] \tag{26}$$

Substitution of real values into formula (25) indicates that Q = 120 N.

Considering the duration of the contact time t_1 of the blade with the root crop head, it is possible to find the turning angle φ_1 of the blade around the point A during the contact time:

$$\varphi_1 = \frac{Q\left[V_o + (\omega - \omega_1)(r + 2l)\right] t_1^2}{2\left[I_c + m(r + l)^2\right](\omega - \omega_1)} + \omega_1 t_1 \tag{27}$$

From expression (27) we can determine the angular velocity ω of turning of the blade around the point O, taking into consideration the circumstance that the root crop is not kicked out of the soil during the stripping process of the remaining leafstalks from the head of the root crop:

$$\omega = \frac{Q V_o t_1^2}{2\left[I_c + m(r + l)^2\right](\varphi_1 - \omega_1 t_1) - Q(r + 2l) t_1^2} + \omega_1 \tag{28}$$

In the same way it is also possible to compute the other parameters of the flexible cleaning blade, for example, the mass m of the blade or its length $2l$. The inertia moment I_c of the blade, which enters the analytical expressions obtained by us, in relation to the axis through the centre of masses of the blade (point C), parallel to the axis of rotation of the shaft (point O), depends on the shape of the cross-section of the blade itself. For a blade of a rectangular parallelepiped shape with the sides $2a \times 2b \times 2l$ the inertia moment I_c will be equal to [9]:

$$I_c = \frac{m}{3}\left(a^2 + l^2\right) \tag{29}$$

where $2a$ – width of the blade;
$2l$ – length of the blade.

If the cleaning blade has the shape of a right circular cylinder, then its inertia moment I_c will be equal to [9]:

$$I_c = \frac{m}{4}\left(\frac{4l^2}{3} + r_1^2\right) \tag{30}$$

where r_1 – radius of the cross-section of the blade;
$2l$ – length of the blade.

Consequently, as a result of the conducted theoretical investigation, final analytical expressions have been obtained providing a possibility to determine directly the design and kinematic parameters of a flexible cleaning blade, which ensure efficient stripping of the remaining leafstalks from the heads of the beet roots.

Conclusions

As a result of the conducted theoretical investigation analytical expressions are obtained in order to determine the design and kinematic parameters of a flexible cleaning blade, which ensure efficient stripping of the remaining leafstalks from the heads of the sugar beet roots, as well as to determine the forces of stripping.

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