МЕХАНИКА
MECHANICS

DOI 10.31489/2019M4/81-89

UDC 621.867.4

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Mathematical model of a root harvester after-cleaning system

A mathematical model of root crops after-cleaning and their movement pattern in a technological run for loading into means of transportation has been presented. The impact of both controlled and uncontrolled factors on the efficient continuous transportation of root crops has been determined on the basis of the above-mentioned model. The use of the suggested mathematical model will enable to narrow the search of the most efficient design, kinematic and dynamic parameters in conducting some experimental research on efficient operation of after-cleaning systems of harvesters with their possible adjustment according to the natural and climatic conditions of harvesting.

Keywords: mathematical model of root crops after-cleaning, root crops movement pattern, transporting-separating system, design, kinematic and dynamic parameters of tools.

Introduction

To provide the quality performance of root crops harvesters, especially concerning sugar beets root crops cleaning of soil and plants remains one needs some complex approach combining both theoretical and practical investigation.

Quality mathematical modeling of some processes of root crops after-cleaning resulted in the recommended limits of design and kinematic parameters will enable to reduce the number of experiments significantly. In this way we will save some time and costs to achieve the target goal.

Auger mechanisms in layout schemes of root crops harvesters are widely used. Theory of root crops movements and other similar products have been described in numerous scientific articles. The problems dealing with this subject are highlighted namely in the papers [1–5].

Minimal damage of the harvested crops during their simultaneous transportation and cleaning is also paid a great attention to in the investigation. These issues have been presented in the papers [6–9].

Some dynamic models of agricultural products transportation providing the quality of technological process performance by necessary tools and their reliable operation have been described in the articles [10–14].

Moreover, minimum power consumption is also important in materials transportation and other technological operations and this problem was discussed in the papers [15, 16].

The investigation results dealing with the sugar beets root crops after-cleaning by augers are given in the articles [17–19].

The made analysis of the known research has proved that the problem of root crops quality cleaning in machine harvesting has not been solved completely.

The purpose of the theoretical research is to find the most effective design, kinematic and dynamic parameters of the auger taking the root crops aside to provide the quality cleaning of root crops.

Material and method

Let's consider the process of an auger-root crop interaction whilst its transportation (Fig. 1). As we have seen in the paper [20], the case when the assumed central axis of a root crop is perpendicular to the belt motion direction is the most unfavorable in terms of sugar beets passing through the clearance between the belt surface 1 and auger rotation surface 2.

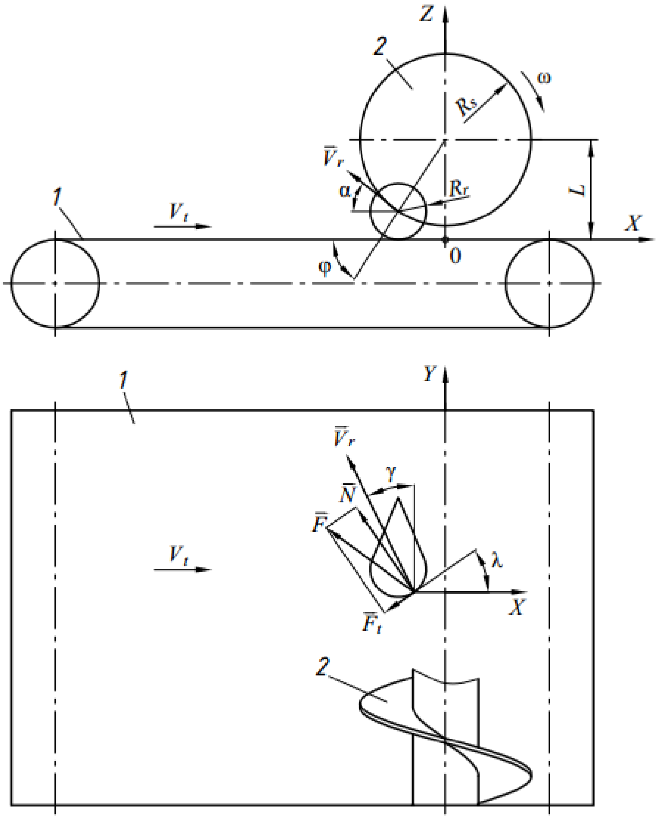

Figure 1. Auger (taking root crops aside)-root crop interaction pattern

In case when a root crop, in plane projection OXZ, is overlapped with the auger rotational surface less than the crown radius value, it will be thrown back with some turning and will be a little risen over the belt surface. It can be explained by the fact, that during the interaction the root crop is acted by the moment whose regularized force will be passing through the beet's center and the arm will be close to the beet crown radius located on the belt surface.

A case when root crop overlapping with the auger rotational surface is more than the crown radius value is scarcely probable for big and medium root crops as the most efficient structural and kinematic parameters of augers are chosen for relatively small, standard root crops (crown diameter is 40 mm).

Thus, when doing some calculations, we'll accept an option when normal reaction force of the auger to the root crop will be passing through the central axis of the latter, and the contact will take place with the beet crown.

So, while doing some calculations, we'll make the following assumptions: a beet crown is of perfect semi-sphere shape; longitudinal and lateral oscillations of the belt are neglected, its surface is considered to be perfectly smooth; screw pitch and height, angle of ascent of auger screw line are the same along the whole length; transporting conveyor linear velocity and angular velocity of auger rotation are constant.

We assume that a rot crop is travelling in horizontal plane on the transporting conveyor surface with the velocity V_t, and the auger, which is perpendicular to the motion direction, is rotating with angular velocity ω and is throwing the root beet aside and back. The root crop and auger contact is taking place when the center of imaginary sphere circling the root crop coincides with the auger edge.

Angle of ascent of screw surface on the given radius in the place of contact

$$\lambda = \operatorname{arctg}\left(\frac{T}{2\pi R}\right),$$

where T — auger pitch; R — radius of imaginary circle in auger-root crop contact point ($R \le R_s$); R_s — auger radius.

The angle between the horizontal line and the line connecting the centers of projections of the root crop sphere and the auger axis is found by

$$\varphi = \arcsin\left(\frac{L - R_r\,(1 - \sin\lambda)}{R}\right),$$

where L — height of auger axis location over the transporting conveyor; R_r — a root crop radius.

Reaction N and friction force $F_{fr} = Nf$ are acting on a root crop from the auger's side, which are directed, respectively, flatwise to the screw surface and at a tangent to it towards screw rotation direction (f — friction coefficient).

Velocity V_r of a root crop takeoff consists of two parts — velocity V_1, which is equal to the projection of linear velocity of the auger contact point on the direction of vectors sum of forces, and velocity V_2 of the root crop thrown back of the surface of stationary by convention auger due to initial velocity of transportation V_t taking into account throwback coefficient K_V.

Vector $\vec{V}_1' = \begin{pmatrix} X_1 \\ Y_1 \\ Z_1 \end{pmatrix}$ is found by the direction of the auger resultant of resistant force

$$\vec{F} = \vec{N} + \vec{F}_{fr} = \begin{pmatrix} X_F \\ Y_F \\ Z_F \end{pmatrix}.$$

To find the vectors direction we use rotation matrixes about axis X and Y, respectively, on angles λ and φ

$$M_\lambda = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\lambda & -\sin\lambda \\ 0 & \sin\lambda & \cos\lambda \end{pmatrix};$$

$$M_\varphi = \begin{pmatrix} \cos\varphi & 0 & -\sin\varphi \\ 0 & 1 & 0 \\ \sin\varphi & 0 & \cos\varphi \end{pmatrix}.$$

Then the correspondent vectors are found by rotation matrixes.

Vector of the auger resultant of resistant force is equal to

$$\vec{F} = M_\varphi M_\lambda \begin{pmatrix} 0 \\ N \\ Nf \end{pmatrix}.$$

Velocity vector of auger-root crop contact point

$$\vec{V}_s = \begin{pmatrix} X_s \\ Y_s \\ Z_s \end{pmatrix} = M_\varphi \begin{pmatrix} 0 \\ 0 \\ \omega R \end{pmatrix}.$$

Modulus of throwing velocity

$$V_1' = V_s \cos\beta,$$

where β — angle between vectors $\vec{V}_1'$ and $\vec{V}_s$, which is equal to the angle between vectors $\vec{F}$ and $\vec{V}_s$, which is found from the known condition of angle cosine between two vectors

$$\cos\beta = \frac{X_F X_s + Y_F Y_s + Z_F Z_s}{\sqrt{X_F^2 + Y_F^2 + Z_F^2}\sqrt{X_s^2 + Y_s^2 + Z_s^2}}.$$

To find takeoff velocity vector $\vec{V}_1$ we find directing vector of force $\vec{F}$ of unit length

$$\vec{\mu} = \frac{\vec{F}}{N\sqrt{1+f^2}},$$

where vector modulus $\vec{F}$ is written in the denominator.

Then the vector value of takeoff speed $\vec{V}_1$ is found as a product of unit directing vector $\vec{\mu}$ and modulus of velocity value of contact point of auger and a root crop in its projection on this vector axis

$$\vec{V}_1 = \begin{pmatrix} X_1 \\ Y_1 \\ Z_1 \end{pmatrix} = \vec{\mu}\omega R_s \cos\beta = \frac{\vec{F}\omega R_s \cos\beta}{N\sqrt{1+f^2}} = \frac{\omega R_s \cos\beta}{N\sqrt{1+f^2}} M_\varphi M_\lambda \begin{pmatrix} 0 \\ N \\ Nf \end{pmatrix}.$$

A root crop velocity due to «mirror» reflection of the auger surface $\vec{V}_2 = \begin{pmatrix} X_2 \\ Y_2 \\ Z_2 \end{pmatrix}$ is determined from the condition of equality of angles of descent and reflection and the coplanarity condition of these vectors with normal vector to the auger surface in the place of contact.

The coplanarity condition of the above-mentioned vectors are determined by their mixed product equality to zero (correspondent determinant)

$$\begin{vmatrix} X_2 & Y_2 & Z_2 \\ X_N & Y_N & Z_N \\ V_t & 0 & 0 \end{vmatrix} = 0,$$

where normal vector to the auger surface in the contact point is found by the dependence

$$\begin{pmatrix} X_N \\ Y_N \\ Z_N \end{pmatrix} = M_\varphi M_\lambda \begin{pmatrix} 0 \\ N \\ 0 \end{pmatrix}.$$

The condition of equality of angles of descent and reflection after some necessary transformations is written in the following way

$$\frac{X_2 X_N + Y_2 Y_N + Z_2 Z_N}{\sqrt{X_2^2 + Y_2^2 + Z_2^2}} = -X_N.$$

Being thrown back of the auger surface taking into account the reflection coefficient the modulus of velocity $\vec{V}_2$ is taking the following value

$$V_2 = K_V V_t = \sqrt{X_2^2 + Y_2^2 + Z_2^2}.$$

Sum velocity of root crop takeoff is found as vector sum of two velocities

$$\vec{V}_r = \begin{pmatrix} X_r \\ Y_r \\ Z_r \end{pmatrix} = \vec{V}_1 + \vec{V}_2 = \begin{pmatrix} X_1 + X_2 \\ Y_1 + Y_2 \\ Z_1 + Z_2 \end{pmatrix}.$$

On the basis of velocity vector $\vec{V}_r$ we calculate vertical α and horizontal γ angles of takeoff and projected throw path length S_L of a root crop

$$\alpha = arctg\left(\frac{Z_r}{\sqrt{X_r^2 + Y_r^2}}\right);$$

$$\gamma = arctg\left(\frac{X_r}{Y_r}\right);$$

$$S_L = \frac{V_r^2 \sin 2\alpha}{g} = \frac{\left(X_r^2 + Y_r^2 + Z_r^2\right)\sin 2\alpha}{g}.$$

A program of calculating velocities, takeoff angles and throw path length for different kinematic and geometrical parameters of the system under consideration has been developed using the above-mentioned formulae to analyze and improve the transport auger design.

Results

Figures 2, 3, 4, 5 show the correspondent calculating curves of dependencies of vertical and horizontal angles α and γ of the root crop takeoff, root crop takeoff velocities V_r and range of throw S_L on the change of basic design and physical parameters of transporting-separating system, namely: auger pitch T, angular velocity of its rotation ω, radius R_s of the auger peripheral surface, linear velocity of the root crop transportation till its contact with the auger rib V_t, friction coefficient of a root crop on the auger surface f, beet crown radius R_r and the coefficient of its throwback of the auger edge K_V.

Analysis of curves shown on Figure 2 proves that radius value R_s of peripheral surface of the auger taking root crops aside and its pitch T are controlled dominant factors which influence the vertical angle α of the root crop takeoff.

Other controlled factors, namely angular velocity of rotation of the auger taking root crops aside ω and linear velocity V_t of the root crop transportation till the moment of its contact with the auger do not make substantial impact on the vertical angle α of the root crop throw by the auger taking root crops aside.

Here it should be noticed that uncontrolled factors, namely the beet crown radius R_r and friction coefficient of a root crop on the auger surface f make substantial impact on vertical angle α of the root crop throw by the auger taking root crops aside, their value increase results in increased value of angle α.

The coefficient of root crop throw away of the auger rib K_V does not make great impact on the vertical angle α.

Analyzing the curves shown on Figure 3, we can state that the dominant controlled factors making impact on horizontal angle γ of a root crop takeoff are the auger pitch T and linear velocity of horizontal transport conveyor V_t. Increased value T results in decreased value of angle γ. Conversely, increased linear velocity of the root crop transportation V_t causes the increased value of angle γ.

Negative sign at angle γ means that a root crop is thrown away in opposite to the axis OX direction.

Compared to the previous factors, which in fact are characterized by linear dependencies of influence on angle γ, the angular velocity of rotation of the auger taking root crops aside ω, while speeding up from 10 to 25 rad/s, results in sharp increase of angle γ absolute value but its further influence on the angle γ can be neglected. Increased value of peripheral surface radius of auger taking root crops aside R_s leads to a small increase of angle γ modulus.

As for the uncontrollable factors, it should be said that high soil humidity and as a result lower value of friction coefficient f makes a great impact on angle γ modulus increase. At the same time, the increased radius of beet crown R_r and the coefficient of its beating off the auger edge K_V on the contrary results in decreased modulus of angle γ.

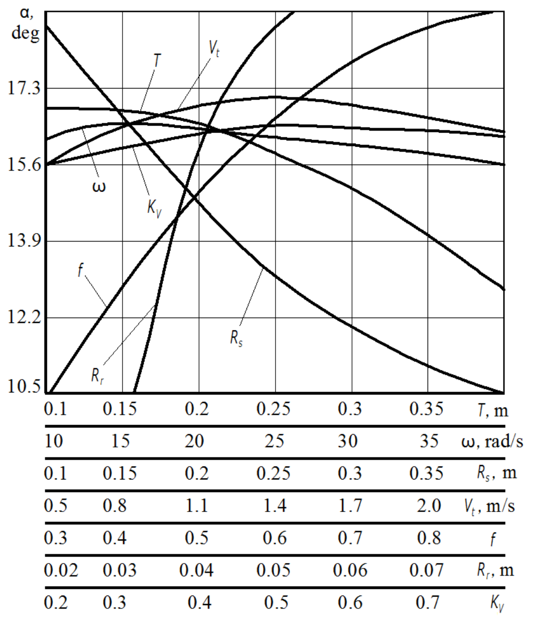

Figure 2. Dependencies of vertical angle α of root crop takeoff on parameters T, ω, R_s,V_t, f, R_r and K_V

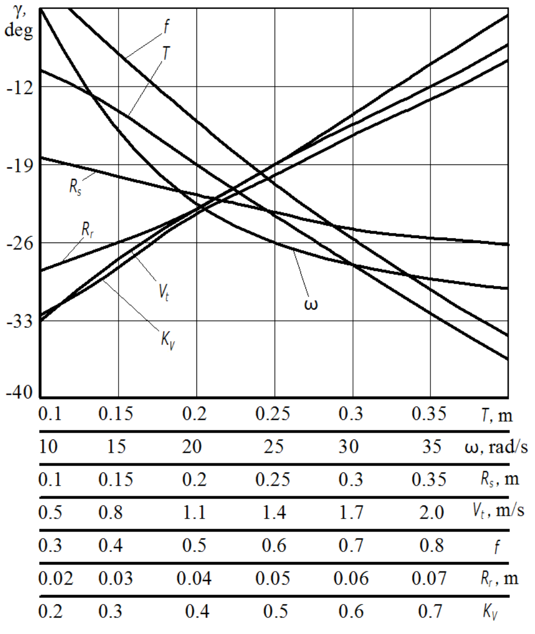

Figure 3. Dependencies of horizontal angle γ of root crop takeoff on parameters T, ω, R_s, V_t, f, R_r and K_V

The analysis of curves (Fig. 4) describing the impact of different factors on the root crop takeoff speed V_r has proved that only increase of radius value of peripheral surface of the auger taking root crops aside R_s and angular velocity ω of its rotation cause the increase of value V_r, while other factors do not make a substantial impact on value V_r change.

Similar to the previous case, only angular velocity ω of rotation of the auger taking root crops aside (considerable impact) and its peripheral surface radius R_s have a significant influence on root crop range of throw S_L (Fig. 5).

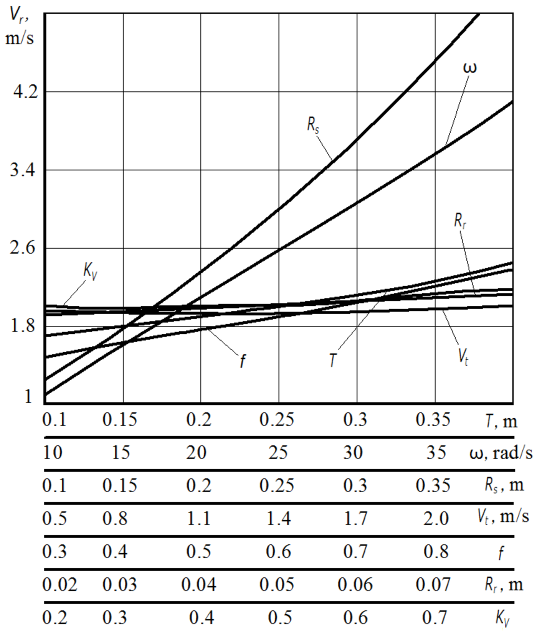

Figure 4. Dependencies of a root crop takeoff speed V_r on parameters T, ω, R_s, V_t, f, R_r and K_V

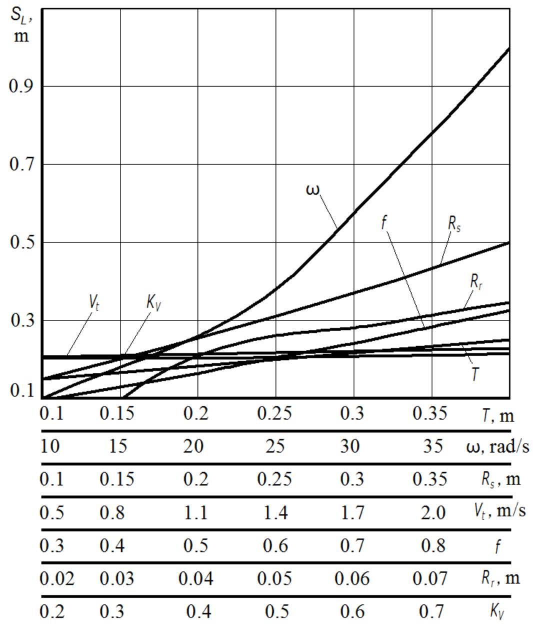

Figure 5. Dependencies of a root crop range of throw S_L on parameters T, ω, R_s, V_t, f, R_r and K_V

Conclusions

On the basis of results analysis of conducted theoretical investigation on root crops movement behavior after their contact with the auger taking root crops aside it has been found out that increased auger pitch from 0.1 to 0.4 m causes decreased angle α (from 17° to 12°) and increased angle γ (from -10° to -37°). At the same time within the given range of auger pitch increase T both the velocity of root crop takeoff V_r and, therefore, the range of its throw S_L is getting increased. Root crops range of throw must be within the limits $0.2\ldots0.6\ m$. At $S_L < 0.2\ m$ root crops separation is not efficient due to little shaking effect after their interaction with the belt. New contacts with the auger are also getting more possible which cause additional damage of the root crops. At $S_L > 0.6\ m$ the root crops will be thrown towards shields and frames structures of the machine hopper, and this also results in their bigger damage. Thus, auger pitch T can't be smaller than 0.15 m.

The bigger the friction coefficient f is, the bigger the range of throw of a root crop is. Though the maximum values $f = 0.8\ldots0.9$ (use of special friction materials for an auger spiral rib making) do not cause the S_L increase for more than 0.5 m.

A beet crown radius R_r increase has caused its range of throw S_L increase, though small root crops ($R_r = 0.02\ldots0.03\ m$) will be thrown not far from (up to 0.15 m).

Coefficient of throwback K_V change can be neglected regarding the range of throw of root crops ($S_L = 0.2\ldots0.215\ m$).

Thus, the variable parameters are recommended to be chosen within certain boundaries: $T = 0.2\ldots0.3\ m$; $\omega = 18\ldots30\ rad/s$;$R_s = 0.15\ldots0.25\ m$;$V_t = 1.2\ldots1.3\ m/s$.

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Түбірлік өсімдіктерді жинау машинасының тазалау жүйесінің математикалық моделі

Мақалада түбірлік дақылдарды тазарту үрдісінің математикалық моделі және олардың қозғалысын көлік құралдарына түсірудің технологиялық табиғаты ұсынылған. Осы модельдің негізінде, бақыланатын және бақыланбайтын факторлардың түбірлік дақылдардың үздіксіз қозғалысын сапалы қамтамасыз етуге әсері анықталды. Ұсынылған математикалық модельді пайдалану түбір жинау машиналары үшін тазарту жүйелерінің тиімді жұмыс істеуіне, жинаудың климаттық жағдайларына сәйкес оларды реттеу мүмкіндігімен, эксперименттік зерттеулер жүргізген кезде қажетті оңтайлы дизайн, кинематикалық және динамикалық параметрлердің өрісін қысқартуға мүмкіндік береді.

Кілт сөздер: түбірлік дақылдарды кейіннен емдеу процесінің математикалық моделі, түбірлік дақылдардың қозғалысы, көлік және бөлу жүйесі, жұмыс органдарының конструктивті, кинематикалық және динамикалық параметрлері.

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Математическая модель системы доочистки корнеуборочной машины

Представлена математическая модель процесса доочистки корнеплодов и характера их движения в технологическое русло для выгрузки в транспортные средства. На основе данной модели было установлено влияние как управляемых, так и неуправляемых факторов на качественное обеспечение непрерывного перемещения корнеплодов. Использование предложенной математической модели позволит сузить поле искомых оптимальных конструктивных, кинематических и динамических параметров при проведении экспериментальных исследований для эффективной работы систем доочистки корнеуборочных машин с возможностью их регулирования в соответствии с природно-климатическими условиями уборки.

Ключевые слова: математическая модель процесса доочистки корнеплодов, характер движения корнеплодов, транспортно-сепарирующая система, конструктивные, кинематические и динамические параметры рабочих органов.

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