

Justification of parameters of vehicles with elastic partitions for transporting potatoes

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Abstract. Elastic partitions have been developed to be installed in the body of a vehicle and allowing to reduce damage to tubers when unloading by reducing the speed and, accordingly, the interaction of potatoes with the working surfaces of the machine and neighboring tubers. A mathematical model of a device for transporting and unloading root crops has been developed, taking into account the physical properties of root crops, the physical and geometric characteristics of the container and elastic partitions, as well as the parameters of the unloading process. As a result of comparative field tests of a serial MAZ 5516 truck body and an experimental MAZ 5516 truck body with installed transverse partitions, it was found that the use of the developed elastic transverse partitions reduces damage to potato tubers from 5.3% to 2.9%.

1 Introduction

Machine technologies for the production of potatoes are a promising direction of development in the world agro-industrial complex [1, 2, 3, 4]. However, when harvesting and subsequent transportation, potato tubers constantly experience dynamic influences and, as a result, are damaged [5, 6, 7]. Elastic partitions have been developed, installed in the body of a vehicle and allowed to reduce damage to tubers when unloading by reducing the speed and, accordingly, the interaction of potatoes with the working surfaces of the machine and neighboring tubers. In order to optimize the main parameters of the developed device, it is necessary to make a theoretical justification and experimentally confirm the need for its application.

2 Materials and methods

Within the framework of the particle dynamics method, it will be assumed that the mass of root crops consists of many spherical elements with a diameter of 0.04-0.15 m. When the elements contact each other, with flexible elastic partitions and with the working surfaces of the container, elastic forces arise, as well as forces of dry and viscous friction (Fig. 1). Under the action of forces, the movement of elements is calculated according to the laws of classical dynamics. It is necessary to reproduce in the model the change in the state of the

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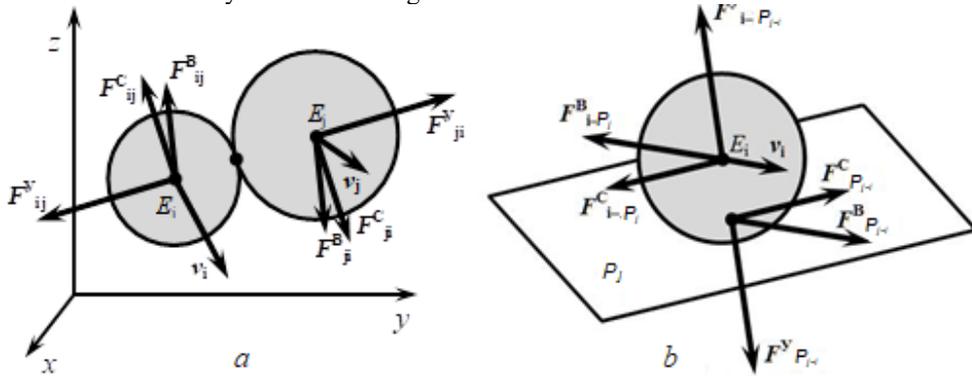
system of elements (the process of unloading or transportation) and to determine the damageability and rolling of elements.

Modeling is done in 3D Cartesian space (x, y, z) . The state of each element E_i is specified by six variables: coordinates of its center (x_i, y_i, z_i) and velocity components (v_{xi}, v_{yi}, v_{zi}) .

The elastic force acts as a force of normal reaction between elements of root and tuber crops, leading to their repulsion, if they come into contact in a case if the distance between the elements r_{ij} is less than $(d_i + d_j)/2$. Distance r_{ij} between the centers of the elements is calculated through the coordinates of the centers according to the Pythagorean theorem [1, 4]:

$$r_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}. \tag{1}$$

The solution to this system of second-order differential equations is functions $x_i(t), y_i(t), z_i(t)$, which determine the trajectories of movement of root and tuber crops and allow to evaluate the efficiency of the unloading.



FY are elastic forces, FC and FB are forces of dry and viscous friction, vector values are indicated in bold

Fig. 1. Forces arising from the contact of two root crops (a) and between the root crop and the surface of the container (b)

Description of elastic partitions.

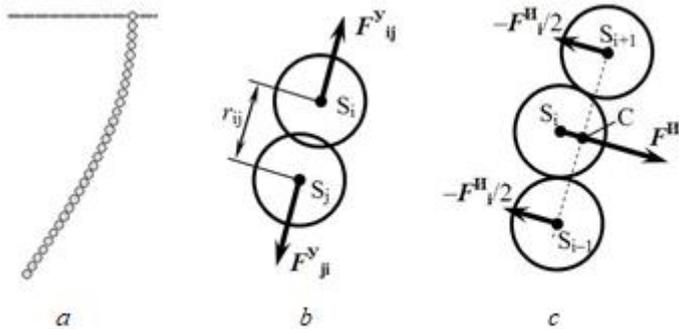
The elastic partitions in the basic version of the model are arranged in two rows of 33 tubes. The rows are located at distances of 1/3 and 2/3 of container length L_k . Each elastic tube consists of 38 spherical elements with a diameter of 0.04 m (Fig. 2, a). The initial location of the centers of elements of elastic tubes $x_{ijk}, y_{ijk}, z_{ijk}$ is given by the following formulas.

$$\begin{cases} x_{ijk} = x_c - \frac{1}{2} L_k + \frac{k}{3} L_k; \\ y_{ijk} = y_c - \frac{1}{2} B_k + \frac{j}{24} B_k; \\ z_{ijk} = z_c + H_k - i \cdot d_{ep}, \end{cases} \tag{2}$$

where i is the number of the element in the elastic partition; j is the number of the elastic partition in the row; k is the number of a row; x_c, y_c, z_c are coordinates of the geometric center of the bottom of the container; L_k, B_k, H_k are the length, width and height of the container; d_{ep} is the diameter of the spherical element of the elastic partition.

Elements of elastic partitions interact with each other by two types of elastic forces (center-to-center and bending) and linear viscous forces. In a pair of neighboring elements,

elastic forces of repulsion or attraction act depending on the introduction of elements into each other or stretching from the equilibrium position and they are proportional to the value of penetration (Fig. 2, b). For the case of stretching, the penetration value is assumed to be negative. The described elastic forces between the centers of the elements ensure the constancy of the length of the elastic partition, but not the constancy of its shape. For realistic damping of vibrations in an elastic system, linear-viscous forces have been added between neighboring elements: friction forces proportional to the relative speed of movement of the centers of neighboring elements.



a - in the form of a set of spherical elements; schemes for calculating elastic forces when partition elements interact: *b* - repulsive forces when the elements are pressed into each other; *c* - restoring forces when bending an elastic partition

Fig. 2. Representation of a flexible elastic partition in the model

In order for the elastic partition to retain its shape close to rectilinear, elastic forces are added (Fig. 2, c). Elastic forces are calculated in triplets of elements: when the second element is displaced relative to a straight line drawn between the centers of the first and third elements, an elastic force appears that tends to return the second element to a straight line and is proportional to the amount of displacement from the axis. The aspect ratio is the bending stiffness and it defines the resistance of the elastic partition to bending.

Representation of a device for transporting and unloading potato tubers in the model.

The working surfaces of the container are represented in the model by five rectangles: a base, two end walls, a sidewall, and a tailgate (Fig. 3). To unify the model, each rectangle is considered to be composed of two triangles. This is done both to simplify the application of analytical geometry methods, and to make it possible, with further refinement of the model, to reproduce the surface of an arbitrary shape of both a container and other objects.

The container is specified by ten base points $A_1 - A_{10}$ (Fig. 3). Base points form 10 elementary triangular surfaces: $T_1(A_1A_2A_4)$, $T_2(A_2A_3A_4)$, $T_3(A_1A_2A_6)$, $T_4(A_1A_5A_6)$, $T_5(A_3A_4A_7)$, $T_6(A_4A_8A_7)$, $T_7(A_2A_3A_7)$, $T_8(A_2A_6A_7)$, $T_9(A_5A_8A_9)$, $T_{10}(A_8A_9A_{10})$.

The angular position of the tailgate plane $A_5A_8A_{10}A_9$ relative to the initial position $A_1A_5A_8A_4$ is set by angle φ_c . The inclination of the entire container relative to the initial position is set by angle φ_k .

At the beginning of the computer experiment, the container was oriented horizontally ($\varphi_k = 0$) and the tailgate was closed ($\varphi_c = 0$). The initial coordinates of base points $A_1 - A_{10}$ of the container were set as follows:

$$\begin{aligned} x_{A1} &= x_{c0} - L_k/2; y_{A1} = y_{c0} - B_k/2; z_{A1} = z_{c0}; \\ x_{A2} &= x_{c0} + L_k/2; y_{A2} = y_{c0} - B_k/2; z_{A2} = z_{c0}; \\ x_{A3} &= x_{c0} + L_k/2; y_{A3} = y_{c0} + B_k/2; z_{A3} = z_{c0}; \\ x_{A4} &= x_{c0} - L_k/2; y_{A4} = y_{c0} + B_k/2; z_{A4} = z_{c0}; \\ x_{A5} &= x_{c0} - L_k/2; y_{A5} = y_{c0} - B_k/2; z_{A5} = z_{c0} + H_k; \end{aligned} \quad (3)$$

$$\begin{aligned}
 x_{A6} &= x_{c0} + L_k/2; y_{A6} = y_{c0} - B_k/2; z_{A6} = z_{c0} + H_k; \\
 x_{A7} &= x_{c0} + L_k/2; y_{A7} = y_{c0} + B_k/2; z_{A7} = z_{c0} + H_k; \\
 x_{A8} &= x_{c0} - L_k/2; y_{A8} = y_{c0} + B_k/2; z_{A8} = z_{c0} + H_i; \\
 x_{A9} &= x_{A1}; y_{A9} = y_{A1}; z_{A9} = z_{A1}; \\
 x_{A10} &= x_{A4}; y_{A10} = y_{A4}; z_{A10} = z_{A4},
 \end{aligned}$$

where x_{c0} , y_{c0} , z_{c0} stand for the position of the center of the container base at the initial time.

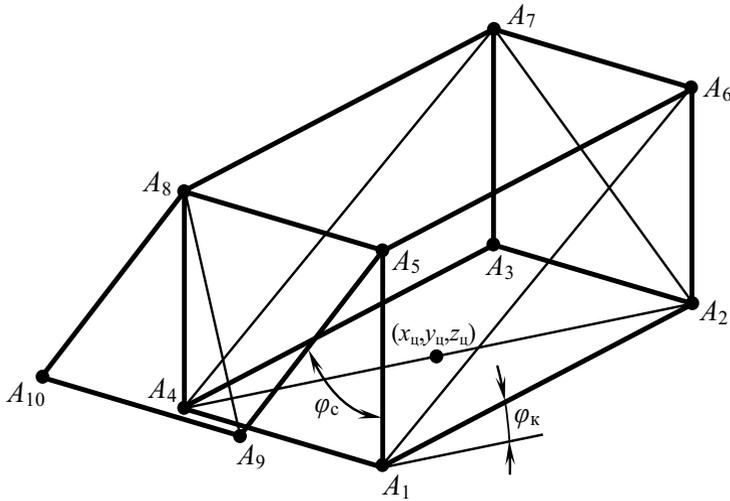


Fig. 3. Representation of the working surfaces of the container as a set of elementary triangular surfaces, edges and corner points

In the process of a computer experiment on unloading, the tailgate is first tilted (angle φ_c increases uniformly), then the container itself is tilted (angle φ_k increases uniformly). Analytically, the change in angles is described as follows:

$$\varphi_t = \begin{cases} 0, t < t_1; \\ \varphi_{tm} \frac{t-t_1}{t_2-t_1}, t_1 \leq t \leq t_2; \\ \varphi_{tm}, t > t_2; \end{cases} \quad (4)$$

$$\varphi_c = \begin{cases} 0, t < t_3; \\ \varphi_{cm} \frac{t-t_3}{t_4-t_3}, t_3 \leq t \leq t_4; \\ \varphi_{cm}, t > t_4, \end{cases} \quad (5)$$

where t_1 and t_2 are the moments of time of the beginning and the end of folding the tailgate; t_3 and t_4 are the moments of start and end of container tilt; φ_{tm} and φ_{cm} are the maximum angles of the tailgate and the container tilts.

Changing angles φ_c and φ_k leads to the need to recalculate the coordinates of the base points $A_2, A_3, A_5 \dots A_{10}$ at each time integration step, while points A_1 and A_4 remain motionless throughout the entire time of the computer experiment.

To tilt points $A_2, A_3, A_5 \dots A_{10}$ of the container relative to A_1A_4 axis, the following rotation transformation is performed:

$$\left\{ \begin{array}{l} r = \sqrt{(x_i - x_{A1})^2 + (z_i - z_{A1})^2}; \\ \varphi = \begin{cases} \arctg \frac{z_i - z_{A1}}{x_i - x_{A1}}, & x_i - x_{A1} \geq 0; \\ \arctg \frac{z_i - z_{A1}}{x_i - x_{A1}} + 180^\circ, & x_i - x_{A1} < 0; \end{cases} \\ x_i = x_{A1} + r \cos(\varphi + \varphi_\kappa); \\ y_i = y_i; \\ z_i = z_{A1} + r \sin(\varphi + \varphi_\kappa), \end{array} \right. \quad (6)$$

where r and φ are polar coordinates of the base points in the coordinate system associated with the tilt axis of the container A_1A_4 ; x_i, y_i, z_i are coordinates of base point i ($i = A_2, A_3, A_5 \dots A_{10}$).

The turn of the tailgate (the placement of points A_9 and A_{10}) is performed by converting the rotation about axis A_5A_8 :

$$\left\{ \begin{array}{l} r = \sqrt{(x_i - x_{A5})^2 + (z_i - z_{A5})^2}; \\ \varphi = \begin{cases} \arctg \frac{z_i - z_{A5}}{x_i - x_{A5}}, & x_i - x_{A5} \geq 0; \\ \arctg \frac{z_i - z_{A5}}{x_i - x_{A5}} + 180^\circ, & x_i - x_{A5} < 0; \end{cases} \\ x_i = x_{A5} + r \cos(\varphi - \varphi_c + \varphi_\kappa); \\ y_i = y_i; \\ z_i = z_{A5} + r \sin(\varphi - \varphi_c + \varphi_\kappa), \end{array} \right. \quad (7)$$

where r and φ are polar coordinates of base points in the coordinate system associated with the axis of rotation of the tailgate A_5A_8 ; x_i, y_i, z_i are coordinates of base point i ($i = A_9$ or $i = A_{10}$).

Calculation of performance indicators.

The developed model makes it possible to determine the main indicators characterizing the productivity and quality of the unloading process. Of the many possible performance indicators, three were selected that most informatively and comprehensively characterize the unloading process: the time of unloading, the average rolling distance of root crops and the share of damaged root crops.

Unloading time t_u is calculated as the time from moment t_1 of the beginning of folding the tailgate up to moment t_n , when the last root crop leaves the container. Determining moment t_n is carried out according to the function of the dependence of the number of roots and tubers remaining in the container on time $N_o(t)$:

$$N_o(t) = \sum_{i=1}^{N_2} \begin{cases} 1, & z_i(t) \geq z_{A1}; \\ 0, & z_i(t) < z_{A1}; \end{cases} \quad (8)$$

$$t_u = t_n - t_1 = t|_{N_o(t)=0} - t_1. \quad (9)$$

Average rolling distance L_r is defined as the displacement of the center of gravity of the root and tuber system relative to discharge edge A_1A_4 :

$$L_r = x_{A1} - \frac{1}{N_n} \sum_{i=1}^{N_n} x_i(t_n). \quad (10)$$

To calculate the share of damaged root crops n_n in the process of a computer experiment on unloading for each root crop, the function of pressure on time $P_i(t)$ is recorded. The

pressure estimate is the sum of forces acting on the root crop from other root crops, container surfaces and elements of elastic partitions, divided by the surface area of the spherical element.

$$P_i = \frac{\sum_{j=1}^{N_{\varnothing}} |\vec{F}_{ij}| + \sum_{j=1}^{N_{\Pi}} |\vec{F}_{i-\Pi j}| + \sum_{j=1}^{N_{\varnothing \Pi}} |\vec{F}_{i-\varnothing \Pi j}|}{\pi d_i / 2}. \quad (11)$$

A root crop is considered damaged if at some point in time t function $P_i(t)$ exceeds limiting value of pressure P_n . Then the proportion of damaged root and tuber crops is determined by the formula of the spherical element:

$$n_{\pi} = \frac{\sum_{i=1}^{N_E} \begin{cases} 1, \max P_i(t) \geq P_n \\ 0, \max P_i(t) < P_n \end{cases}}{N_E}. \quad (12)$$

Algorithmic basis of the model.

The developed model is inherently not analytical, but algorithmic: since performance indicators cannot be calculated explicitly using formulas, they are calculated using an iterative algorithm.

Thus, a mathematical model of a device for transporting and unloading root crops was developed, taking into consideration the physical properties of root crops, physical and geometric characteristics of the container and elastic partitions, as well as parameters of the unloading process. The model allows to evaluate the effect of equipping the container with rows of elastic partitions and determine their optimal parameters.

3 Results and discussion

Further theoretical research is based on repeated computer experiments on unloading root crops from the proposed device.

At the beginning of the computer experiment, it was necessary to place root and tuber crops in the body of a vehicle similarly to the actual placement. For this, at the moment of model time $t = 0$ s, a given number of root and tuber crops was distributed evenly over the volume of the container (Figure 4, a). Within 0.7 s, root-tubers settled under the action of gravity and formed a random dense packing in the lower part of the vehicle body (Figure 4, b).

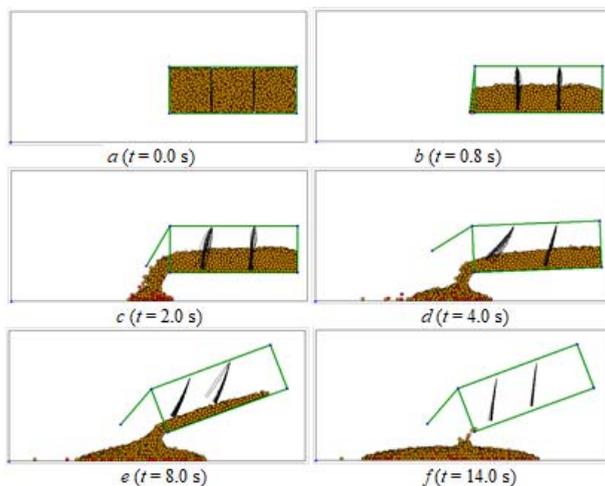


Fig. 4. Changes in the system of root and tuber crops in a computer experiment on unloading root crops from the body of a vehicle.

In the time interval 0.7-3.5 s, the tailgate was turned around the axis with a constant angular velocity (Figure 4, c). Root crops located between the tailgate and the first row of elastic partitions began to spill out of the vehicle body.

At the moment of time 3.0 s, the inclination of the entire vehicle body began, which continued at a constant angular velocity until the moment of time 8.0 s (Figure 4). After the first third of the vehicle body had been freed from the root tubers, the elastic partitions of the first row were lifted and passed the mass of root tubers located between the first and second rows of elastic partitions. After releasing the second third of the vehicle body, the elastic partitions of the second row were lifted and the unloading of the remaining third of the root crops began. It should be noted that the developed device with two elastic partitions provides an almost constant unloading speed, as evidenced by the almost linear nature of the graph in Figure 4a in the interval of 2.0-9.0 s.

After stopping the tilt of the vehicle body, the remaining layer of root and tuber crops continued to spill out for about 6 s, and by time $t = 14$ s, the vehicle body was completely released (Figure 4, f).

Average rolling distance L_r rapidly increased from 0 to 0.8 m after the tailgate was folded back (in the interval of 0.0-2.5 s) (Figure 4, b). After that, the rolling distance increased slowly and almost linearly during the remaining unloading time and by the time the vehicle body was released it did not exceed 1.5 m.

It was possible to investigate various aspects of damage to root and tuber crops in various versions of the model. The damage in the basic version of the model was observed mainly to the first root and tuber crops when falling from the highest height after folding the tailgate. This is evidenced by a sharp increase in dependence of the share of damaged root crops on time (Figure 4, c) and the location of the balls highlighted in red, standing for the damaged root crops, mainly in the lower layer of unloaded root crops (Figure 4, c-f). In the course of further unloading, tuberous roots fall from a lower height, therefore, in the future, the amount of damage increases slightly (Figure 4, c). The developed elastic partitions provide a fairly small share of damaged root crops (4.6 %) when unloading.

A similar computer experiment was carried out for unloading from a standard vehicle body without installed elastic partitions of the same overall dimensions, with the same kinetic parameters of the unloading process. The comparison showed that the proposed elastic partitions allow reducing the average rolling distance from 1.60 to 1.52 m, reducing the proportion of damaged root and tuber crops from 6.3 to 4.6%, with a slight increase in the unloading time from 9.7 to 11.0 s. Thus, the proposed elastic partitions make it possible to increase the accuracy of unloading and reduce the damage of root and tuber crops.

Tests were carried out in LLC "Agrariy" of Kasimovskiy district of Ryazan region when harvesting potatoes from 2017-2019. The total volume of potatoes transported by one experimental vehicle in 2019 amounted to 315 tons.

Transverse elastic partitions were installed on the body of vehicles, in particular MAZ 5516 vehicles (Fig. 5).

This is due to the fact that despite the high productivity of transport operations, this vehicle damages the transported potato tubers during transportation and unloading. Since the volume of the MAZ 5516 car body is 12.5 m^3 , then when unloading, a simultaneous descent of potato tubers is observed, which causes excessive pressure on the lower layers of tubers, which were unloaded first.

As a result of comparative field tests of a serial MAZ 5516 truck body and an experimental MAZ 5516 truck body with installed transverse partitions, it was found that the use of the developed elastic transverse partitions reduces damage to potato tubers from 5.3% to 2.9%. When unloading potato tubers from the vehicle body equipped with transverse elastic partitions, unloading occurs gradually. First, close to the tailgate potatoes

are unloaded. Then potatoes from the middle part of the body are unloaded, and then those from the far part of the body.

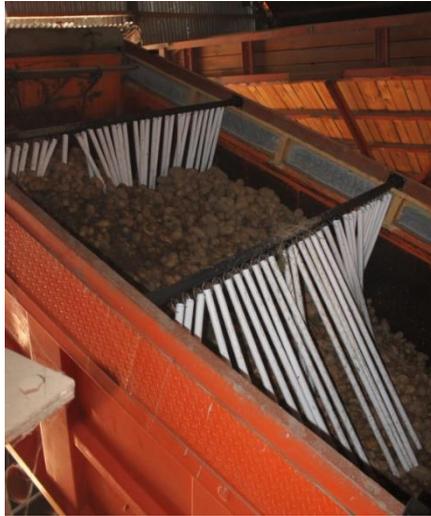


Fig. 5. Beginning of unloading potato tubers from the body of a MAZ 5516 vehicle equipped with transverse elastic partitions.

Based on the analysis of the results of the study, it was found that damage to potato tubers when unloading from a serial MAZ 5516 truck and an experimental MAZ 5516 truck with installed transverse elastic partitions was 5.3% and 2.9%, respectively.

4 Conclusion

As a result of a computer experiment, an assessment was made of comparing unloading from a standard vehicle body with the one having installed elastic partitions of the same overall dimensions, with the same kinetic parameters of the unloading process. Comparison showed that the proposed device made it possible to reduce the average rolling distance from 1.60 to 1.52 m, with a slight increase in the unloading time from 9.7 to 11.0 s. Thus, the proposed device makes it possible to increase the accuracy of unloading and reduce the damage of root and tuber crops. As a result of comparative field studies of the serial body of the MAZ 5516 truck and the experimental body of the MAZ 5516 truck with elastic transverse partitions, it was found that their use can reduce damage of potato tubers from 5.3% to 2.9%.

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