Modeling the process of liquid-mechanical cleaning of the bottom dish of the bottom conveyor of a beet harvester

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Abstract. Increasing the machinery productivity is a significant factor affecting the production cost. The study of technological processes of the equipment functioning and the identification of opportunities for the growth of their use indicators is an important task. For example, when analyzing the work of beet harvesting machinery, a significant amount of time was found to be wasted for cleaning the bottom dish of the bottom conveyor from soil contamination. In this case, the total drop in the daily productivity of harvesting with a beet harvester can reach 20 percent. To solve the problem of increasing the productivity of beet harvesting machinery, it is proposed to use the technology of wetting the surface of the conveyor bottom with some liquid (water). In this case, it is of interest to study the processes of interaction of soil masses with the bottom surface and their removal using mechanical action from the conveyor scrapers. This paper presents a mathematical model of the process of liquid-mechanical cleaning of the conveyor, built on the basis of classical mechanics. It allows carrying out the calculations to determine the rational modes of liquid consumption, cleaning time, and economic efficiency of the proposed solutions. The proposed results can be used to substantiate the mechanism of such processes in agricultural and other machinery.

1. Introduction
Sugar beet is one of the most important industrial crops in the world. The size of the areas under sugar beet crops is growing steadily. Simultaneously with the need to expand the sown areas, the task of increasing the efficiency of using highly productive and reliable machinery arises [1].

When harvesting sugar beets with beet harvesters, the discharge conveyor becomes dirty, in particular the bottom conveyor of the hopper [2-3]. Heavy contamination may result in damage or failure of the conveyor. So, it is required to carry out cleaning operations of the conveyor and hopper, or to repair it. In this case, the downtime of the harvester reaches 20% of the shift time, which significantly reduces the productivity of the machine [4-5].

Today, manual labor is used to clean the bottom conveyors of beet harvesters. We proposed a hypothesis about the need to separate two media (metal surface and soil masses) from close interaction with each other [6]. The available liquid (water) is considered as a third order pair [7]. A mathematical model was developed to determine the possible effect of using the liquid interlayer.

2. Materials and methods
In the mathematical model of the process of liquid-mechanical cleaning of the bottom dish of the bottom conveyor, the simulated soil masses consist of multiple (about $10^3...10^5$) elements. Solving the equations of the mechanical movement of elements allows one to determine the trajectories of their movement.
inside the hopper, and thereby reproduce in the model the evolution of the layer of soil masses in the process of cleaning the hopper [8].

Based on the symmetry of the problem - along the horizontal transverse direction, the process proceeds in the same way, - a two-dimensional space \((x, z)\) is used for modeling. Each element is described by its position \((x_i, x_j)\) and speed \((v_{xi}, v_{zi})\) in the modeling space. Among the possible options for describing the mechanical interaction between the elements, an elastic-viscous option is selected. This allows transferring such mechanical properties of soil masses into the model as the modulus of elasticity and the coefficient of friction [9].

When elements are inserted into each other, repulsive forces appear proportional to the amount of penetration (figure 1). Along with increasing the distance to a certain limit \(\Delta d_s\) in the connected elements, linear restoring forces arise.

![Figure 1](image_url)

**Figure 1** - Possible options for the interaction of elements: *a* - repulsive forces, proportional to the value of penetration; *b* - forces of attraction, proportional to the distance to the threshold value \(\Delta d_B\).

To describe the movement of elements, Newton's equations are used for two Cartesian components \(x\) and \(z\).

\[
\begin{align*}
&\frac{m_i \frac{d^2 x_i}{dt^2}}{m_i} = \sum_{j=1}^{N_e} \begin{cases} 
-c_i \left( \frac{d_i + d_j}{2} - r_j \right) (x_i - x_j) + k_i \left( \frac{d_i + d_j}{2} - r_j \right) (v_{xi} - v_{xj}), & r_j < \frac{d_i + d_j}{2} + \Delta d_z; \\
0, & r_j \geq \frac{d_i + d_j}{2} + \Delta d_z;
\end{cases} \\
&\frac{m_i \frac{d^2 z_i}{dt^2}}{m_i} = \sum_{j=1}^{N_e} \begin{cases} 
-c_j \left( \frac{d_i + d_j}{2} - r_j \right) (z_i - z_j) + k_j \left( \frac{d_i + d_j}{2} - r_j \right) (v_{zi} - v_{zj}), & r_j < \frac{d_i + d_j}{2} + \Delta d_z; \\
0, & r_j \geq \frac{d_i + d_j}{2} + \Delta d_z;
\end{cases}
\end{align*}
\]

Where \(m_i\) - the element’s mass; \(i\) - the element’s counting number; \(x_i\) and \(z_i\) - coordinates of the element; \(t\) - modelling time; \(j\) - the counting number of the neighboring element; \(N_e\) - total number of the elements; \(c_i\) - coefficient of rigidity of the interaction; \(d_i\) - diameter of the i-th element; \(v_{xi}\) and \(v_{zi}\) - velocity components; \(d_B\) - the minimum distance between elements where the elements are supposed to be not interacting; \(g\) - gravity acceleration.
Calculation of the distance $r_{ij}$ between the centers of elements is quite computationally expensive in the process of software implementation of the model:

$$r_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}.$$  \hfill (2)

The compiled system of differential equations (1) is solved numerically. Among the numerical methods, the Runge-Kutta second order method is chosen [8]:

$$x^{t+1}_i = x^t_i + v^t_{xi} \cdot \Delta t + \alpha^t_{xi} \cdot (\Delta t)^2 / 2; \quad v^{t+1}_{xi} = v^t_{xi} + \alpha^t_{xi} \cdot \Delta t,$$

$$z^{t+1}_i = z^t_i + v^t_{zi} \cdot \Delta t + \alpha^t_{zi} \cdot (\Delta t)^2 / 2; \quad v^{t+1}_{zi} = v^t_{zi} + \alpha^t_{zi} \cdot \Delta t,$$  \hfill (3)

Where $\tau$ and $\tau+1$ – the time step counting numbers; $\Delta t$ – the length of the step of numerical integration.

For the initial preparation of the model for a computer experiment, the following algorithm is used. Depending on the specified thickness of the layer of soil masses $h$, the number of elements that must be placed in the model space is identified:

$$N_E = \frac{S_c}{k_{yn}S_g} = \frac{4L_xh}{k_{yn}\pi D_E^2}.$$  \hfill (4)

Where $S_c$ and $S_g$ – layer area (in a two-dimensional model, it is not the volume of soil masses that is considered, but the area) and one separate element; $k_{yn}$ – packing coefficient of the elements taking into consideration the layer’s porosity (which is about 1.4); $L_x$ – the length of the modelled space; $D_E$ – element’s diameter.

For the initial formation of the layer of soil masses, the elements are first placed throughout the entire modeling area in a random manner according to a uniform distribution law and maintained for 1 second (one second) of the model time under the action of gravity. The elements sediment to the lower part of the modeling area, forming a random dense group, and come to a stable mechanical state. After that, the modeling of the main process begins: the movement of the clearing strips along the layer of soil masses [10].

The cleaning strip of the conveyor is represented in the model in the form of a rectangle, consisting of 150 elements-circles (figure 2). To unify and increase the physical adequacy of the model, the clearing strip consists of elements of the same diameter as the elements of soil masses, but with the corresponding properties (coefficients of rigidity, viscous friction, stickiness) when calculating the steel-soil contact.

![Figure 2](image-url)
3. Results
The proposed model is implemented as a computer program. Figure 3 shows the view of the soil masses, water particles, and the cleaning strip of the hopper, presented in the program that implements the developed mathematical model.

![Figure 3. Representation of soil masses, cleaning strips, and the bottom of the hopper in the model: 1 - bottom dish of the hopper; 2 - cleaning strip of the bottom conveyor; 3 - elements of soil masses (in the form of brown spheres); 4 - elements of the applied liquid (water) (in the form of blue spheres).](image)

The algorithm implemented in the program is based on a numerical integration cycle, at each step of which:

- The forces affecting the elements are calculated;
- The new position of the elements and the cleaning strip is calculated;
- Indicators of rate and quality of cleaning are calculated.

The specified values are captured as digital data for further processing.

4. Discussion
Using a mathematical model in the process of theoretical research, it is possible to carry out computer experiments for cleaning the bottom of the hopper. The model allows one to drive various data on the characteristics of soil conditions, such as interacting surfaces. This will make it possible to determine the key parameters of cleaning (the time of passage of one scraper, the height of the layer of mud masses after the passage of the scraper, the consumption of the working fluid). The model makes it possible to become the basis for evaluating the efficiency of the proposed solutions for various operating conditions.

5. Conclusion
In order to increase the productivity of beet harvesters, a mathematical model of the process of cleaning the hopper of a beet harvester from soil masses was developed, which has high level of detail and adequacy. It is capable of adapting to various operating conditions and taking into account the physical and chemical properties of soils. The model is based on generally accepted methods of classical mechanics, and is fully implemented on the basis of the computational capabilities of modern computers.

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