UKRAINIAN JOURNAL OF MECHANICAL ENGINEERING AND MATERIALS SCIENCE
**Vol. 11, No. 1, 2025**

**Volodymyr Topilnytskyy[1], Nestor-Taras Velykyi[2]**

[1]Department of Mechanical Engineering and Automotive Engineering, Lviv Polytechnic National University, 12, S. Bandery Str., Lviv, Ukraine, e-mail: volodymyr.g.topilnytskyi@lpnu.ua, ORCID 0000-0002-5191-326X
2Department of Mechanical Engineering and Automotive Engineering, Lviv Polytechnic National University, 12, S. Bandery Str., Lviv, Ukraine, e-mail: nestor-taras.i.velykyi@lpnu.ua, ORCID 0009-0001-8550-4974

# DESIGN OF A VIBRATING MACHINE FOR DRY CLEANING OF ROOT VEGETABLES USING NONLINEAR MATHEMATICAL AND THREE-DIMENSIONAL MODELING

Received: January 24, 2025 / Accepted: February 27, 2025



https://doi.org/

**Abstract.** The design of a highly efficient vibrating machine for dry cleaning root vegetables of various types, shapes, and sizes has been developed. First, a schematic diagram of the machine was built, containing all the future machine's main components. A nonlinear mathematical model was constructed to describe its dynamics during its operation to determine the future machine's optimal geometric, kinematic, and power parameters. The mathematical model is based on the apparatus of asymptotic methods of nonlinear mechanics and Lagrange's equations. Based on the schematic diagram of the machine and the obtained parameters, three-dimensional and two-dimensional models of the machine were developed in the environment of the Autodesk Inventor Professional 2025 CAD system, which will make it possible to manufacture it further. The obtained geometric models will become the basis for the direct manufacture of this vibrating machine for dry cleaning of root vegetables, and the mathematical model for describing its dynamics will allow choosing the optimal operating parameters of this equipment. The presence of the vibrating machine of a working chamber with a cylindrical mesh, rods, placement of the working chamber on vertical springs, and the drive by two independent unbalances ensure the cleaning of root vegetables without the use of water (dry method) with the removal of contaminants outside the machine, reduce operating energy costs, improve the quality and productivity of the cleaning process, make its continuity possible, increase the reliability of the machine and the versatility of its use for cleaning various types of root vegetables.

**Keywords:** dry cleaning of root vegetables, vibrating machine, mathematical modeling, cylindrical mesh, working chamber, independent unbalanced drive.

## Introduction and Problem Statement

One of the important stages of preparing harvested agricultural products for further processing and storage is the stage of cleaning from contamination. This issue is especially relevant for vegetable roots (carrots, beets, radishes, radishes, potatoes, etc.). Root vegetables are harvested on farms in an automated manner under different weather conditions. As a result, a lot of dirt (including soil, pathogenic flora, etc.) can accumulate on their surfaces. To transport root vegetables to processing plants or consumers, they must be cleaned superficially, sorted, and packaged. Usually, root vegetables can be washed with water [1], [2], [3], [4]. However, with this cleaning method, the following three tasks should be solved: water supply and drainage, water consumption, and subsequent high-quality drying of washed vegetables (because storing completely undried vegetables will lead to their rapid spoilage). The solution to these problems is quite expensive, which will certainly affect the price of the final product made from this raw material or the selling price of the vegetables themselves. A significantly cheaper alternative to water washing is dry cleaning of root vegetables, in which there are no costly operations with water and their subsequent drying [5]. Such cleaning equipment ensures the relative movement of root vegetables in the bulk volume and removes contaminants from their surfaces due to friction. Developing new universal designs of equipment for dry vegetable cleaning is an urgent task.

## Review of Modern Information Sources on the Subject of the Paper

The range of designs of machines for cleaning vegetables and fruits is quite wide [1]. Dry peeling has advantages over wet peeling, i.e. washing [5]. Accordingly, root vegetables should be dry-cleaned before they are stored, and washing can be used immediately before food production at processing plants. If the raw materials are to be processed without storage, the cleaning process can be divided into two stages: dry cleaning, which will help remove a large percentage of dirt from the surfaces of the raw materials, and washing. This will save money on water use (cost of water, water supply, water filtration, drainage) and time and money for drying wet vegetables and fruits.

The disadvantage of modern dry cleaning equipment is its narrow focus, i.e., it is designed to clean raw materials of a certain type or size [6], [7], [8]. An urgent task today is to develop universal equipment for the dry cleaning of various types of root vegetables, the optimal design of which can be obtained through a preliminary theoretical study of both the cleaning process itself and the equipment for its implementation by mathematical modeling of its operation. Previous studies of this type solved these problems in a linear formulation [9] or were again narrowly focused. It is the development of mathematical models in the nonlinear formulation of the description of the dynamics of the equipment of the dry method of cleaning root vegetables that will allow us to quickly and cost-effectively obtain its optimal design and modes of optimal functioning.

## Main Material Presentation

The article's authors have developed a new design of a machine for cleaning root vegetables by a dry method, in which the cleaning of their surfaces occurs through the mutual friction of root vegetables with each other. The machine is a vibration type with a small amplitude of oscillations. The relative movement of root vegetables in their bulk volume is provided by the energy of the oscillatory movement of the working container of the machine in which they are placed. The machine is universal for cleaning various root vegetables, both by type and size. The machine's oscillating energy level can be varied, so the mode of cleaning a particular root crop can be chosen. The machine is also characterized by high productivity. It can provide simultaneous dry cleaning and movement of the raw material to be cleaned. This machine also serves as a piece of transport equipment, a very important indicator in the technological chain of agricultural product processing.

Figs. 1–3 shows a diagram of the proposed design of a machine for cleaning root vegetables from contamination by a dry method. In particular, Fig. 1 – diagram of a vibrating machine for dry cleaning of root vegetables, main view; Fig. 2 – diagram of a vibrating machine for dry cleaning of root vegetables, top view; Fig. 3 – section according to A-A in Fig. 1. This machine consists of: 1 is the working chamber, 2 is the loading tray, 3 is the cylindrical mesh, 4 is the central axis in the form of a rod, 5 is the radial rods, 6 is the unloading tray, 7 is the outlet for removing removed contaminants, 8 is the spring suspension (vertical springs of increased transverse stiffness), 9 is the frame, 10 is the unbalances, 11 is the protrusions, 12 is the electric motors, 13 is the elastic couplings.

The proposed vibrating machine for dry cleaning of root vegetables contains a horizontally arranged cylindrical working chamber 1 with a loading tray 2. A concentrically rigid cylindrical mesh 3 is inserted into the working chamber along its entire length with a gap between the side surfaces of the mesh 3 and the working chamber 1. The mesh 3 is made by welding from steel wire (or from a steel sheet with perforation of holes for the mesh and subsequent formation of the sheet into a cylinder) and welded to the inner end surface of the working chamber. Under loading tray 2, a hole is made in the cylindrical grid 3 for loading unpeeled root vegetables into the middle of the grid. The grid has a central axis 4 in the form of a rod connected to the grid by several radially placed rods 5, which are welded to axis 4 and grid 3. Axis 4 and rods 5 separate the mixture of root vegetables during cleaning, clean the root vegetables with their surfaces and increase the rigidity of the grid structure. At the opposite end of the working chamber 1 from the loading tray 2, there is an unloading tray 6 for unloading the peeled root vegetables. The working chamber 1 has an outlet for removing contaminants 7 in the central lower part. The working chamber 1 is mounted on a spring suspension 8, namely vertical springs of increased transverse stiffness on the frame 9.

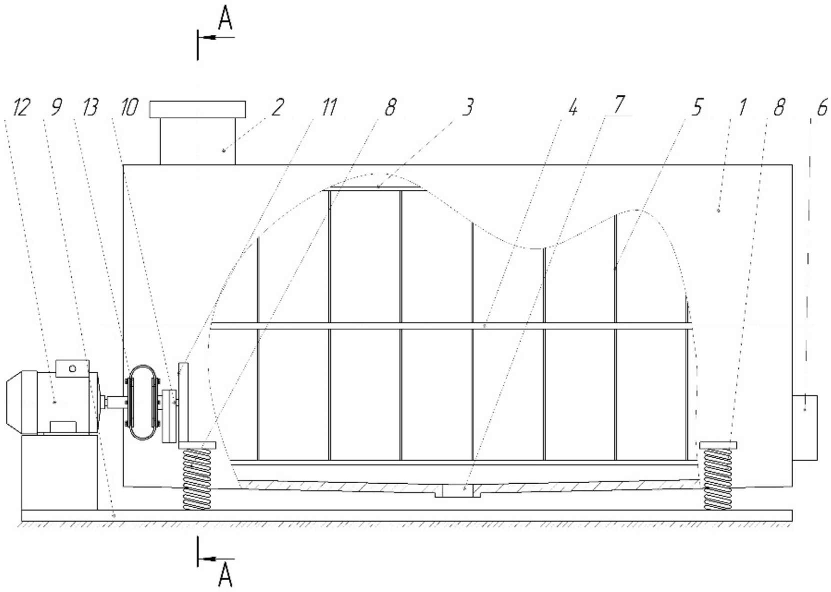


**Fig. 1.** Scheme of a vibrating machine for dry cleaning of root vegetables, main view

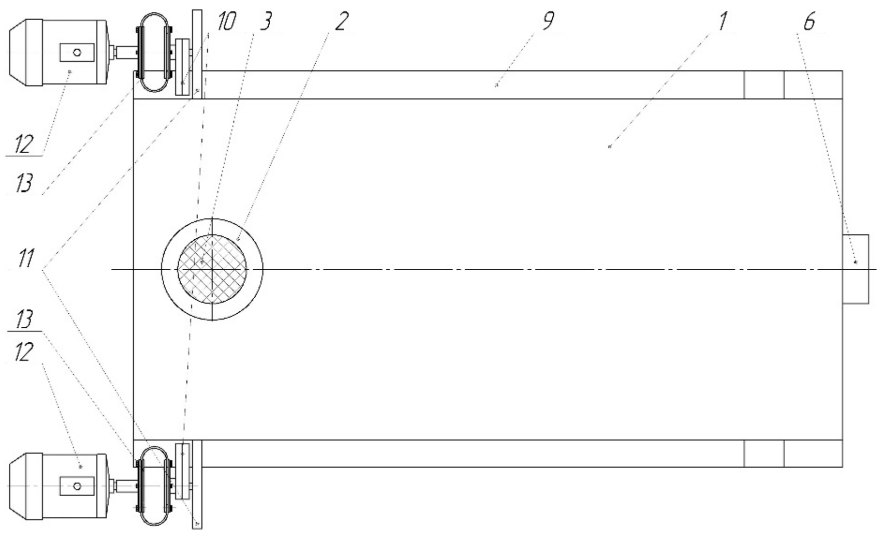


**Fig. 2.** Scheme of a vibrating machine for dry cleaning of root vegetables, top view

The movement of the working chamber 1 is carried out by a vibration drive in the form of two independently rotating unbalances 10, which are installed symmetrically relative to the vertical axis of the working chamber 1 on the side surface of the cylinder of the working chamber 1 from the side of the loading tray 2 and have separate electric motors 12. The axes of rotation of the unbalances 10 are parallel to the axis of the working chamber 1. The unbalances 10 are pivotally attached to the protrusions 11 welded to the working chamber 1. The rotational movement of the unbalances 10 is provided by electric motors 12 mounted on frame 9 through elastic couplings 13. The vibrating machine is controlled via the control panel.

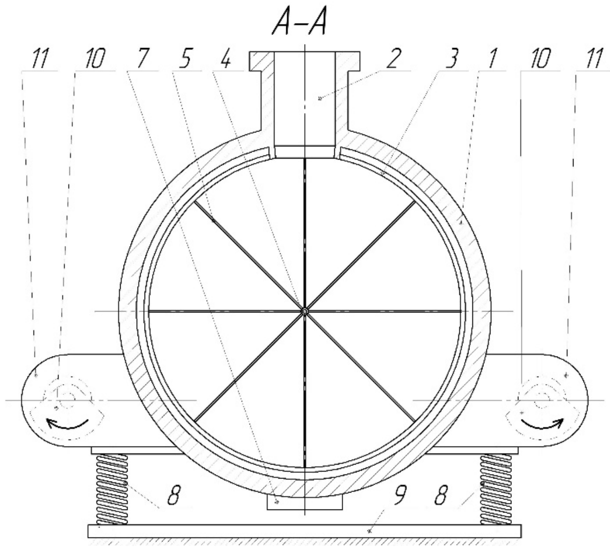


**Fig. 3.** Scheme of a vibrating machine for dry cleaning of root vegetables, section A-A in Fig. 1.

The proposed vibrating machine for dry cleaning of root vegetables works as follows. Root vegetables are poured portionwise or continuously into working chamber 1 into the inner surface of grid 3 through loading tray 2. Electric motors 12 through elastic couplings 13 ensure the rotation of the unbalances 10 in opposite directions - opposite or from each other. Due to the rotating unbalanced masses of the unbalances 10, the working chamber 1 with the grid 3 oscillates on the spring suspension 8 in the plane of rotation of the unbalances 10. The oscillating energy of working chamber 1 is transmitted to the unpeeled root vegetables, which begin to actively mix and are formed into two oncoming streams that will move towards each other and interact (mix) in the vertical plane. The formation of such two streams in the working chamber 1 provides better mixing of root vegetables, increases the friction of root vegetables between each other, the grid 3, the central axis in the form of a rod 4 and radial rods 5, and therefore increases the intensity of cleaning the surfaces of root vegetables from contamination only in a dry way without the use of water. The location of the unbalances 10 on the side surface of the cylinder of the working chamber 1 from the side of the loading tray 2, due to the redistribution of the amplitude of oscillations along the axis of the working chamber 1, ensures the simultaneous transportation of root vegetables during cleaning along the axis of the working chamber 1 to the unloading tray 6. During the cleaning process, the removed contaminants fall through grid cell 3 into the lower part of the inner surface of the working chamber 1 cylinder, accumulate in the gap space between grid 3 and chamber 1, and are discharged through the removed contaminants outlet 7 in the central lower part of the working chamber 1 due to vibration movement along the inner surface of the working chamber 1 cylinder.

The amplitude of oscillations of the working chamber 1 and the grid 3 can be adjusted as follows: by changing the masses of the unbalances 10 and/or their eccentricity (changing the angular relative position of the unbalanced components); by changing the stiffness of the spring suspension 8; by changing the weight of the root vegetables loaded in the chamber 1; by changing the number of revolutions of the unbalances 10 (oscillation frequency).

The working chamber 1 can be designed of any length, based on considerations of the maximum level of dry cleaning of root vegetables and the required transportation distance.

## Results and discussion

The next stage of the work was to study the effect of the parameters of the developed design of the machine for cleaning root vegetables from contaminants by the dry method on the intensity of its functioning. This task was solved using the developed mathematical model of this machine, which describes its dynamics. The model was built using asymptotic methods of nonlinear mechanics and the Lagrange equation [10], [11],

[12]. All machine parameters, which are of three types – geometric, power, and kinematic are displayed in the model in a symbolic format. That is, their numerical values in the real range of change can be substituted directly into the model, which will describe the oscillatory motion of an arbitrary point of the machine, build its trajectory, and determine the amplitude of its oscillations. The latter value will be one of the important factors that will determine the intensity of the dry cleaning process of root vegetables and the speed of their movement along the working container of the machine. From a mathematical point of view, the model will be reflected in the system of analytical dependencies of the generalized coordinates of the description of the movement of the working chamber of the machine for dry cleaning of root vegetables from contaminants $x_{o3}$, $y_{o3}$, and $\varphi$ of the form (1), (2), and (3):

$$
\begin{aligned}
x_{o3} = {} & x_0 \sin\left(\sqrt{\frac{c}{M}}t + \alpha_x\right) + \frac{\varepsilon}{\sqrt{\frac{c}{M}}}\int_0^t \left( -\ddot{\phi}\left( M_K S\cos\phi + M_{D1}\left( \begin{aligned} & r_1\cos(\omega_1 t + \phi + \alpha_0) + \\ & + l_1 \sin\phi - k_1\cos\phi \end{aligned}\right) + \right. \right. \\
& \left. + M_{D2}\left(r_2\cos(\omega_2 t + \phi + \psi_0) - l_2\sin\phi - k_2\cos\phi\right) \right) - \\
& - \left(\dot{\phi}\right)^2 \left( \begin{aligned} & M_K S\sin\phi + M_{D1}\left(-r_1\sin(\omega_1 t + \phi + \alpha_0) + l_1\cos\phi + k_1\sin\phi\right) + \\ & + M_{D2}\left(-r_2\sin(\omega_2 t + \phi + \psi_0) - l_2\cos\phi + k_2\sin\phi\right) \end{aligned}\right) + \\
& + M_{D1} r_1 \sin(\omega_1 t + \phi + \alpha_0)\left(\omega_1^2 + 2\omega_1\dot{\phi}\right) + M_{D2} r_2 \sin(\omega_2 t + \phi + \psi_0)\left(\omega_2^2 + 2\omega_2\dot{\phi}\right) - \\
& - C_1\left( \sqrt{(x_{o3} - b\cos\varphi + f\sin\varphi + b)^2 + \left(y_{o3} - b\sin\varphi - f\cos\varphi + f + L_{np} - \frac{Mg}{c}\right)^2} - L_{np} \right) \times \\
& \times \left( - \frac{x_{o3} - b\cos\varphi + f\sin\varphi + b}{\sqrt{(x_{o3} - b\cos\varphi + f\sin\varphi + b)^2 + \left(y_{o3} - b\sin\varphi - f\cos\varphi + f + L_{np} - \frac{Mg}{c}\right)^2}} \right) - \\
& - C_2\left( \sqrt{(x_{o3} + q\cos\varphi + f\sin\varphi - q)^2 + \left(y_{o3} + q\sin\varphi - f\cos\varphi + f + L_{np} - \frac{Mg}{c}\right)^2} - L_{np} \right) \times \\
& \left. \times \left( - \frac{x_{o3} + q\cos\varphi + f\sin\varphi - q}{\sqrt{(x_{o3} + q\cos\varphi + f\sin\varphi - q)^2 + \left(y_{o3} + q\sin\varphi - f\cos\varphi + f + L_{np} - \frac{Mg}{c}\right)^2}} \right) \right) \times \\
& \times \sin\left(\sqrt{\frac{c}{M}}(t - u)\right) du,
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
y_{o3} = {} & y_0 \sin\left(\sqrt{\frac{c}{M}}t + \alpha_y\right) + \frac{\varepsilon}{\sqrt{\frac{c}{M}}}\int_0^t \left( -\ddot{\phi}\left( M_K S\sin\phi + M_{D1}\left( \begin{aligned} & r_1\sin(\omega_1 t + \phi + \alpha_0) - \\ & - l_1 \cos\phi - k_1\sin\phi \end{aligned}\right) + \right. \right. \\
& \left. + M_{D2}\left(r_2\sin(\omega_2 t + \phi + \psi_0) + l_2\cos\phi - k_2\sin\phi\right) \right) -
\end{aligned} \tag{2}
$$

$$-\left(\dot{\varphi}\right)^2\left(M_K S\cos\varphi + M_{D1}\left(r_1\cos\left(\omega_1 t+\varphi+\alpha_0\right)+l_1\sin\varphi - k_1\cos\varphi\right)+ M_{D2}\left(r_2\cos\left(\omega_2 t+\varphi+\psi_0\right)-l_2\sin\varphi - k_2\cos\varphi\right)\right)+$$

$$-M_{D1}r_1\cos\left(\omega_1 t+\varphi+\alpha_0\right)\left(\omega_1^2+2\omega_1\dot{\varphi}\right)-M_{D2}r_2\sin\left(\omega_2 t+\varphi+\psi_0\right)\left(\omega_2^2+2\omega_2\dot{\varphi}\right)-$$

$$-\frac{C_1}{2}2\left(\sqrt{\left(x_{o3}-b\cos\phi+f\sin\phi+b\right)^2+\left(y_{o3}-b\sin\phi-f\cos\phi+f+L_{np}-\frac{Mg}{c}\right)^2}-L_{np}\right)\times$$

$$\times\left(-\frac{y_{o3}-b\sin\phi-f\cos\phi+f+L_{np}-\frac{Mg}{c}}{\sqrt{\left(x_{o3}-b\cos\phi+f\sin\phi+b\right)^2+\left(y_{o3}-b\sin\phi-f\cos\phi+f+L_{np}-\frac{Mg}{c}\right)^2}}\right)-$$

$$-C_2\left(\sqrt{\left(x_{o3}+q\cos\phi+f\sin\phi-q\right)^2+\left(y_{o3}+q\sin\phi-f\cos\phi+f+L_{np}-\frac{Mg}{c}\right)^2}-L_{np}\right)\times$$

$$\times\left(-\frac{y_{o3}+q\sin\phi-f\cos\phi+f+L_{np}-\frac{Mg}{c}}{\sqrt{\left(x_{o3}+q\cos\phi+f\sin\phi-q\right)^2+\left(y_{o3}+q\sin\phi-f\cos\phi+f+L_{np}-\frac{Mg}{c}\right)^2}}\right)+Mg\Bigg)\times$$

$$\times\sin\left(\sqrt{\frac{c}{M}}\left(t-u\right)\right)du,$$

$$\phi\left(t\right)=\phi_0\cos\left(\omega_0 t+\theta\left(t\right)\right). \quad (3)$$

In this system of expressions (mathematical models), we distinguish the following main parameters: $M$ is the mass of the working chamber; $M_{Di}$ is the size of the corresponding unbalanced rotating mass of the drive with angular velocity; is the amount of displacement of the center of mass of the unbalanced rotating mass from the axis of its rotational motion; $C_i$ is the stiffness of the springs of the working chamber mounting. The model also contains some geometric parameters that reflect the placement of the suspension, the fastening of the rotating masses of the drive, the dimensions of the working chamber and sieves, etc.

All the parameters of the studied dry cleaning machine were divided into three groups according to the complexity of change during operation: parameters that are easy to change, possible to change, and difficult to change. These parameters were taken in a numerical format in the ranges of their change and substituted for various combinations in a mathematical model in the environment of the automated mathematical calculation program MathCAD.

The input values for the study of some parameters (the possible range of their change) to obtain the corresponding graphical dependencies to determine their influence on the nature of the working chamber motion will be, for example, as follows: a) $r_1 = r_2$ = 0 – 0.105 m – the range of change in the value of the displacement of the center of mass of the unbalanced rotating mass from the axis of its rotational motion; b) $\omega_i$ = 30s$^{-1}$ - 140s$^{-1}$ – the range of change in the angular velocities of the unbalanced rotating mass of the drive; c) $M_{Дi}$ = 1 – 4 kg – the range of change in the value of the corresponding unbalanced rotating mass; d) $M$

= 150 – 250 kg – the range of change in the mass of the working chamber with root vegetables; e) $C_i$ = 9 – 20 kH/m – the range of change in the stiffness of the springs of the working chamber fastening.

As a result of the studies, the amplitude of the oscillatory motion of the dry root crop cleaning machine was determined to depend on the parameters that can be changed during the machine's operation. After the studies, specific numerical values of the vibrating machine's geometric, power and kinematic parameters were obtained, at which the cleaning of root vegetables will be optimal. Such parameters of the machine as the total oscillating mass, the value of the displacement of the center of mass of the unbalanced mass of the vibration oscillation drive from the axis of its rotational motion and the angular velocity of this motion, the size of this unbalanced rotating mass, the stiffness of the working chamber mounting springs, the distance between the working chamber supports provide the most significant impact on the intensity of the process of dry cleaning of root vegetables.

Having these parameters, a 3D model was developed, and from it, a 2D model of this vibrating machine in the CAD system Autodesk Inventor Professional 2025 (Fig. 4 and Fig. 5).

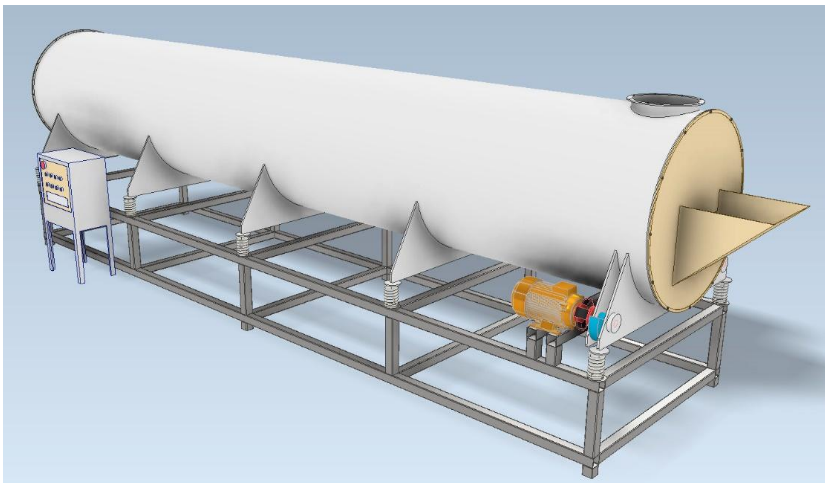

**Fig. 4.** Three-dimensional model of a vibrating machine for dry cleaning of root vegetables, view from the side of root vegetables loading

The three-dimensional model was obtained by conducting a detailed study of all the components and parts of the machine. The obtained geometric models will become the basis for the direct manufacture of this vibrating machine for dry cleaning of root vegetables, and the mathematical model for describing its dynamics will allow choosing the optimal operating parameters of this equipment.

## Conclusion

As a result of the conducted complex of design and research works, the design of a vibrating machine for dry cleaning of root vegetables was obtained with the determination of its geometric, power, and kinematic parameters by mathematical modeling of its dynamics. To solve this problem, first of all, a machine scheme was proposed, and then a nonlinear mathematical model was developed to describe its dynamics. Having the scheme and the calculated optimal parameters of the machine, its three-dimensional and two-dimensional models were developed in the environment of the applied computer-aided design system.

In general, the presence in a vibrating machine for dry cleaning of root vegetables of a working chamber with a rigid cylindrical mesh installed with a gap, rods, placement of the working chamber on vertical springs of increased transverse stiffness near its opposite ends, drive of the working chamber by two rotating independently of each other unbalances, which are installed symmetrically relative to the vertical axis of the chamber on the side surface of the working chamber cylinder from the side of the loading tray, provide cleaning of root vegetables without the use of water (by dry method) with the removal of contaminants outside the machine, reduce operating energy costs, improve the quality and productivity of the root crop cleaning process, make it possible to ensure its continuity, increase the reliability of the machine and its versatility for cleaning various types of root vegetables.

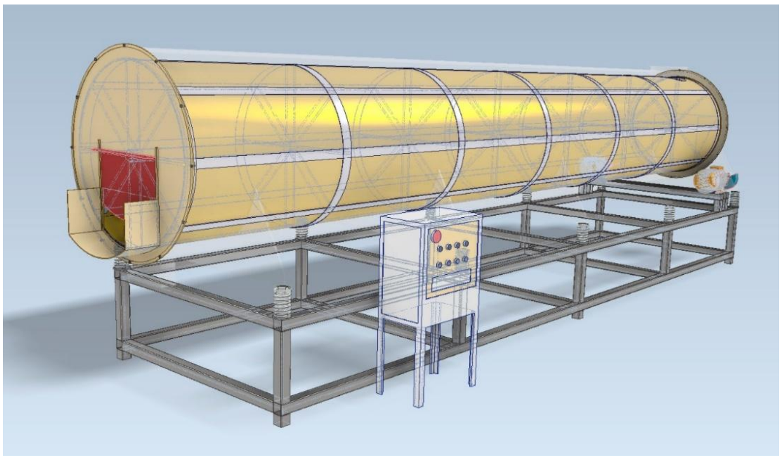

**Fig. 5.** A three-dimensional model of a vibrating machine for dry cleaning of root vegetables view from the side of root crop unloading (display of invisible ribs is enabled, and the working chamber is shown as translucent)

## References

[1]. Postnov H. M., Afukova N.O., Dmytrevskyi D.V., "Mechanical equipment", *Kharkiv: Khark. derzh. un-t kharchuvannia ta torhivli*, 198 p., 2014.

[2]. Krysak F.M., "Areas of improvement of machines for washing root vegetables", *Zb. nauk. prats Vinnytskoho natsionalnoho ahrarnoho universytetu*, 11, pp. 284–288, 2012 [In Ukrainian]

[3]. Wang L., Ding X. "Experimental investigation washing vegetables with submerged jets of water", *Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering*, 23, pp. 124–130, 2007.

[4]. Muhammad Farooq, Muhammad Mohsin Waqas, Yasir Niaz, Muhammad Ashraf, "Development and evaluation of carrot washer to improve farm productivity through mechanized approach", *Acta Mechanica Malaysia (AMM)*, 6(1), pp. 29-34, 2023.

[5]. Vsevolodov A. N., Hladushniak A. K., "Optimization of the process of "dry washing" of root vegetables", *Kharchova nauka i tekhnolohiia*, 3, pp.83–87, 2012. [In Ukrainian]

[6]. Hevko R., Brukhanskyi R., Flonts I., Synii S., Klendii O., "Advances in methods of cleaning root vegetables", *Bulletin of the Transilvania University of Brasov, Series II: Forestry, Wood Industry, Agricultural Food Engineering*, 11, pp. 127–138, 2018.

[7]. Frolov V. J., Bychkov A. V., Sidorenko S. M., Efremova V. N., Shmatko G. G., "The parameters of the process of dry cleaning root vegetables with using screw separator", *Research journal of pharmaceutical, biological and chemical sciences*, 7, pp. 376–382, 2016.

[8]. Hongguang Yang, Jianchun Yan, Hai Wei, Huichang Wu, Shenying Wang, Longlong Ji, Xiaowei Xu, Huanxiong Xie, "Gradient Cleaning Method of Potato Based on Multi-Step Operation of Dry-Cleaning and Wet Cleaning", *MDPI, Agriculture*, 11, 11:39, 14 p., 2021.

[9]. Tkachenko I., Vyviurka N., "Mathematical modeling of roots cleaning process at their impulse loading", *Visnyk TDTU*, vol. 1, pp. 40–46, 2004.

[10]. Yu. Mytropolskyi, "Methods of Nonlinear Mechanics", *Kyiv: Naukova Dumka*, 527 p., 2005.

[11]. Rebot D., Topilnytskyy V., Svidrak I., Stotsko R., Shevchuk A., "Constructing the schematic and mathematical model of the dynamics of a vibratory drum separator", *Vibroengineering Procedia. Vol. 55: 69th International conference on vibroengineering, September 26-29, 2024, Lviv, Ukraine*, pp. 33–39, 2024.

[12]. Topilnytskyy V., Vyshatytskyy V., "Developing a mathematical model for describing the motion of a vibratory type separator with sequential screens", *Ukrainian Journal of Mechanical Engineering and Materials Science*, Vol. 10, № 1. pp. 70–76, 2024.