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Model of material movement on the working surface of a vibrating machine

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Summary This article presents studies related to the calculation of the peculiarities of the movement of bulk material on the working surface of a vibrating machine – for example, on a sowing surface – in terms of the intensity of the potential force field acting on the material being processed. This approach makes it possible to adjust its design to the selected technological process at the design stage of the vibrating machine, which further makes it possible to minimize energy consumption for vibration processing of bulk raw materials without reducing the quality of its preparation.

Key words: vibrating screen, bulk material, fraction, vibration field, sieving surface

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Introduction

Reducing energy costs in various industries that use vibration methods of raw material processing can be achieved by improving the quality of its preparation at the stages of transportation and sorting [12, 16–19]. At present, transportation and sorting of bulk raw materials is most often carried out using vibrating machines of various configurations. The characteristic differences of such machines are: the dimensions of the working surface that is in contact with the material flow, in particular, the surface area of the sieves; the number and location of vibration exciters; the design of the working body of the machine and its support system. These variations affect the main technical characteristics of the machines in various ways, namely, their feeding capacity and the efficiency of material screening (for screens) [13, 14, 20, 21]. The practice of operating vibrating machines for sorting bulk material shows that while the performance of the machine's feeding is ensured in the first place, the efficiency of screening the material is not always sufficient for various reasons. The energy efficiency of a screen is determined by the specific energy consumption per unit of high-quality end product. Therefore, the efficiency of the screen is an important characteristic that affects the energy efficiency of

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the machine. Obviously, the simplest and most popular way to increase screening efficiency is to increase the total area of the screening surface. But this inevitably entails a change in the weight and inertial characteristics of the working body, which in turn affects the excessive energy consumption and the sieving efficiency of the machine. Therefore, to ensure the optimization of power, design and technological indicators of vibrating machines for sorting and transportation of bulk raw materials, it is necessary to develop a mathematical model of its movement, which will take into account the main parameters of the process and allow to predict the behavior of raw materials under the influence of vibration forces, evaluate the efficiency of transportation and sorting, as well as optimize of machine operation parameters.

The review of existing studies shows a significant number of works aimed at solving the above problems, and all these works can be grouped into two main approaches, namely use of the discrete element method (DEM) [2, 4, 7, 11, 15] and deterministic dynamic models of movement of a single particle of material [1, 3, 5, 6, 8, 9].

Currently, the DEM method is a powerful tool for modeling screening processes due to its flexibility, accuracy, and predictive capabilities. Studies [2, 4, 15] provide examples of its application to simulate the motion of individual particles with regular shapes and their interaction with surfaces to optimize the design parameters of vibrating machines. To improve alignment with real-world conditions, the authors of study [7] propose a modification of the standard method by accounting for the geometric shape of particles using multi-sphere models. The integration of DEM with other methods, such as CFD [11], enables the simulation of multiphase systems.

The main drawbacks of the DEM method include the inability to account for the physico-mechanical properties of materials, which can influence process dynamics, and the significant computational costs associated with simulating large-scale systems or multi-physics problems. To address the latter, simplified models, such as analyzing the motion of a single material particle, are promising for the initial assessment of the system. Studies [1, 3, 8] describe the kinematics of particles on a vibrating surface with elliptical oscillations, including transverse vibrations. This method is widely used to examine the characteristics and efficiency of new types of vibrating screens, such as those with pendulum oscillation trajectories [6]. It also enables the analysis of how vibration parameters – such as amplitude and frequency – affect the kinematic characteristics of particles as they pass through a screen [9]. Thus, this method provides a detailed study of particle trajectories and allows for the optimization of vibrating machine parameters.

The common drawback of the aforementioned methods is that in all cases, the load perceived by the charge layer or a single particle from the working body of the machine, which performs harmonic oscillations, is set as an average value of the force of inertia, which changes in time in accordance with the change in the acceleration vector of the working body both in value and in direction. This does not allow taking into account the spatial and time distribution of vibration oscillations in the structure, which are formed under the action of variable forces applied to the system, which significantly affects the processes of transportation and sorting of bulk materials.

The purpose of the study is to substantiate the vibration effect of the working body of a vibrating machine on the movement of bulk material in terms of a vibration field intensity vector varying in space and time. The law of change of this vector depends on the weight and inertial characteristics of the working body, its geometry, as well as the parameters, number and location of vibration exciters on it. The computational and analytical approach outlined in the work presented for consideration makes it convenient, even at the stage of designing or adapting a vibrating machine to a particular technological process, to minimize energy consumption for vibration processing of bulk raw materials without reducing the quality of its preparation.

Methodology

When designing vibrating equipment for sorting and transporting purposes, it is first of all necessary to ensure maximum productivity and efficiency of sieving bulk material according to the required parameters with the lowest energy consumption. In particular, for vibratory transport, it is necessary to ensure the necessary movement of material particles, and for machines that separate bulk material into fractions, it is also necessary to maintain the highest possible screening efficiency. Let's solve this problem by considering the bulk material processed by vibration as being in a specific field of inertial forces. In turn, this force field is generated by the vector field of the vibration field intensity applied to the material particles. To do this, we will make several assumptions, which we will formulate into six postulates.

Postulate 1: The space covered by the working element can be represented as a vibrating potential field. At each point of this field, the working body generates a stress vector of a certain value.

In the following, we will distinguish between vibration fields generated by the working body and those imposed by it on the bulk material, i.e., those that actually perceive product particles in contact with the surface of the working body.

The particles processed by the working body are continuously under the influence of the constant strength of the Earth's gravitational field, and only for a limited, cyclically repeated time under the influence of the generated, but distorted by the conditions of the viscous field. Since the intensity of the Earth's gravitational field is the acceleration of free fall g, the intensity of the generated vibration field is the acceleration of the corresponding point of the working body. The cyclic effect of the vibration field on the particle is explained by the influence of its special connection with the surface of the working body, namely, the influence of a one-way and unconditional connection with the surface of the working body in the normal direction to the contact surface and a conditional two-way connection in the tangential direction. Thus, the considered vibration field has the following properties: in the normal direction along the direction of one-way communication, there is a complete transfer of energy to the material particle from the generated vibration field; in the normal direction against the one-way coupling, there is no energy transfer from the vibration field generated by the working body to the particle of bulk solids; in the direction of conditional coupling by means of friction forces, there is a partial transfer of energy, which is provided by friction patterns.

Postulate 2: The concentration of particles processed by a vibrating working body occurs in the zones with the lowest energy, which have the lowest values of the total intensity from the induced vibration and gravitational fields (in the zones of local minima of the intensity of the generated vibration field).

This postulate is based on the relevant conclusions of the Lagrange–Dirichlet theorem on the criterion of stability of the motion of a conservative system [10].

Postulate 3: The movement of an array of particles along the working body of a vibrating machine originates from the zone of greater total intensity of the induced vibration and gravitational fields to the zone of lower intensity in the direction of the gradient vector to the total intensity generated by the working body. The speed of this movement is proportional to the magnitude of the gradient, and the direction coincides with the direction of the gradient vector.

The postulate is based on the general conclusions of Lyapunov's theorem on the stability of the motion of a conservative system [10].

Postulate 4: The concentration of particles in an array subjected to gravitational and induced vibration fields in the direction of the normal from its sole moves from smaller to larger particles.

This behavior of particles is explained by the dependence of their vibrational motion on their own mass. The greater the inertia of a particle (and, accordingly, its mass as a measure), the smaller the space covered by the range of its vibration displacement. But in this case, the gaps that occur between the massive particles and the surface of the vibration-generating working body are filled with smaller particles with greater dispersion. These particles, forming a secondary generating surface, push the larger particles away from the massive sole. This continues until all the small particles, without exception, are located between the larger particles and the base of the array. Thus, under the influence of the applied vibration field in the stagnation zone of the particle array, its layer-by-layer structuring by particle size occurs over time, and in the movement zone of the array, a stable tendency to segregation of small particles to the surface of the working body arises.

Postulate 5: The resistance to sifting of particles through a vibrating sieving surface decreases when zones of concentration of large impassable particles occur.

This is due to the fact that the concentration of large particles in a limited area of the array reduces the obstacles to the flow of passable particles through the sieving surface in all remaining areas.

Postulate 6: The resistance to particle sifting through a vibrating sieving surface depends on the effective passage aperture of the surface opening.

The effective passing aperture of the aperture of a vibrating sieving surface with a certain amplitude should be understood as the difference between the aperture of the aperture and the transverse direction of its oscillations. Here, the effect of back reflection of particles that collide with the perimeter of the vibrating hole is observed. This effect depends on many factors: the nature of the vibrational motion of the hole; its location in the generated vibration field; the geometry of the holes of the seeding surface and the shapes of the material particles that come to contact with their walls.

Decomposition of the generated vibration field intensity by the characteristic directions of the working body contact surface

The acceleration of any point of the working body of a vibrating machine, as an absolutely solid body, will be determined by the vector sum of the acceleration of its center of mass and the acceleration of the point in question in rotation around the center of mass:

$$\vec{a}_i(t) = \vec{a}_C(t) + \frac{d^2}{dt^2}\left\{\int [\vec{\omega}(t) \times \vec{r}_{iC}]dt\right\}, \tag{1}$$

where $\vec{a}_C(t)$ is the linear acceleration of the center of mass of the working body as a function of time, $\vec{r}_{iC}$ is the radius vector of the position of the selected point of the working body relative to its center of mass and $\vec{\omega}(t)$ is the vector of angular velocity of rotation of the working body of a vibrating machine around its center of mass as a function of time.

Eq (1) determines the intensity vector of the generated vibration field at any point of the working body of the vibrating machine. The coordinate system associated with the working body and the angles of the axes are shown in Figure 1.

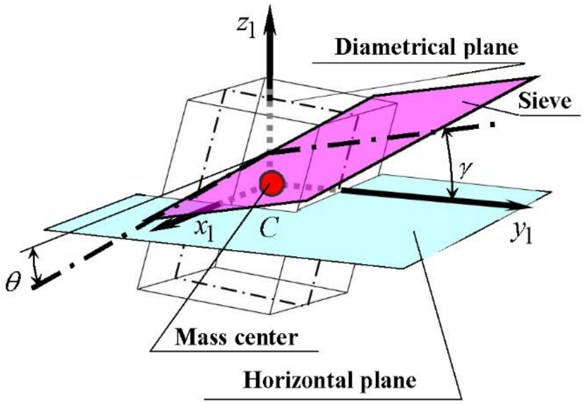


Figure 1. The coordinate system associated with the working body and the angles of the sieve installation

Typically, it is of practical interest to study the motion of an array of timing bars on a sieving surface. Let us determine the projections of the intensity vector of the generated vibration field at each point of an absolutely rigid sieve onto the normal and tangential axes.

Angle of inclination of the sieve surface around the axis C_{x1} mark γ, and its angle of inclination around its longitudinal axis C_{y1}, accordingly, Θ. These angles will be calculated by following the right-hand screw rule for each of the indicated turns (i.e., the directions of inclination shown in the figure will be considered positive).

If the intensity vector of the generated vibration field is defined in the axes is $x_1y_1z_1$, we can find its projections on the axes associated with the normal and two perpendicular tangents to the sieve surface. To do this, we will use linear transformations, taking into account the fact that two consecutive rotations of the coordinate axes have been made. The first transformation is associated with the rotation of the sieve by an angle γ around the axis C_{x1}, and the second one with the sieve rotated at an angle Θ around its longitudinal axis C_{y1}. Let's make the matrices of these sequential transformations:

$$[\gamma] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\gamma & \sin\gamma \\ 0 & -\sin\gamma & \cos\gamma \end{bmatrix}; \quad (2)$$

$$[\theta] = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix}. \quad (3)$$

The acceleration vector of any point of the sieve of the working body of the vibrating tire in the projections on its normal axis, as well as on the longitudinal and transverse axes, will take the form:

$$\vec{a}_{ei}(t) = [\theta] \cdot [\gamma] \cdot \vec{a}_i(t). \quad (4)$$

Thus, the vibration field intensity generated by the working body of the vibrating machine for the points of the considered absolutely solid sieve in its characteristic directions can be calculated by Eq (4).

Calculation of the main vector of generated stress by the characteristic directions of the sieve surface

The particle is affected by the intensity vector of the generated vibration field, but at the same time it is constantly under the influence of the gravitational field. Given that the axes of the absolute coordinate system coincide with the vertical and horizontal planes (by preliminary assumptions), we can represent the effect of the gravitational field similarly to the generated vibration effect. By analogy with (4), the gravitational field strength vector can be represented in projections on the sieve plane and the normal to it, as follows:

$$\vec{g}_{ei}(t) = [\theta] \cdot [\gamma] \cdot \vec{g}, \quad (5)$$

where g is the acceleration of free fall.

The need for this approach is caused by the possible variability in time of the respective angles of the sieve installation for design reasons or due to the accounting of its deformation, if necessary.

The main stress vector generated as a result of the action of both fields is equal to the vector sum of the corresponding stress vectors:

$$\vec{A}_{ei}(t) = \vec{g}_{ei(t)} + \vec{a}_{ei}(t). \quad (6)$$

Or in an expanded form, after removing the common factors

$$\vec{A}_{ei}(t) = [\theta] \cdot [\gamma] \cdot [\vec{a}_i(t) + \vec{g}], \quad (7)$$

where, in the global system, the initial projections of the gravitational component are given by a vector of the form:

$$\bar{g} = \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix}. \tag{8}$$

Calculation of the induced stress in projections on the characteristic axes of the sieve

It is known that the friction force of particles on a surface is defined as the product of the friction coefficient and the normal pressing force. Then, the acceleration of the particle along the bearing surface will be determined by a part of the normal acceleration to this surface.

The projection of the main generated stress vector onto the plane of the système in absolute value is determined by the relation:

$$[A_{ei}(t)]_\tau = \left| \sqrt{[A_{ei}(t)]_x^2 + [A_{ei}(t)]_y^2} \right|. \tag{9}$$

The directional vectors of the projection of the main generated stress vector onto the sieve plane:

$$\left[\vec{u}_{A_{ei}}\right]_\tau = \begin{bmatrix} \dfrac{[A_{ei}(t)]_x}{|[A_{ei}(t)]_\tau|} \\ \dfrac{[A_{ei}(t)]_y}{|[A_{ei}(t)]_\tau|} \\ 0 \end{bmatrix}. \tag{10}$$

The normal projection of the generated stress vector in terms of its algebraic value can be obtained from (7):

$$[A_{ei}(t)]_n = [A_{ei}(t)]_z \tag{11}$$

The vector of this projection is fully transmitted to the particle by its unconditional connection with the sieve surface in the normal direction. Therefore, the vector of the induced elasticity in the normal direction to the sieve will take the form:

$$\left[\vec{A}_{ri}(t)\right]_n = [A_{ei}(t)]_n \cdot \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}. \tag{12}$$

The part of the projection of the main vector that is transmitted to the particle of the generated stress on the sieve plane will be determined by the law of friction in its absolute value:

$$|[A_{ri}(t)]_\tau| = k \cdot |[A_{ei}(t)]_n|. \tag{13}$$

The directionality of this vector completely coincides with the directional vector (8). Thus, the force acting on the particle in the sieve plane is completely determined by the strength of the induced field in this direction, the vector of which takes the form

$$\left[\vec{A}_{ri}(t)\right]_\tau = |[A_{ri}(t)]_\tau| \cdot \left[\bar{u}_{A_{ei}}\right]_\tau. \tag{14}$$

Thus, the intensity vector of the induced field can be represented as the geometric sum of the normal (12) and its tangential component (14):

$$\vec{A}_{ri}(t) = \left[\vec{A}_{ri}(t)\right]_n + \left[\vec{A}_{ri}(t)\right]_\tau. \tag{15}$$

To take into account the effect of the one-way coupling of the particle and the sieve along the normal axis, we have to discard all values of the vector that correspond to negative values of its projection onto the normal. At negative values of its normal component, only the gravitational field will act on the particle according to the law (5) with regard to (8). That is, it is necessary to create an additional condition for the existence of the induced stress vector so that its real values can be chosen:

$$\vec{A}_{ri}(t) = \begin{cases} \vec{A}_{ri}(t), \text{provided that } [A_{ei}(t)]_n \geq 0 \\ \vec{g}_{ei}(t), \text{provided that } [A_{ei}(t)]_n < 0 \end{cases} \tag{16}$$

Thus, the distribution function of the induced field for a material particle located at any point on the surface of contact with the working body of a vibrating machine has been determined.

As can be seen, the resulting vector function depends on three variable parameters: two coordinates of the particle's position on the sieve surface and time. To simplify the analysis of the behavior of the particle flow formed by the sieve surface, we can use the averaged effective parameters of the above equation.

Determination of the parameters of the flow of material particles on the surface of contact with the working body of the vibrating machine

The strength of the induced field perceived by a material particle is actually the acceleration it acquires at a given point on the contact surface. From a practical point of view, it makes sense to consider the motion of a whole array of points rather than one particular point. In this case, the nature of the motion of an array of particles is subject to generalized postulates.

In some cases, it will be useful to consider effective parameters rather than real ones. By effective parameters, we mean the integral value of the induced field for the period of a single oscillation of the working body. We distinguish between the effective nodal stress, as well as the effective longitudinal and effective transverse stress of the induced field.

The effective nodal induced stress is determined for the selected node of the geodesic grid of the sieve. If we denote the number of the transverse grid node as *i* and the longitudinal node as *j*, we have

$$\vec{A}_{ref}(t,i,j)=\begin{bmatrix}\frac{1}{T}\cdot\int_0^T A_r(t,i,j)_x dt\\ \frac{1}{T}\cdot\int_0^T A_r(t,i,j)_y dt\\ \frac{1}{T}\cdot\int_0^T A_r(t,i,j)_z dt\end{bmatrix}. \tag{17}$$

The effective transverse induced stress is determined along the transverse and longitudinal geodesic lines of the working surface, respectively

$$\left[\vec{A}_{ref}(t,i,j)\right]_i=\frac{1}{T}\cdot\int_0^T A_{ri}(t,i,j)_x dt; \tag{18}$$

$$\left[\vec{A}_{ref}(t,i,j)\right]_j=\frac{1}{T}\cdot\int_0^T A_r(t,i,j)_{jy} dt. \tag{19}$$

Based on the effective values of the stress vector, it becomes possible to make a general assessment of the motion of the array of particles located on the working surface of the working body of the vibrating machine.

The directionality of the particle flow along the working surface can be estimated by the directionality of the vector of the effective longitudinal intensity of the induced field. The longitudinal averaged flow velocity is determined by the ratio

$$\vec{V}_{rj}(t)=\int\left[\vec{A}_{ref}(t,i,j)\right]_j dt. \tag{20}$$

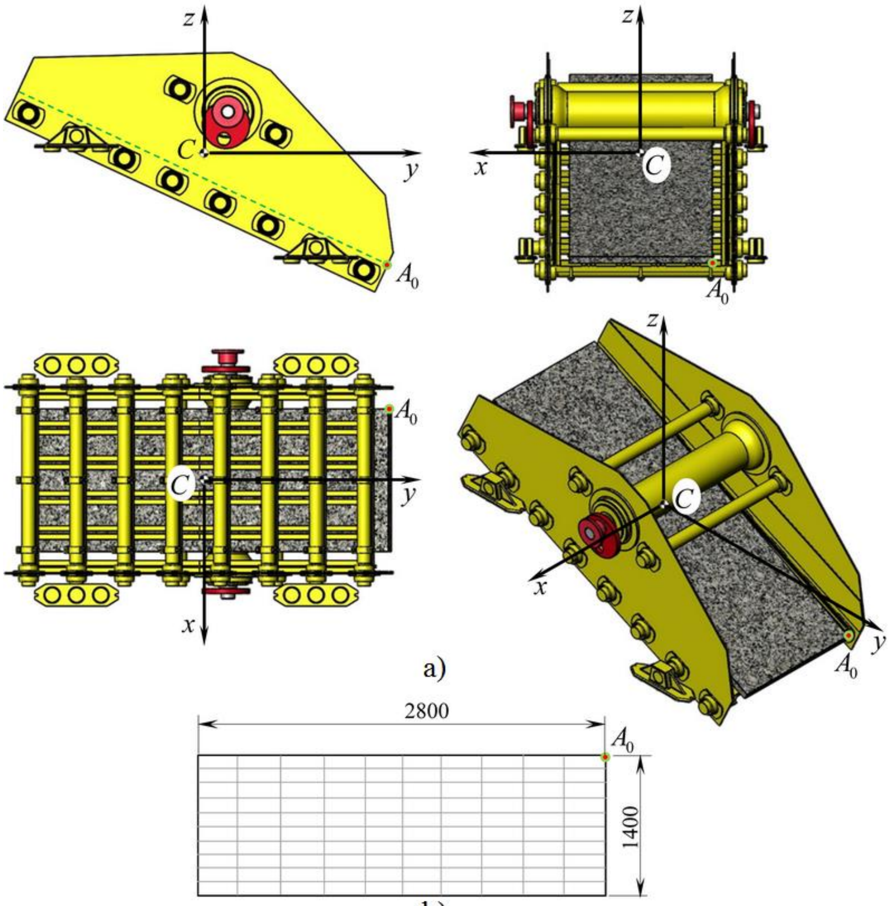
The next integration will give the law of the average longitudinal motion of the particle flow over the contact surface in time.

$$\vec{r}_r(t)=\int\vec{V}_{rj}(t)dt. \tag{21}$$

The law of change in the average transverse velocity of the particle flow and the law of this motion are determined in a similar way.

Results

In order to verify the adequacy of the above methodology, we performed calculation of the induced vibration field intensity along the sieve surface using as initial data the technical characteristics of a heavy-duty inertial screen GIT-51N (Figure 2) with a screening surface size of 1400×2800 mm, that is currently used in metallurgical production. To perform the calculation, we used the central coordinate system *C-xyz* (Figure 2, a), the origin of which is located the center of mass of the system *C*, and the axes are associated with the horizontal and vertical planes. The surface of the sieve was divided into nodal points using a geodesic grid superimposed on it, the initial node is designated as A_0 (Figure 2, b), in array of which the vibration field intensity function and the gradient of this function. During the operation of a screen loaded with bulk material, the sieve surface performs oscillatory movements, and its points describe an elliptical trajectory (Figure 3). The geometric dimensions and coordinates of the characteristic points are shown in Figure 3 in meters.



a)

b)

Figure 2. Calculation scheme: a) GIT-51N screen; b) sieve surface with nodal points

According to the calculation results, we obtained the following: the stress applied to the material stress as a function of time in the diametric plane on the unloading (Figure 4, a), central (Figure 4, b), and loading (Figure 4, c) parts, respectively, across, along, and along the sieve normal from left to right and its averaged over the period of oscillations at the nodal points of the sieve surface along (Figure 5, a), along the normal (Figure 5, b), and in the diametric plane.

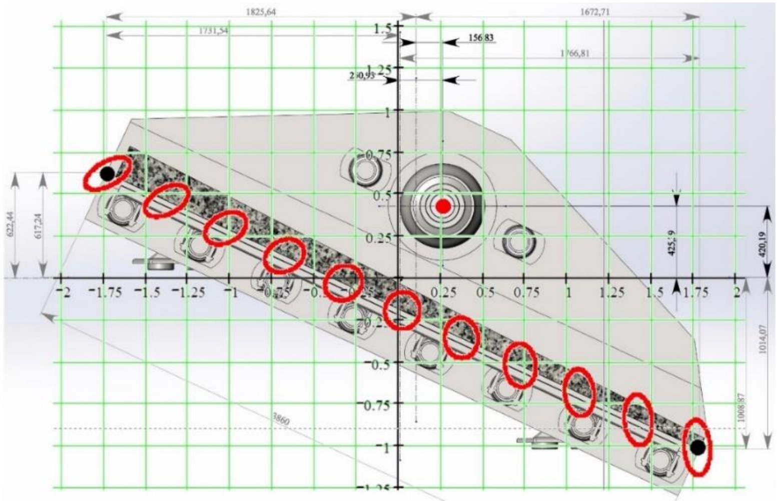
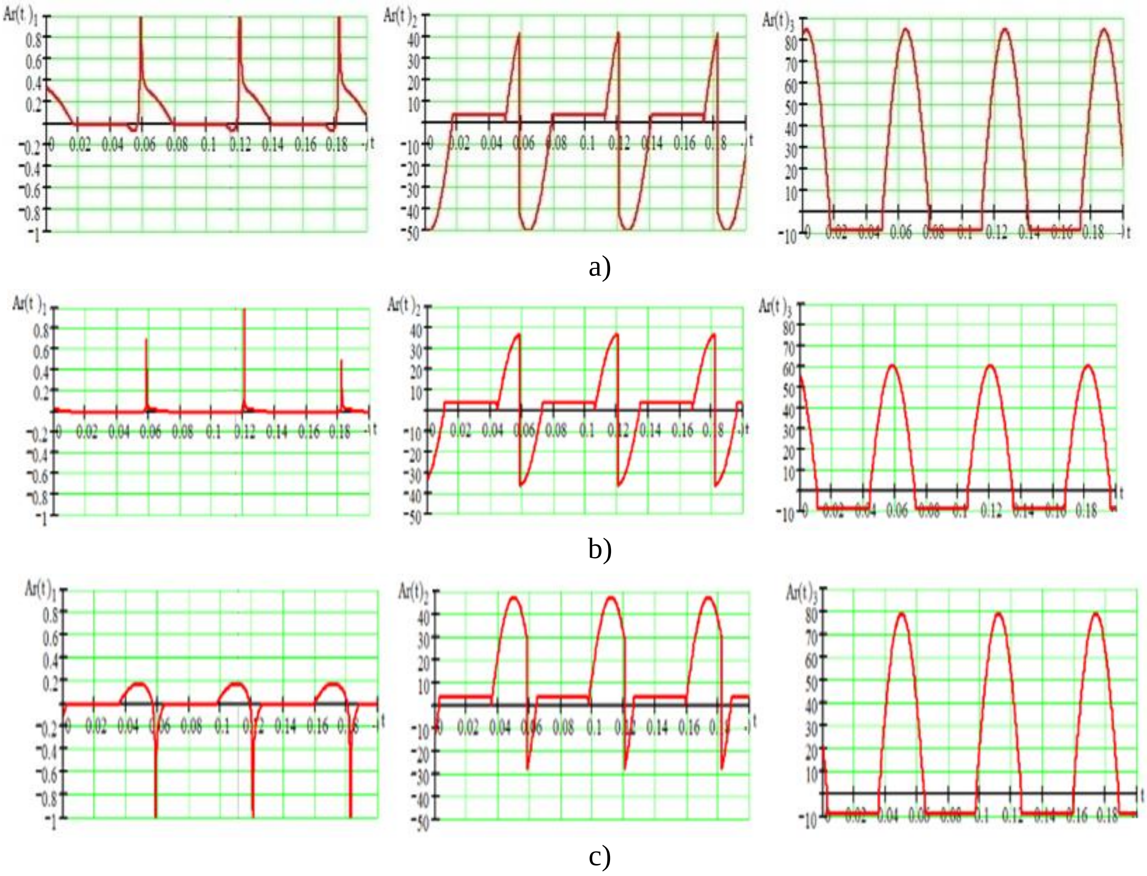


Figure 3. The trajectories of the points of the screening surface (coordinates on the axes are designated in meters)

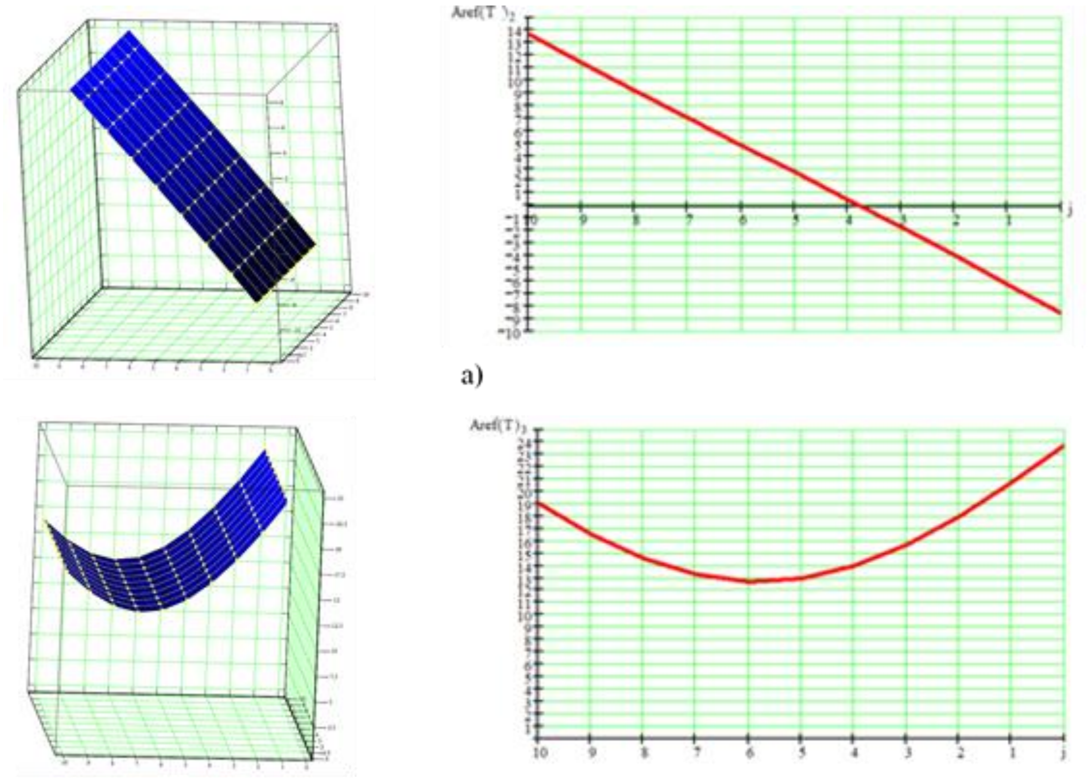


a)

b)

c)

Figure 4. Stresses applied to the material as a function of time in the diametric plane in different sections of the sieve (m/s^2) across, along, and along the normal of the sieve from left to right: a) stress applied to the material as a function of time in the diametric plane on the discharge side of the sieve; b) stress applied to the material as a function of time in the diametric plane in the center of the sieve; c) the stress applied to the material as a function of time in the diametric plane on the loading side of the sieve



a)

b)

Figure 5. The average stress (m/s^2) applied to the material during the period of sieve oscillation: a) along the sieve; b) normal to the sieve

Based on the obtained dependences of the distribution of the value of the material over the nodes of the geodesic grid of the sieve, it is clear that in nodes from 4 to 6, both along and normal to the sieve, the function has a minimum value, which indicates the presence of a zone with the lowest energy and, as a consequence, the concentration of particles processed by the vibrating working body.

To establish the speed and direction of movement of the particle array along the working body of the vibrating machine, the gradient of the function of the average stress applied to the material during the period of sieve oscillation along the nodes of the geodesic grid of the sieve surface (Figure 6).

From the results obtained, it can be seen that the highest rate of material movement is observed on the loading side of the sieve, and in the middle part of the sieve, there is a zone of stagnation of the material, which significantly reduces the feeding performance. From the experience of operating the analyzed vibrating machine, it was found that the screen has a performance lower than the declared one, due to the serious effect of material inhibition in the middle part of the sieving surface. This forced manufacturers to reduce its length, which led to an increase in the speed of movement of the material along the screen, but reduced the efficiency of its screening efficiency.

Thus, the results of theoretical research have been confirmed on practice.

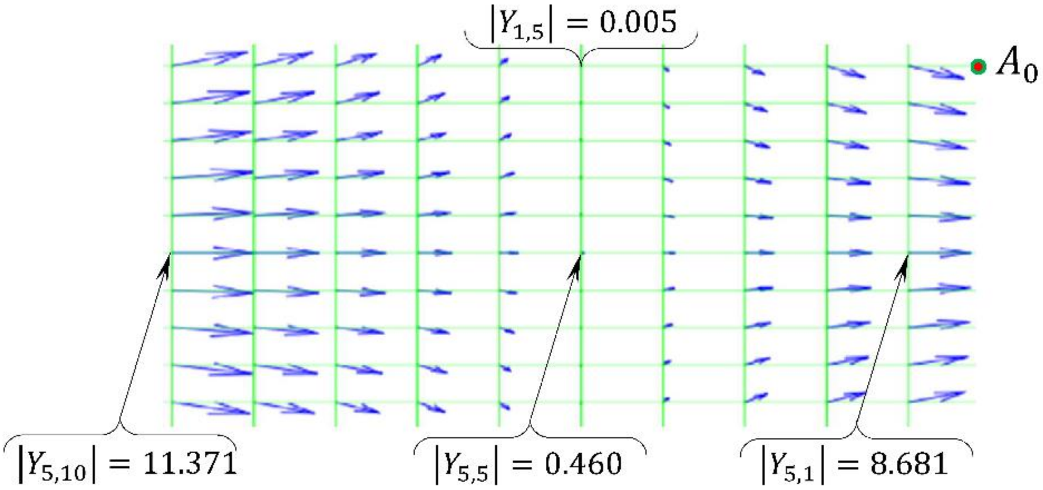


Figure 6. The gradient of the function of the average stress (m/s^2) applied to the material during the period of sieve oscillation

Conclusion

In the course of the study, the mechanism of material movement on the working surface of vibrating machines. Based on the analysis, it was found that the use of the average value of the inertia force does not allow taking into account the spatial and temporal distribution of vibration oscillations in the screen structure, which significantly affects the processes of transportation and sorting of bulk materials. In this research, the vibration effect on dry bulk materials is considered as the effect of a potential force field on them.

Based on the idea of the effect of the vibration force field intensity method for determining the parameters of material movement along the surface of the working body of the vibrating machine, which allows to choose its rational kinematic and dynamic parameters.

The proposed method is based on open software environments, which allow for numerical mathematical transformations of large data sets, allows predicting the behavior of the material in the process of transportation and can serve as a basis for further improvement of the design of vibrating machines. The results obtained are of practical importance for optimizing technological processes in various industries where vibration methods of transportation and sorting of bulk materials.

References

[1] Chenlong Duan, Jiale Yuan, Miao Pan, Tao Huang and others. Variable elliptical vibrating screen Particles kinematics and industrial application. *International Journal of Mining Science and Technology*, 31(6):1013–1022, 2021. https://doi.org/10.1016/j.ijmst.2021.07.006

[2] Elskamp. F. and Kruggel–Emden H. Review and Benchmarking of Process Models for Batch Screening based on Discrete Element Simulations. *Advanced Powder Technology*, 26(3):679–697, 2015. https://doi.org/10.1016/j.apt.2014.11.001

[3] Franchuk V.P., Naduty V.P. and Levchenko P.V. Determination of the trajectory of motion of the material, taking into account the transverse oscillations vibrating screen. *Proceedings of the National Technical University. Series: Chemistry, Chemical Engineering and Environment*, 57 (965):142–148, 2013.

[4] Guifeng Wang, Xin Tong. Screening efficiency and screen length of a linear vibrating screen using DEM 3D simulation. *Mining Science and Technology*, 21(3):451–455, 2011.
https://doi.org/10.1016/j.mstc.2011.05.026

[5] Haddad, Jamil and Momani, Waleed. A comparison of two theoretical methods of the materials transportation in the vibrating screen machines and improve the significance of their experimental results. *IOSR Journal of Mechanical and Civil Engineering*, 11(4):46–52 2014.
https://doi.org/10.9790/1684-11484652

[6] Jianzhang Xiao, Xin Tong. Characteristics and efficiency of a new vibrating screen with a swing trace. *Particuology*, 11(5):601–606, 2013.
https://doi.org/10.1016/j.partic.2012.07.014

[7] Kruggel-Emden Harald, and Frederik Elskamp. Modeling of screening processes with the discrete element method involving non-spherical particles. *Chemical Engineering & Technology*, 37(5):847–856, 2014.
https://doi.org/10.1002/ceat.201300649

[8] Lala ZHAO, Chusheng LIU, Junxia YAN. A virtual experiment showing single particle motion on a linearly vibrating screen-deck. *Mining Science and Technology*, 20(2):276–280, 2010.
https://doi.org/10.1016/S1674-5264(09)60197-6

[9] Lu J X, Liu C S, Nie J Z, Cao Z F. Kinetic characteristic analysis of single particle during process of screening of vibration screen. Coal Mine *Machinery*, 28(11):66–68, 2007.

[10] M.A. Pavlovsky. *Theoretical mechanics*. Technika, Kyiv, 2002.

[11] Rahul K. Soni, Soni Jaiswal, S. Dash, C. Eswaraiah. CFD and DEM numerical modelling of industrial vibrating desliming screen for performance optimization and minimal misplacement. *Powder Technology*, 426:118630, 2023.
https://doi.org/10.1016/j.powtec.2023.118630

[12] M.I. Sokur, V.S. Biletsky, O.I. Egurnov, O.M. Vorobyov, V.O. Smirnov, D.P. Bozhyk. Preparation of minerals for enrichment. Shcherbetykh, Kremenchuk, 2007.

[13] A.D. Uchitel, V.V. Severnyuk, V.P. Lyalyuk, V.I. Bolshakov, *Sorting of mineral raw materials and charges on vibrating screens*. Porogi, Dnipropetrovsk, 1998.

[14] L.A. Vaisber, A.N. Korovnikov, V.A. Trofimov A new generation of highly efficient screens for bulk materials and pulps. *Ore dressing*, 5: 25–28, 2001.

[15] Xiaoqiu Wu, Zhanfu Li, Huihuang Xia and Xin Tong. Vibration Parameter Optimization of a Linear Vibrating Banana Screen Using DEM 3D Simulation. *Journal of Engineering and Technological Sciences*, 50(3):346–363, 2018.
https://doi.org/10.5614/j.eng.technol.sci.2018.50.3.3

[16] V.I. Zaselsky *Inertial screens with inhomogeneous vibrations*. Porogi, Dnipropetrovsk, 2007.

[17] V.I. Zaselskiy, D.V. Popolov, I.G. Ivanov, M.I. Shepelenko, D.V. Sagalay. Preparation of Coking Batch in Vibrational Impact Equipment. *Coke and Chemistrythis*, 64(4): 163–168, 2021. https://doi.org/10.3103/s1068364x21040098

[18] V. Zaselskiy, D. Popolov, H. Zaytsev, M. Shepelenko. Upgrade of conveyor line for coal charge preparation with the use of modern grading-and-mixing equipment. *Science and Innovation*, 17(3): 67–77, 2021. https://doi.org/10.15407/scine17.03.067

[19] V.I. Zasel'skiy, D.V. Popolov, G.L. Zaytsev, D.V. Sagalay. Steeply Inclined Vibrational Screen in Coal Preparation at Coke Plants. *Coke and Chemistrythis*, 63(7): 351–355, 2020. https://doi.org/10.3103/S1068364X20070078

[20] V.Y. Zaselsky. Technological requirements for sinter screens. *Metallurgical and Mining Industry*, 5:105–107, 2007.

[21] V.Y. Zaselskyi, D.V. Popolov, G.L. Zaitsev, S.V. Blodidenko et al. *Improvement of equipment and processes of coal preparation and coke sorting in metallurgical production*. Literiy, Kryvyi Rih 2019.

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