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Laboratory studies on the effect of vibro-impact action of the screening surface on the main technological indicators of metallurgical raw material screening

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Дослідження впливу віброударної дії просіювальної поверхні на основні технологічні показники грохочення металургійної сировини

Abstract. *The article presents the results of a study on the effect of vibro-impact action of the screening surface on the main technological indicators of metallurgical raw material screening. The screening process is one of the key technological operations in the preparatory processes of metallurgical production, as it directly influences the quality of raw material fractionation and process productivity. The issue of screen aperture clogging significantly limits the efficiency of screening, leading to a decrease in the quality of prepared charge and an increase in energy costs. The purpose of the study is to investigate the effect of vibro-impact action of the screening surface on aperture clogging and the productivity indicators of metallurgical raw material screening. To achieve this goal, a laboratory model of a vibratory screener was developed, allowing for the simulation of various vibration modes of the box and studying their impact on the raw material screening process. The research methodology included a series of experiments with varying amplitude and angular frequency of box oscillations, analysis of the results using mathematical statistics methods, and the construction of mathematical models of the dependence of transportation productivity and clogging coefficient on vibration parameters. Experiments were conducted for two types of screening surfaces – fixed and freely laid, which allowed for assessing the impact of vibro-impact loads on screen aperture self-cleaning. The results showed that maximum transportation productivity is achieved at a forced oscillation amplitude of* $2\cdot10^{-3}$ *m and an acceleration of 28…32* m/s^2*. At the same time, the clogging coefficient significantly decreases at an amplitude of 1.8…2.2*$\cdot10^{-3}$ *m and an oscillation frequency of 94.2…102* s^{-1}*. The constructed mathematical models allow predicting changes in the technological parameters of the process depending on the dynamic characteristics of the box and assist in selecting optimal operating modes for vibratory screeners. The scientific novelty of the work lies in determining the effect of vibro-impact action on the efficiency of metallurgical raw material screening and forming new approaches to reducing screen surface clogging. The practical significance of the study is due to the possibility of using the obtained results to modernize existing screeners and develop new designs with improved technological characteristics, which will contribute to enhancing the efficiency of preparatory processes in metallurgical production.*
Key words: *screening, vibro-impact action, screening surface, productivity, clogging, metallurgical raw materials, mathematical modeling.*

Анотація. *У статті представлено результати дослідження впливу віброударної дії просіювальної поверхні на основні технологічні показники грохочення металургійної сировини. Процес грохочення є однією з ключових технологічних операцій у підготовчих процесах металургійного виробництва, оскільки безпосередньо впливає на якість фракціонування сировини та продуктивність процесу. Проблема забивання отворів сита значно обмежує ефективність грохочення, що призводить до зниження якості підготовленої шихти та збільшення енергетичних витрат. Метою дослідження є вивчення впливу віброударної дії просіювальної поверхні на забивання отворів та показники продуктивності грохочення металургійної сировини. Для досягнення цієї мети було розроблено лабораторну модель вібраційного грохота, яка дозволяє імітувати різні режими коливань короба та досліджувати їхній вплив на процес грохочення сировини. Методика дослідження включала серію експериментів зі змінними амплітудою та кутовою частотою коливань короба, аналіз результатів методами математичної статистики та побудову математичних моделей залежності транспортної продуктивності та коефіцієнта забивання від параметрів вібрації. Експерименти проводилися для двох типів просіювальних поверхонь – закріпленої та вільно покладеної, що дозволило оцінити вплив віброударних навантажень на самоочищення отворів сита. Результати показали, що максимальна транспортна продуктивність досягається при амплітуді вимушених коливань* $2\cdot10^{-3}$ *м та прискоренні 28…32 м/с². Водночас коефіцієнт забивання значно зменшується при амплітуді 1,8…2,2*$\cdot10^{-3}$ *м та частоті коливань 94,2…102* $с^{-1}$*. Побудовані математичні моделі дозволяють прогнозувати зміни технологічних параметрів процесу залежно від динамічних характеристик короба та сприяють вибору оптимальних режимів роботи вібраційних грохотів. Наукова новизна роботи полягає у визначенні впливу віброударної дії на ефективність грохочення металургійної сировини та формуванні нових підходів до зменшення забивання просіювальних поверхонь. Практична значущість дослідження зумовлена можливістю використання отриманих результатів для модернізації існуючих грохотів та розробки нових конструкцій з покращеними технологічними характеристиками, що сприятиме підвищенню ефективності підготовчих процесів у металургійному виробництві.*
Ключові слова: *грохочення, віброударна дія, просіювальна поверхня, продуктивність, забивання, металургійна сировина, математичне моделювання.*

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Introduction

Screening is one of the most important technological operations in the preparatory processes of metallurgical production, as it significantly affects the production cost during the sintering or smelting of raw materials. Currently, various types of inertial screeners are widely used for the fractionation of metallurgical raw materials, differing in size as well as dynamic and kinematic parameters. These parameters determine the key technological indicators of the screening process, such as productivity, efficiency in removing unsuitable product fractions, and the degree of clogging of the screening surface with difficult-to-screen particles.

The productivity of screening is determined by the requirements of the technological line in metallurgical production, whereas the efficiency and clogging of the screening surface depend not only on productivity but also on the optimal choice of dynamic and kinematic parameters. However, the efficiency of screening under current conditions remains insufficient, requiring improvement. The main problem is the clogging of the screening surface, which limits the possibility of increasing the efficiency of the process in existing inertial screeners. This is due to the fact that the acceleration of their working elements is limited to the range of (1.5…3)·g, which is insufficient for modern fractionation requirements of metallurgical raw materials.

Thus, finding ways to intensify the screening process to reduce screening surface clogging and increase fractionation efficiency without losing the necessary productivity is a relevant task. Research in this area is of great importance for optimizing the preparatory processes of metallurgical production.

Literature review and problem statement

The most commonly used screeners in the mining and metallurgical industry for removing fines are center-of-mass machines with unbalanced vibration exciters operating in the sub-resonant region. These machines are characterized by simple construction, good vibration isolation, and fairly stable operating modes. However, the intensity of the working element's impact on the material in such screeners is low and distributed randomly across stages. Additionally, the kinematic parameters of the working element are chosen independently of the properties of the screened material. Studies [1-6] provide the main structural and dynamic parameters, as well as technological indicators, of the most common screeners.

According to these studies, oscillation frequency ranges from 73 to 96 s^{-1}; oscillation amplitude from 3 to 6 mm; vibration angle from 30° to 50°; sieve inclination angle from 0° to 18°; specific productivity from 40 to 60 $t/h \cdot m^2$; specific metal consumption from 400 to 3600 kg/m^2; and specific power from 2 to 7.2 kW/m^2.

The analysis of screen surface clogging depending on oscillation accelerations is well-detailed in [7], where it was found that the clogging degree ranges from 58 to 70% at accelerations of 26…32 m/s^2. Thus, the screening efficiency remains very low – between 28 and 50 %, which does not meet modern requirements and fails to adequately prepare charge materials for sintering and smelting. According to the research in [8], significant improvements in blast furnace performance can be achieved if screening efficiency reaches at least 70…75 %.

This level of efficiency can be achieved by reducing the clogging of screen apertures if sufficient acceleration is applied to the screening surface. According to [9], the required accelerations for sinter fractions of 5 mm should reach 54 m/s^2, as shown in Fig. 1.

However, the implementation of such accelerations is possible at a vibration machine operating mode coefficient of (5.5…6.2)·g, which significantly exceeds the recommended value of (1.5…3)·g when designing vibration machines [10]. Such high dynamic modes lead to a significant reduction in the reliability of the main working elements and result in an increase in the metal and energy intensity of the overall process of screening metallurgical raw materials.

Therefore, conducting research aimed at identifying ways to intensify the screening process of metallurgical raw materials before sintering and melting through the application of vibrational-impact loading is fully justified and represents an important scientific task.

Research objective and tasks

The objective and tasks of the research involve studying the impact of vibrational-impact action of the screening surface of the screen on its clogging and the performance indicators of screening metallurgical raw materials.

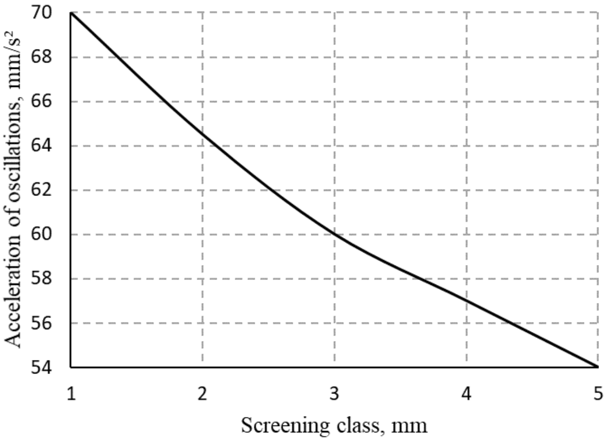


Figure 1. Dependence of the acceleration values ensuring the non-clogging of the screening surface openings on the class of agglomerate screening.

Materials and research methods

To study the impact of vibrational-impact action on the technological indicators of the screen, a laboratory model was developed, as shown in Fig. 2.

As optimization parameters that most fully reflect the technological efficiency of the vibrating screen, transport capacity and screen surface clogging were selected.

The factors considered were parameters that fully characterize the state of the dynamic system – angular frequency of forced box oscillations (ω = 94.2 s^{-1}; ω = 125.6 s^{-1}; ω = 157 s^{-1}) and their amplitude (A = 0.001 m; A =0.002 m; A = 0.003 m).

The inclination angle of the screen surface to the horizontal plane and the vibration angle to the normal drawn to the supporting surface of the underscreen frame in the longitudinal plane remained constant across the entire range of factor values and were equal to α = 10° and β = 45°, respectively.

The studies were conducted with directed box oscillations using both fixed and freely placed screen surfaces.

For the experiments, methods of mathematical processing of the results were applied in accordance with the requirements of the theory of mathematical statistics. [11]

Transport capacity was determined using a solid bottom surface (see item 11 in Fig. 2) without the dividing knife (item 12) by measuring the time required t_{fill} to fill the receiving hopper (item 13) with a transported material mass m_{mat}, according to the formula:

$$Q_{\text{тр}} = \frac{m_{mat}}{t_{fill}} \text{kg}/s. \qquad (1)$$

The experiments were conducted with a constant material layer height H_{lh} = 60 mm, varying the angular frequency of forced box oscillations and their amplitude. For each combination of factors, the tests were repeated three times. Limestone with a fraction size of 1.6…3 mm was used as the test material.

The clogging of the screen surface was evaluated using the clogging coefficient, determined by the formula

$$K_{clo} = \frac{S_{cl}}{S_{o.a}} \cdot 100\ \%, \qquad (2)$$

where S_{cl} is the area of clogged openings on the screen surface (m²), and $S_{o.a}$ is the open area of the screen surface (m²).

The clogging patterns of the screen surface were assessed by photographing it after each experiment for every pair of dynamic parameters. The box executed directed harmonic stable oscillations with both fixed and freely placed screens.

Screen clogging tests used agglomerate fines with a granulometric composition selected to maximize aperture clogging. For a screen surface with circular apertures of 5 mm diameter, a fraction size of 5…6 mm was applied. The experiments were conducted under constant specific loading for the feed input, maintaining a constant layer height of 60 mm.

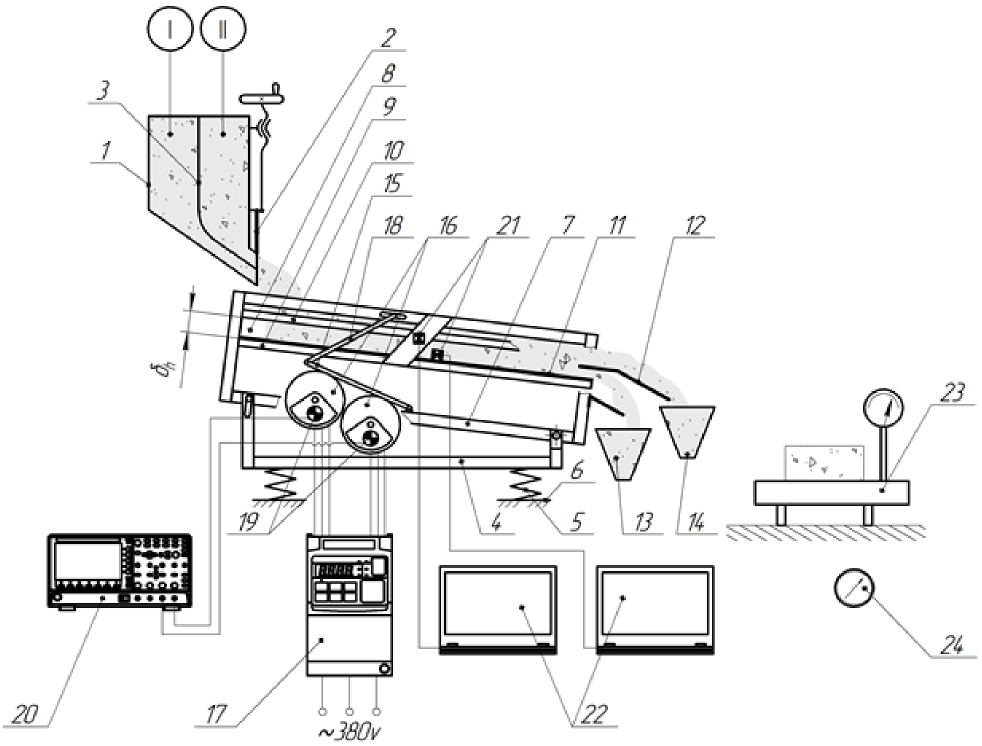


Figure 2. Structural diagram of the laboratory stand: 1 - hopper; 2 - slide gate valve; 3 - partition; 4 - carriage; 5 - spring supports; 6 - foundation; 7 - frame; 8 - box; 9 - fixed support angle bracket; 10 - movable support angle bracket; 11 - screening surface; 12 - dividing knife; 13, 14 - receiving hopper; 15 - sub-vibrator plate; 16 - motor vibrator; 17 - frequency converter; 18 - rod; 19 - phase sensor; 20 - oscilloscope; 21 - acceleration sensor; 22 - laptop; 23 - electronic scales; 24 – stopwatch.

Research results

Fig. 3 presents the dependencies of transport productivity on the amplitude and angular velocity of box oscillations with both fixed and freely laid sieve surfaces.

The figure shows that, within the studied range, the transport productivity function exhibits a stable dependence on the amplitude of the box oscillations and the angular frequency, with the functional relationship having an extreme nature. Considering that under identical dynamic parameters of the box, the transport productivity of the screener with a fixed sieve surface exceeds that of the vibratory-impact machine with a non-rigid connection between the box and the sieve, this confirms the necessity of ensuring the required transport speed of the sieved material by increasing the inclination angle of the sieve surface, due to the specifics of its galloping mode.

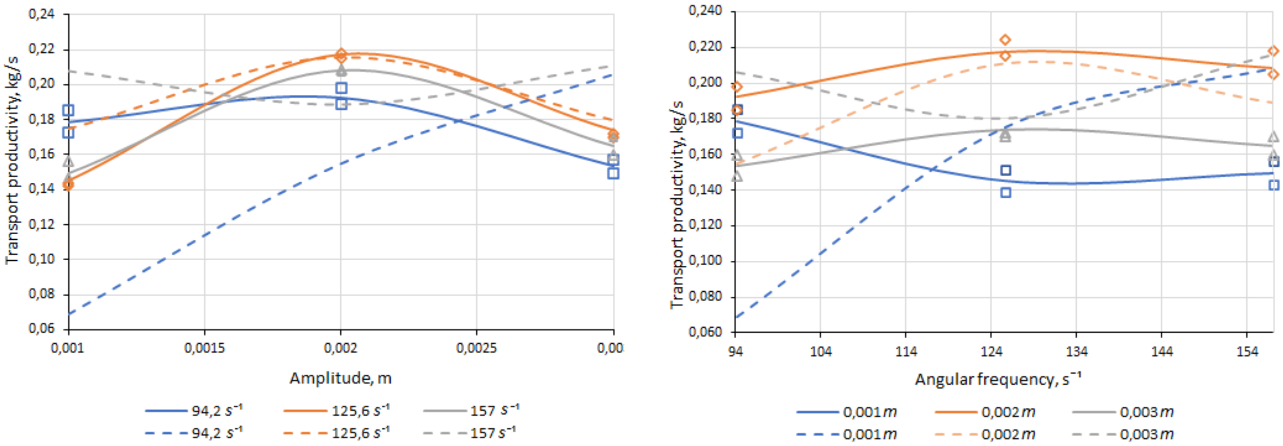


Figure 3. Dependence of transport productivity on the amplitude (a) and angular frequency (b) of box oscillations.

The distinct nature of the functional dependencies of the transport productivity for the screener with fixed and freely laid sieve surfaces indicates the impossibility of adapting existing theoretical models for transport productivity assessment through the determination of corrective coefficients. Therefore, to study the influence of the selected factors on the transport productivity of the vibratory-impact machine with a non-rigid connection between the box and the sieve, a full factorial experiment was conducted, implementing an orthogonal second-order plan matrix.

The mathematical description of the dependence of transport productivity on the selected factors was performed using a quadratic regression equation, which was verified for adequacy using Fisher's criterion and presented as follows

$$Q_{tr} = 0{,}0154 + 78 \cdot A + 0{,}0015 \cdot \omega + 0{,}5732 \cdot A \cdot \omega - \\ -34000 \cdot A^2 - 9{,}94 \cdot 10^{-6} \cdot \omega^2 \;\; kg/s, \qquad (3)$$

where A – amplitude of forced box oscillations, m; ω – angular frequency of oscillations, s^{-1}.

The obtained regression equation (3) represents a mathematical model that demonstrates the influence of the box's dynamic parameters – amplitude (ranging from 0.001 to 0.003 m) and angular frequency (ranging from 94.2 to 157 s^{1}) on the transport productivity of the vibratory-impact machine with a non-rigid connection between the box and the sieve, at a 20 % significance level.

The derived mathematical model (3) was subjected to graphical analysis, which allowed determining the extent of each factor's influence on the optimization parameter (Fig. 4).

The obtained surface graph shows that the maximum transport productivity of the vibratory-impact machine with a non-rigid connection between the sieve and the box, which performs directed, harmoniously stable oscillations, is achieved under oscillation conditions with acceleration of 28…32 m/s² at an amplitude of 0.002 m.

Fig. 5 illustrates the dependence of the clogging coefficient on the amplitude and angular frequency of the box oscillations and includes a photo of the sieve surface from one of the experimental studies of its clogging.

The obtained graphs show that the clogging coefficient of the freely placed sieve surface, unlike the fixed one, is on average 10 times lower under identical dynamic parameters of the box. This indicates a more efficient selfcleaning process of the sieve surface apertures in vibratory-impact machines with a non-rigid connection between the sieve and the box.

The amplitude of box oscillations has the greatest impact on the self-cleaning process, characterized by a decreasing nonlinear dependence with asymptotic convergence. As the amplitude increases to 0.002 m and the box acceleration reaches 32 m/s², the clogging coefficient decreases, reaching its minimum of 0.035%. Further increases in amplitude have little effect on it, indicating stabilization of the process and the establishment of a constant level of sieve surface clogging.

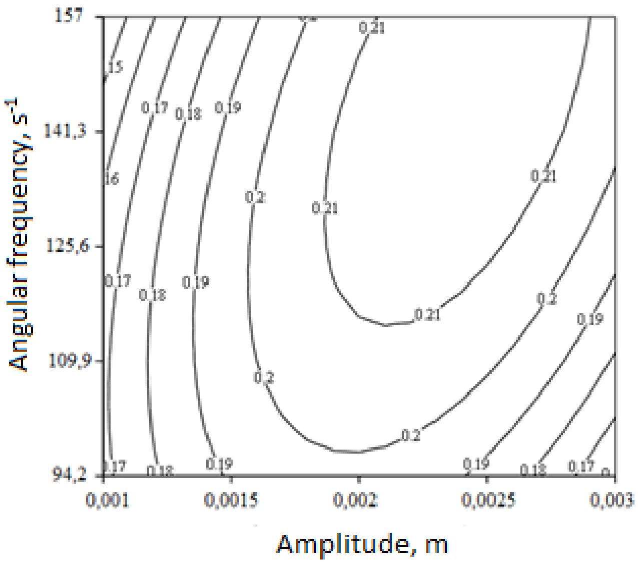
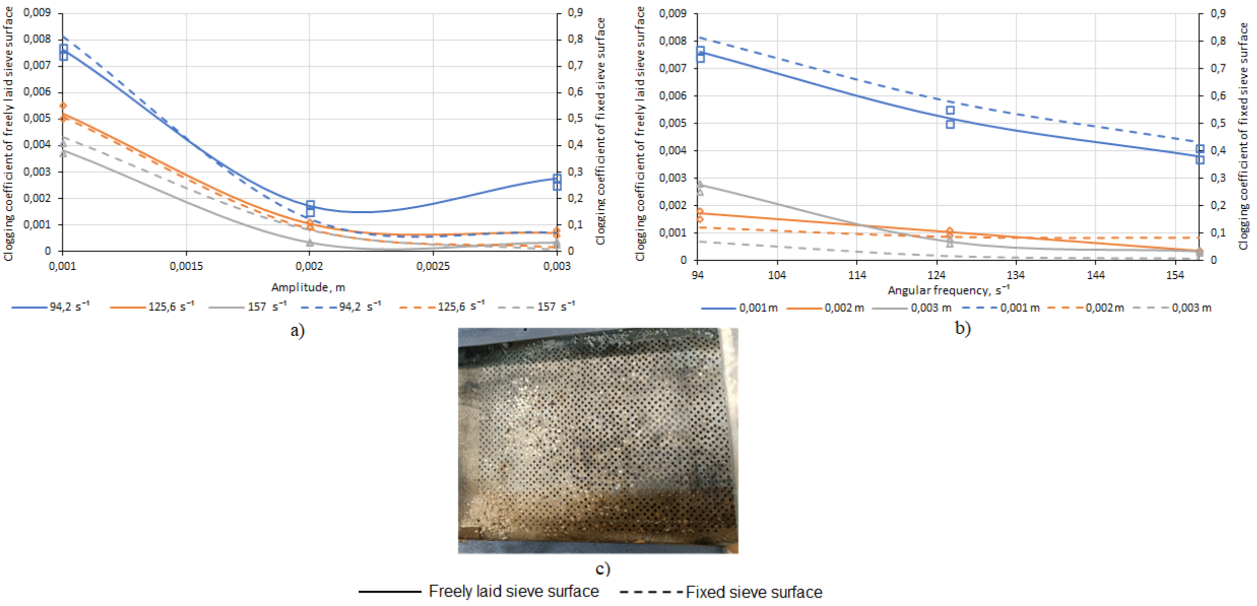


Figure 4. Dependence of transport productivity on the amplitude and angular frequency of box oscillations.



a)

b)

c)

Freely laid sieve surface
Fixed sieve surface

Figure 5. Dependence of the clogging coefficient on the amplitude (a) and angular frequency (b) of box oscillations; c – sieve surface.

To study the interaction between the amplitude of the forced oscillations of the vibratory-impact machine's box with a non-rigid connection and their angular frequency on the clogging coefficient of the sieve surface, a full factorial experiment was conducted using an orthogonal second-order design matrix.

The mathematical description of the dependence of the sieve surface clogging coefficient on the selected factors was performed, as in the case of the screening productivity analysis, using a quadratic regression equation that was verified for adequacy using Fisher's criterion

$$K_{clo} = 0{,}003 - 1610 \cdot A + 0{,}035 \cdot \omega + 1{,}115 \cdot A \cdot \omega + 340000 \cdot A^2 - 0{,}0002 \cdot \omega^2\ \%. \qquad (4)$$

The obtained equation is also a mathematical model demonstrating the influence of the box's dynamic parameters – amplitude (ranging from 0.001 to 0.003 m) and angular frequency (ranging from 94.2 to 157 s^{-1}) on the clogging coefficient of the sieve surface in vibratory-impact machines with a non-rigid connection between the box and the sieve, with a significance level of 20 %.

The resulting mathematical model underwent graphical analysis (Fig. 6), which allowed for determining the degree of influence of each factor on the optimization parameter.

From the obtained graph, it can be seen that the intensification of the cleaning process of the sowing surface in the vibration-impact machine with an uncontrollable connection between the sieve and the box occurs when both the amplitude of the box oscillations and its frequency are increased. From the perspective of energy efficiency and effectiveness of the cleaning process, the most acceptable value of the clogging coefficient is 0.2 %, which is achieved with the following dynamic parameters of the box: an oscillation amplitude of 0.0018…0.0022 m at a frequency of 94.2…102 s^{-1}, corresponding to accelerations from 16 to 23 m/s², and 0.0022 m at a frequency of 125.6 s^{-1}, which is equivalent to an acceleration of 35 m/s².

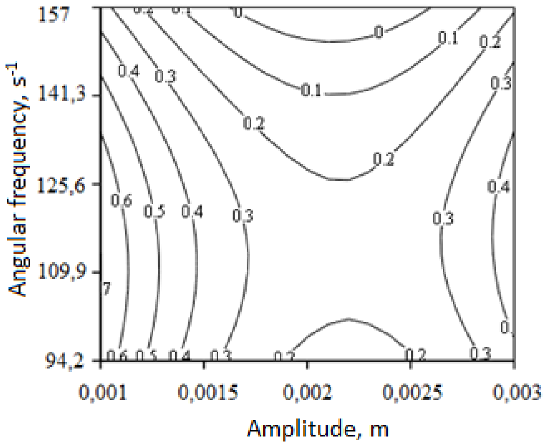


Figure 6. Dependence of the clogging coefficient of the sowing surface on the amplitude and angular frequency of the box oscillations.

Conclusions

As a result of the conducted studies on the developed laboratory model of the screen with a fixed and freely laid sowing surface, which generates vibration-impact action, its influence on productivity and the process of clogging sieve holes during the sieving of metallurgical raw materials was studied.

Based on the research, a mathematical model was obtained that links transport productivity and the clogging coefficient of the sowing surface of the vibration-impact machine with an uncontrollable connection between the sieve and its box at a 20% significance level. It was found that the maximum transport productivity is achieved at an oscillation mode with accelerations of 28…32 m/s² at an amplitude of $2\cdot10^{-3}$ m, and the most acceptable value of the clogging coefficient at this productivity is 0.2%, which is achieved with an oscillation amplitude in the range of $(1.8…2.2)\cdot10^{-3}$ m at a frequency of oscillations of 94.2…102 s^{-1}.

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