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Investigation of the dependence of the amplitude of vertical vibration displacements of the working element of a vibrating platform on its inertial and stiffness parameters using a three-factor experiment

During preliminary experimental studies, it was established that the amplitude of vibration displacements of the moving frame points of the vibration platform is most significantly influenced by such characteristics as the stiffness of vibration-isolating supports, the distance from the centre of oscillation, and the mass of the moving part. These factors were selected as independent factors in the research using a three-factor experiment. As a result of mathematical and statistical processing of the experimental data, a second-order multiple regression equation was obtained. The calculated values of the variance at the zero point, the variance of adequacy, and Fisher's criterion confirm the possibility of using the obtained equation to describe the studied process. Based on the research results, three three-dimensional response surfaces were constructed, describing the dependence of the amplitude of vibration displacements of selected points on the surface of the working body of the vibration platform on two variable input factors at a fixed value of the third factor at the base level. The results obtained allow for optimal regulation of vibration-isolating supports with variable stiffness, which, in turn, allows for improving the quality of concrete product compaction.

Keywords: amplitude of vibration displacements, vibration platform, vibration support, stiffness, three-factor experiment

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Introduction

Vibrating platforms with a load capacity of up to 300 kg, primarily used for volumetric or surface compaction of concrete mixtures, are employed in the manufacturing of small-sized and precast concrete elements. Typically, they belong to the class of single-mass vibrating machines operating in a harmonic, super-resonant mode [1]. Their moving frames or plates are mounted on resilient vibration-isolating supports and set into oscillatory motion by external unbalanced vibratory exciters.

The nature of oscillations in vibrating machines used for concrete compaction largely depends on their design features, the physical and mechanical properties of the compacted medium, the synchronization principles of the vibration exciters, and the presence of additional loading [1].

The most common systems are vibrating platforms with vertically directed oscillations, operating at forced vibration frequencies ranging from 25 to 50 Hz, with displacement amplitudes of the working element between 0.3 and 0.6 mm [2–4]. It is also known that as the mass of the compacted medium increases, the amplitude of the forced oscillations of the working element decreases.

Determining the amplitude of the forced vertical displacements of the working elements of vibrating platforms used in the production of small concrete elements, depending on their oscillating mass and the stiffness of the vibration isolation supports, requires a series of tests to build a reliable mathematical model of the process.

Analysis of Recent Research and Publications

Scientific literature provides numerous examples of the use of multifactorial experiments for investigating various technological processes. For instance, in [6], a two-factor experimental design is discussed, where peak impact acceleration and cement consumption are the main influencing factors determining the strength of lightweight aggregate concrete products.

Study [7] investigates the compaction modes of lightweight concrete mixtures using an impact-vibration setup based on the method of mathematical experiment design. A three-factor experiment was used to study the influence of structural parameters of the vibrating system on the strength of the formed concrete products.

Identification of Unresolved Aspects of the General Problem

Analysis of the available literature confirms the relevance of research in the field of vibration compaction of construction mixtures. Existing works address the influence of vibration parameters on concrete strength, compaction modes, and equipment design features. It has been established that amplitude, frequency, and oscillation type significantly affect compaction quality and energy efficiency [8, 9].

However, issues related to the optimization of the stiffness characteristics of vibration-isolating supports, particularly under resonance conditions, remain insufficiently explored. There is a need to develop designs with adjustable parameters to adapt the dynamic behavior of the system to changing operating conditions.

The problem of systematically optimizing the relationship between support stiffness, moving mass, and the spatial position of the point relative to the oscillation center—factors that determine the amplitude of vertical vibration displacements—remains unresolved. Addressing this issue requires targeted experimental studies and the development of a mathematical model capable of quantitatively describing the effect of key parameters on the efficiency of concrete mixture compaction.

Problem Statement

The aim of this article is to present the results of determining the optimal stiffness of vibration-isolating supports for a vibrating platform operating in a harmonic super-resonant mode with a given oscillating mass, using the method of mathematical experiment planning.

Main Material and Results

The amplitude of forced oscillations of the vibrating platform's working element is influenced by various external independent factors: frequency of forced oscillations, mass of the working element, mass and rheological characteristics of the concrete mixture, stiffness of the vibration-isolating supports, static moment of imbalance, excitation force, presence and mass of additional loading, compaction time, and others.

Based on preliminary tests, it was found that the most significant factors affecting the amplitude of surface point displacements of the vibrating platform's working element are: stiffness of the vibration support, distance from the oscillation center, and mass of the moving part of the platform. These factors are controllable, independent, and measurable at three levels.

To establish the functional relationship between the amplitude of forced oscillations and the selected factors, a three-factor experimental design was chosen [10].

Ranges and variation intervals of these input variables were determined based on the technical specifications of the test equipment. Their numerical values are presented in Table 1.

During the experiments, according to the chosen design, each factor was varied at three levels—low (-1), base (0), and high (+1). Experimental studies were carried out following a standard experimental matrix within the defined ranges of factor variation.

The numerical values of the amplitudes of forced vertical vibrations were measured using a GM-63A digital vibrometer at fifteen predefined points on the surface of the vibrating plate.

Table 1 – Input factors, their levels and variation intervals

Levels of the studied factors	Researched factors					
	Vibration isolation mount stiffness c, H/m		Distance from the center of oscillation l, m		Mass of the moving part of the vibrating platform m, kg	
	X_1	x_1	X_2	x_2	X_3	x_3
Top level $X_{i\max}$	200 000	+1	0	+1	220	+1
Main level X_{0i}	400 000	0	0,25375	0	164	0
Bottom level $X_{i\min}$	600 000	-1	0,5075	-1	108	-1
Variation interval ΔX_i	- 200 000	1	- 0,25375	1	56	1

Since the input factors are heterogeneous, differing in dimension and influence on the vibration amplitude, they were converted into a unified computational system by transforming actual values into coded ones. The coding of input factors, which represents a linear transformation of the factor space, was performed using the formula (Eq. 1):

$$x_1 = \frac{X_1 - X_{0i}}{\Delta X_i} \tag{1}$$

where x_i – coded value of the *i*-th factor;

X_i – actual (natural) value of the *i*-th factor;

X_{0i} – actual value of the i-th factor at the base level;

ΔX_i – variation interval of the i-th factor.

To obtain the functional relationship between the amplitude of forced vibrations and the selected input variables, a statistical analysis was carried out in the form of multiple regression based on a second-order central composite design.

As a result of the mathematical and statistical processing of the data from the three-factor experiment, a second-order regression equation was obtained. This equation describes the dependence of the amplitude of forced vertical displacements at the surface points of the vibrating plate on the selected input factors expressed in coded form:

$$
\begin{aligned}
& y_i = 0,220840 + 0,022x_1 + 0,0401x_2 - 0,019x_3 + \\
& +0,047628x_1^2 - 0,023872x_2^2 - 0,008872x_3^2 - \\
& -0,000875x_1x_2 + 0,12125x_1x_3 + 0,013625x_2x_3
\end{aligned} \quad (2)
$$

where y_i – the response function representing the amplitude of vertical vibrations at selected points on the vibrating plate surface;

x_1, x_2, x_3 – input variables (factors) in coded form.

The accuracy of the measurements and the adequacy of the obtained mathematical model were evaluated using methods of mathematical statistics. Dispersion estimates and the model's adequacy were assessed through statistical analysis. The results of the adequacy check for the mathematical model of the experiment are presented in Table 2.

Table 2 – The value of the Fisher criterion for obtaining a mathematical model of the experiment

Evaluation criteria	Designation of the criterion	Response function y_i
Zero-point variance	$S_0^{\ 2}$	0,000024333
Adequacy variance	$S_{ad}^{\ 2}$	0,000232354
Calculated Fisher exact value	F_p	9,549
Fisher exact critical value for 5% significance level	$[F_p]$	19,30

To determine the critical values of the influencing factors (in coded form), first-order partial derivatives of the regression (Eq. 2) with respect to the independent variables x_1, x_2, x_3 were calculated and set to zero:

$$
\begin{cases}
0,095256x_1 - 0,000875x_2 + 0,012125x_3 + 0,022 = 0; \\
-0,047744x_2 - 0,000875x_1 + 0,013625x_3 + 0,0401 = 0; \\
-0,017744x_3 + 0,012125x_1 + 0,013625x_2 - 0,0019 = 0.
\end{cases} \quad (2)
$$

The resulting system of linear algebraic equations (Eq. 3) was solved using Cramer's method [11]. Its approximate solution (with an accuracy of up to 0.001) is:

$$(x_1, x_2, x_3) \approx (-0,279; 0,973; 0,448)$$

By means of mathematical analysis, it can be shown that the identified critical point of the response function, approximated by a second-order polynomial in three variables, is not an extremum.

To determine the optimal values of the influencing factors on the amplitude of forced vibrations of the vibrating platform, we decode the critical values from coded to natural units:

$X_1 = 2,64 \cdot 10^5$ Н/м = 1,08 X_{01};
$X_2 = 0,06166$ м = 0,243 X_{02};
$X_3 = 104$ кг = 1,08 X_{03};

By expressing the input factor values in their natural scale, we obtain the response function (Eq. 3), which describes the dependence of the amplitude of forced vibrations on the investigated input variables:

$$
\begin{aligned}
& y = 0,44078 - 8,81 \cdot 10^{-7} X_1 + 0,19391 X_2 - 0,00029 \times \\
& \times X_3 + 1,19 \cdot 10^{-12} X_1^2 - 0,37068 X_2^2 + 2,82 \cdot 10^{-6} X_3^2 - \\
& -1,72 \cdot 10^{-8} X_1 X_2 - 1,08 \times 10^{-9} X_1 X_3 - 0,00096 X_2 X_3
\end{aligned} \quad (4)
$$

Thus, the influence of the selected input factors on the amplitude of forced vibrations is nonlinear in nature, which is explained by the existence of optimal values of the influencing parameters—beyond which the response function increases only insignificantly.

To visualize the experimental results, we construct three-dimensional response surfaces. For this purpose, in the mathematical model of the experiment (Eq. 4), one of the factors is fixed at its base level, while the other two vary within their respective measurement ranges. The response surfaces, plotted in natural coordinates of the input variables, are presented in Fig. 1–3.

The surfaces were generated using the engineering computational software PTC Mathcad Prime 10.

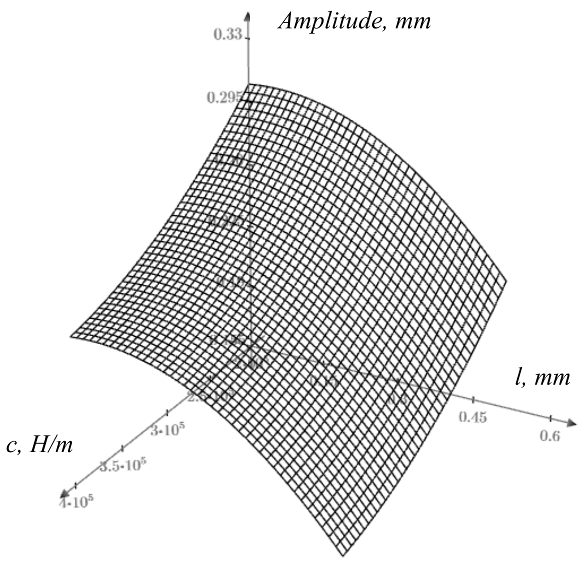

Figure 1 - Response surface of the amplitude of vertical vibrations on stiffness and distance from the center of vibrations with a fixed mass of the moving part

The signs of the response function coefficients for X_1 and X_3 are negative, indicating a decrease in the amplitude of forced vibrations with increasing stiffness of the vibration isolation support and the mass of the vibrating platform's moving part.

Analysis of Figures 1 and 2 confirms that as the distance from the center of oscillation increases, the amplitude of forced vibrations of the platform consistently decreases.

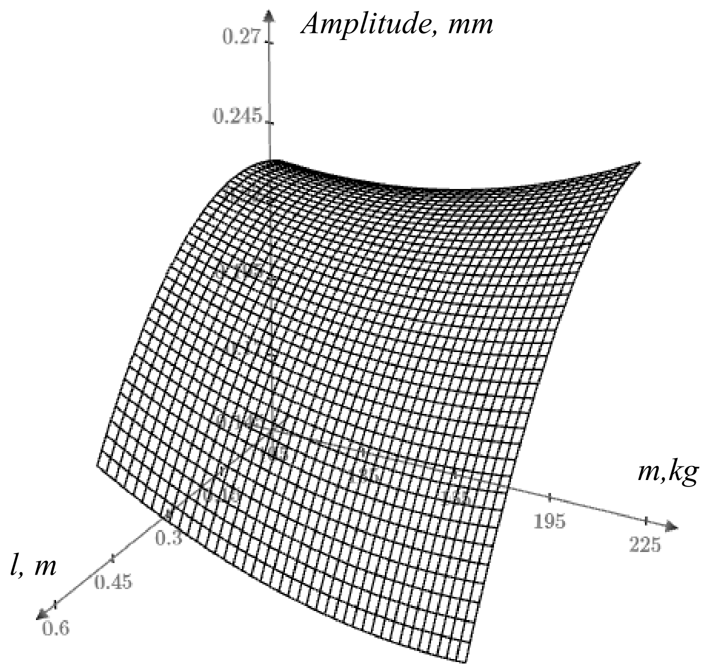

Figure 2 - Response surface of the amplitude of vertical vibrations from the mass of the moving part and the distance from the center of vibrations at a fixed stiffness of the vibration mounts

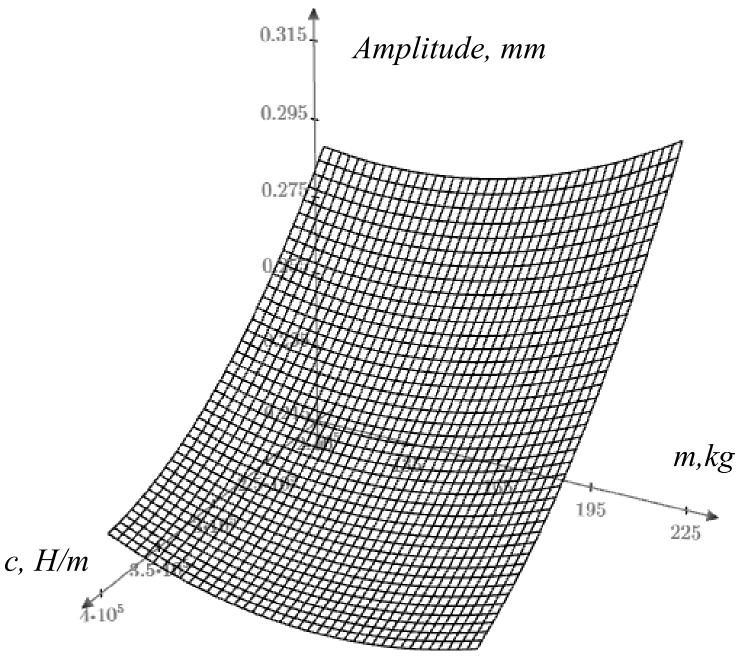

Figure 3 - Response surface of the amplitude of vertical vibrations from the stiffness and mass of the moving part at a fixed distance from the center of oscillations

In terms of comparative influence, the mass of the moving part of the platform (varying in the range from 108 kg to 220 kg) has the least effect on the amplitude of forced vibrations.

The factors X_1 and X_2 exert different influences on the response function. At a fixed value of the moving mass, the amplitude of vibrational displacements of the surface points of the working body increases with the stiffness of the vibration isolation support and decreases with increasing distance from the oscillation center.

Conclusions.

To investigate the amplitude of forced vibrational displacements of the vibrating platform's working body, a three-factor experimental design was developed and implemented. The primary independent input factors were selected as the stiffness of the vibration isolation support, the distance from the oscillation center, and the mass of the moving part of the vibrating platform.

As a result of statistical processing of the experimental data, regression models describing the relationship between the amplitude of forced vibrational displacements and the main input factors were obtained. The most influential factors affecting the amplitude of vibrational displacements of the working body surface points were identified as the stiffness of the vibration isolation support and the distance from the oscillation center. To visualize the nature of these effects, three-dimensional response surfaces were constructed based on the obtained mathematical model.

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Дослідження залежності амплітуди вертикальних вібропереміщень робочого органу віброплощадки від її інерційних та жорсткісних параметрів за допомогою трифакторного експерименту

Під час проведення пробних експериментальних досліджень було встановлено, що на амплітуду вібропереміщень точок рухомої рами віброплощадки найсуттєвіший вплив створюють такі її параметри, як жорсткість віброізоляційних опор, відстань від центра коливань та маса рухомої частини. Саме ці чинники були обрані як незалежні фактори проведенні досліджень за допомогою трифакторного експерименту. Серед зазначених факторів особливу увагу слід приділити жорсткості віброізоляційних опор, оскільки їхнє завдання полягає у зниженні рівня передавання вібрацій від робочого органу на опорні конструкції. Ефективна ізоляція дозволяє запобігти виникненню небажаних резонансних коливань, зменшити втрати енергії, підвищити стабільність вібраційного процесу та забезпечити більш якісне ущільнення бетонної суміші. Ізоляційні характеристики конструкції віброплощадки безпосередньо впливають на точність процесу формування виробів, а також на зменшення зносу елементів конструкції. Розраховані значення дисперсії в нульовій точці, дисперсії адекватності та критерію Фішера підтверджують можливість використання отриманого рівняння для опису досліджуваного процесу. На основі моделі побудовано три тривимірні поверхні відгуку, які відображають залежність амплітуди вібропереміщень вибраних точок поверхні робочого органа віброплощадки від зміни двох незалежних факторів при фіксованому значенні третього фактору на основному рівні. Графічне представлення результатів дозволяє наочно оцінити вплив кожного параметра та вибрати оптимальні умови для роботи віброплощадки. Отримані результати дають змогу здійснювати оптимальні регулювання віброізоляційних опор зі змінною жорсткістю, що, в свою чергу, сприяє підвищенню ефективності ущільнення бетонних виробів, зниженню енерговитрат та підвищенню технологічної надійності обладнання.

Ключові слова: амплітуда вібропереміщень, віброплощадка, вібраційна опора, жорсткість, трифакторний експеримент

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