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Calculation of structural parameters of a vibratory machine

The article is dedicated to the development of a vibratory machine for compacting concrete mixtures, ensuring the adaptation of vibration modes to the mixture's condition to enhance energy efficiency and concrete quality. The study was conducted through literature analysis, vibration parameter modeling, and calculation of structural characteristics. It was established that modern methods, such as DEM and CFD, highlight the need for flexible vibration control to prevent microstructure defects. A machine design based on elastic pneumatic shells operating in resonant mode is proposed. Key formulas for calculating the vibratory platform are provided. The design achieves a 15% reduction in energy consumption compared to traditional machines, stable compaction, and adaptability to various mixture types. The results confirm the effectiveness of the proposed solution for forming a dense concrete microstructure. Further research involves experimental validation and parameter optimization.

Keywords: vibratory machine, concrete compaction, resonant mode, elastic shells, energy efficiency, concrete quality, concrete mixture

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Introduction

The quality of hardened concrete significantly depends not only on the control of preliminary technological operations, such as the scientifically grounded selection of components (cement, aggregates of various fractions, water, chemical admixtures) [1], precise dosing to achieve the required granulometric composition and to ensure high homogeneity of the mixture during mixing [2], but also on the efficiency of vibration compaction [3]. The optimization of its parameters (frequency, amplitude, duration) plays a decisive role in the formation of a dense microstructure [4] and in achieving the required physical and mechanical properties of the final product [5]. The aim of this study is to develop the design of a vibration machine that allows the adaptation of vibration parameters to the state of the concrete mixture, while ensuring energy efficiency and stability of quality.

Review of Research Sources and Publications

The process of compacting a concrete mixture by vibration is the central stage in the entire technological chain of concrete and reinforced concrete production. The efficiency of this stage directly determines not only the strength, but also the overall structural stability, durability, and absence of internal defects [5], [6]. Although vibration compaction has been studied for many years, its true intricacies have been revealed only with the introduction of digital simulations, sensor technologies, and artificial intelligence-based algorithms [3], [7], [8]. These tools enable, for the first time, an in-depth understanding of the behavior of a concrete mixture at the moment of dynamic disturbance—precisely where micropores close and aggregate grains rearrange [4], [9].

One of the key approaches in recent studies has been the discrete element method (DEM), which allows for modeling the behavior of each individual element within the system. In [3], DEM was used to visually demonstrate the response of fresh concrete particles to vibrational loading—how they move, interact with one another, and how contact configurations change. These visualizations effectively transform abstract assumptions into comprehensible models. Continuing in this direction, [7] combined DEM with CFD (computational fluid dynamics) modeling, making it possible not only to observe particle motion but also to track changes in the rheological characteristics of the mixture under vibration.

Another important aspect is the settlement of aggregates, which directly affects the homogeneity and strength of the concrete structure. Study [9] found that vibration causes local concentrations of aggregate that disturb structural balance and may lead to internal defects. An alternative approach, presented in [4], proposes a method of precise vibration control, enabling the optimization of vibration parameters according to the actual state of the mixture, thereby reducing the risk of uneven compaction and pore formation.

The duration of vibration also lacks a universal optimum. In particular, for high-density and high-strength concretes (so-called UHPC—ultra-high-performance concretes), even slight over-compaction leads to the destruction of the delicate microstructure. Authors of [6] concluded that microcracks emerge at a stage that visually appears fully satisfactory. A similar sensitivity is observed in slipform systems [5], where both insufficient and excessive vibration duration reduce compactness, leading to premature structural wear.

On the other hand, new approaches to evaluating the energy efficiency of compaction—such as the model proposed in [2]—enable quantitative analysis of how much energy is transferred to the concrete mass and how it correlates with the degree of compaction. This allows moving away from empirical parameters toward a scientifically grounded compaction control system.

Another current trend is the changing nature of concrete mixtures themselves. With the introduction of composites, nanodispersed additives, and complex forms, traditional visual control methods for compaction have largely lost their effectiveness. Here, machine learning and artificial intelligence technologies are coming into play. In [10], a method for evaluating vibrational effects in nanocomposite structures was proposed, opening prospects for adaptive compaction control based on real-time data.

Studies [8] and [11] focus directly on real-time algorithms capable of analyzing sensor readings during compaction and automatically detecting deviations—such as reduced density, incomplete settlement, or excessive porosity. These systems are integrated into production processes and can potentially adjust vibration parameters in real time.

Problem Statement

Based on the above, it becomes clear that vibration parameters cannot be considered fixed values but should be adjusted depending on the current state of the mixture. Rigidly set parameters are no longer effective. Without adaptation and flexible regulation, quality instability, resource overuse, and ultimately, risks of structural failure arise.

The use of vibration machines in near-resonant modes makes it possible to significantly reduce loads on the drive mechanism and, accordingly, lower the overall energy consumption of the equipment. This is because, when operating close to the natural frequency of the oscillatory system, energy is spent only on compensating for losses, rather than on forced excitation—the coefficient of dynamic efficiency here plays a key role [1; 3, 12]. Under such conditions, the energy required to maintain stable oscillations decreases in proportion to the dynamic sensitivity of the system, making resonance mode highly attractive for energy-efficient compaction of concrete mixtures.

However, ensuring stable operation in this range requires a highly accurate control system—specifically, maintaining the imbalance rotation frequency within a very narrow band around the resonance peak. Implementing such functions necessitates complex electronic circuits, digital controllers, and feedback loops based on acceleration, strain, or density sensors [6; 8]. From a technical standpoint, this is feasible, but from an economic perspective, it is not always practical: the cost of the control system often rises faster than the productivity of the equipment itself. This is especially noticeable in large-scale vibration platforms, where electronics can represent a significant share of total system costs [1].

Additionally, as machine power increases, the dynamic forces to be compensated by the control system also grow. This demands more reliable components, backup algorithms, and maintenance by highly qualified personnel. As a result, the energy savings achieved through resonance mode are partially or fully offset by the costs of maintaining high-tech control systems [11].

A second important aspect of efficient vibration compaction of concrete mixtures is the use of vibro-impact mode. Initially, the mixture must be vigorously agitated, which requires large amplitude and low frequency. Subsequently, for effective compaction, frequency increases while amplitude decreases [13].

Main Material and Results

Based on the identified issues and the analysis of the literature, a design of a vibration machine was developed that adapts vibration regimes to the state of the mixture, ensuring both energy efficiency and operational stability. Its core is a movable upper platform (pos. 2), on which a mold with the concrete mixture (pos. 1) is placed. It interacts with the lower stationary support (pos. 5). Between these elements, elastic pneumatic shells (pos. 6) are installed, serving as the source of reciprocating motion. To prevent unwanted horizontal displacements of the moving part, guides (pos. 4) are provided.

Compressed air is supplied from a compressor (pos. 10) or from the plant's main pneumatic line. Its distribution is controlled by spool pneumatic distributors (pos. 7), which regulate air delivery to the pneumatic shells. To reduce pressure fluctuations in the system, a receiver (pos. 9) is installed. A controlled valve (pos. 8) allows rapid interruption or initiation of air supply.

The operating frequency of the pneumatic distributors is regulated by an electric drive (pos. 11), which controls the rotation speed. To enhance the downward movement of the platform, additional elastic elements (pos. 3) are used, accumulating the energy of the return impulse.

The asynchronous motor 11 is controlled via frequency converters, allowing smooth adjustment of rotational speed over a wide range while maintaining high efficiency. The use of such a frequency converter eliminated the need for a more expensive DC motor.

In the presented schematic, cylindrical compression springs with constant stiffness are used as springs (pos. 3). As noted in [14], the vibration platform operates steadily in resonance mode. To ensure resonance in this design, variable stiffness of the elastic shells (pos. 6) and springs (pos. 3) is required.

The stiffness of the shells is determined by the following formula:

$$C=C_1+C_2+C_3 \qquad (1)$$

where: C_1 – stiffness of the elastic layer of compressed air (N/m); C_2- stiffness determined by the effective area (N/m); C_3 – stiffness of the elastic rubber–cord shell (N/m).

As follows from formula (1), the stiffness values C_2 and C_3 for a structurally selected elastic shell vary only within narrow limits. The stiffness value C_1 is determined as:

$$\mathrm{C}_1 = n\,(b_\text{к} + L_\text{к})\,p \qquad (2)$$

де: n – number of elastic shells;

$b_\text{к} = \frac{\pi\left(r-\frac{y}{2}\right)}{2}\left(1 + k_1\frac{y}{2} + k_2\left(\frac{y}{2}\right)^2\right)$ – width of contact of the elastic shell in the transverse cross-section with the table (m); $L_\text{к}$ – length of contact between the elastic shell and the table (m); p – compressed air pressure (Pa).

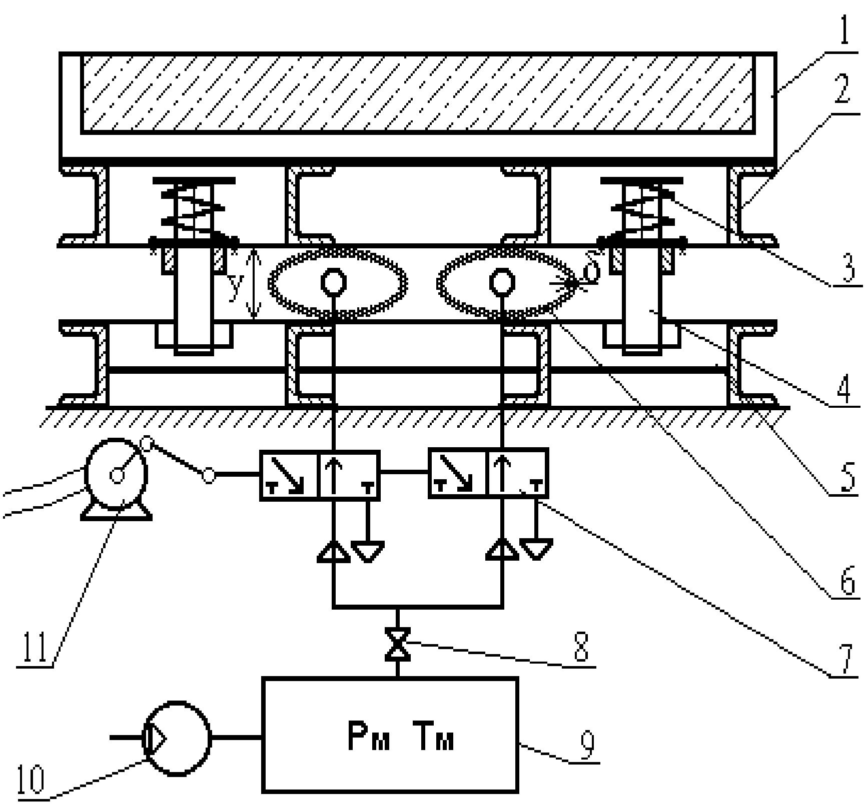

Figure 1 – Schematic diagram of a vibrating platform on elastic shells
1 – mold with concrete mix; 2 – upper movable table; 3 – springs; 4 – guides; 5 – fixed table; 6 – elastic shells; 7 – pneumatic distributor; 8 – valve; 9 – receiver; 10 – compressor; 11 – electric motor.

Taking into account the width of contact between the shell and the table surface, expression (2) takes the form:

$$\mathrm{C}_1 = n\,p\left[\frac{\pi(r-\frac{y}{2})}{2}(1 + k_1\frac{y}{2} + k_2(\frac{y}{2})^2 + L_\text{к}\right] \qquad (3)$$

where: r - inner radius of the shell in the initial state (m); y – radial deformation of the shell (m); k_1, k_2 - empirical or experimentally selected coefficients accounting for the geometry and elasticity of the material.

On the basis of expression (2), under the given constructive length of the table and the size of the elastic shell, the change in stiffness C_1 will be determined by the variation in compressed air pressure.

The stiffness C_3 in this case can be approximated through the radial stiffness of a cylinder compressed between two planes, according to the formula:

$$C_3 = \frac{E_{гк} L_к}{\ln(\frac{8R}{t})} \quad (4)$$

where: $E_{гк}$ - elastic modulus of the rubber–cord; R - outer radius of the shell (m); $L_к -$ length of the shell (along the guiding axis, i.e., its "length lying on the table") (m).

The stiffness determined by the effective area C_2 constitutes about 6–8% of the sum of stiffnesses C_1 and C_3.

The stiffness of the upper springs and lower elastic shells is found from the resonance amplitude condition:

$$C = \frac{F_{ін} \pm G}{2 * A_{рез}} \quad (5)$$

The energy expended for the displacement of inertial masses of the vibration platform (primarily the moving table (2) with the mold and the concrete mixture (1)) is described by the power balance equation. This equation accounts for the work of resistive forces that dissipate energy. For harmonic oscillations in steady-state mode, viscous damping forces proportional to velocity play a key role.

The general power balance equation is:

$$P_{прив} = P_{демп} + P_{терт} + P_{бет} + P_{інш} \quad (6)$$

where: $P_{демп}$- power dissipated through system damping; $P_{терт}$ - power lost to overcome friction in guides; $P_{бет}$- power transmitted into the concrete mixture to overcome its viscous resistance; $P_{інш}$- power dissipated in other elements.

For energy over a vibration period T:

$$E_{прив} = \int_0^T P_{прив} dt = E_{демп} + E_{терт} + E_{бет} + E_{інш} \quad (7)$$

The dissipative energy due to damping per period T:

$$E_{демп} = \int_0^T b_{екв} (x'(t))^2 dt \quad (8)$$

where: $b_{екв}$- equivalent viscous damping coefficient of the system (N·s/m); $x'(t)$- velocity of the moving table (m/s).

Thus, the instantaneous energy dissipated by damping is:

$$E_{демп}(t) = F_{демп} x'(t) = b_{екв} (x'(t))^2 \quad (9)$$

where: $F_{демп} = b_{демп} x'(t)$ - damping force.

For harmonic oscillations:

$$x(t) = A sin(\omega t) \quad (10)$$

$$x'(t) = A\omega cos(\omega t) \quad (11)$$

where: A- amplitude (m); ω - angular frequency (rad/s).

Then the energy dissipated by the damper per period is:

$$E_{демп} = b_{екв} \int_0^T (A\omega cos(\omega t))^2 dt = b_{екв} A^2 \omega^2 \int_0^T cos^2(\omega t) dt$$

$$E_{демп} = \pi b_{екв} A^2 \omega \quad (12)$$

The equivalent damping coefficient is defined as:

$$b_{екв} = b_р + b_{пр} + b_{напр} + b_{бет} + b_{інш} \quad (13)$$

where: $b_р = \frac{\eta Кос(P)}{\omega}$ - equivalent damping of elastic shells, proportional to air pressure $P;$ $b_{пр}$- damping in metal springs (small, since $\eta_{ст} \approx 0.001 - 0.01$); $b_{напр} = \frac{4 F_{терт}}{\pi A \omega}$ - damping associated with friction in guides (for harmonic oscillations);

$b_{бет} = \beta \mu_{бет} V_{бет}$- damping due to concrete, β- experimentally determined proportionality coefficient, $\mu_{бет}$ - dynamic viscosity of the concrete mixture, $V_{бет}$ - volume of concrete in the mold;

$b_{інш}$- other damping (supports, joints, etc.), typically 5–7% of the equivalent damping.

Energy dissipated by friction in guides:

$$E_{терт} = 4 F_{терт} A = 4 \mu N A \quad (14)$$

where: $F_{терт} = \mu N$- friction force; μ- friction coefficient; N- normal force.

Energy consumed for compaction of concrete is determined by:

$$E_{бет} = \int_0^T P_{бет} dt = \frac{1}{2} k \mu_{бет} A^2 \omega^2 V_{бет} T \quad (15)$$

where: k- empirical coefficient accounting for mold geometry and distribution of the concrete mixture within it.

The influence of concrete on the dynamics of the vibration platform is a well-known problem considered in studies [15–17].

Key advantages of the proposed design include:

- *universality*: the machine adapts to different types of concrete mixtures thanks to adjustable vibration parameters, allowing optimization of the compaction process depending on material composition.
- *energy efficiency*: resonance mode operation with elastic elements reduces energy consumption by 10–20% compared with similar machines.
- *compaction quality*: uniform distribution of vibrational energy ensures high density and homogeneity of concrete products while minimizing defects.

Conclusions

This paper presents the development of a vibration machine design that enables the adaptation of vibration regimes to the state of the concrete mixture, ensuring both energy efficiency and quality stability. Based on the analysis of modern studies, the need for flexible control of vibration parameters was identified, which formed the basis for problem formulation. The proposed design on elastic shells, with stiffness calculated for resonance mode, demonstrates the feasibility of achieving optimal compaction conditions. The results confirm that the developed machine reduces energy consumption and provides high-quality concrete products. Future research may focus on experimental validation of the design and optimization of its parameters for different types of concrete mixtures.

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Розрахунок конструктивних параметрів вібраційної машини

Стаття присвячена розробці вібраційної машини для ущільнення бетонної суміші, що забезпечує адаптацію режимів вібрації до її стану для підвищення енергоефективності та якості бетону. Дослідження проводилося шляхом аналізу літератури, моделювання параметрів вібрації та розрахунку конструктивних характеристик. Встановлено, що сучасні методи, такі як DEM та CFD, вказують на потребу гнучкого управління вібрацією для уникнення дефектів мікроструктури. Запропоновано конструкцію машини на еластичних пневмооболонках, яка працює в режимі. Наведені основні формули для розрахунку запропонованого вібромайданчику. Конструкція забезпечує зниження енерговитрат до 15% порівняно з традиційними машинами, стабільність ущільнення та адаптацію до різних типів сумішей. Результати підтверджують ефективність запропонованого рішення для формування щільної мікроструктури бетону. Подальші дослідження передбачають експериментальну перевірку та оптимізацію параметрів.

Ключові слова: вібраційна машина, ущільнення бетону, резонансний режим, еластичні оболонки, енергоефективність, якість бетону, бетонна суміш.

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