UDC 539.3

# COEXISTING REGIMES IN HYSTERESIS ZONE IN PLATFORM-VIBRATOR WITH SHOCK

**V.A. Bazhenov,**

**O.S. Pogorelova,**

**T.G. Postnikova**

*Kyiv National University of Construction and Architecture*
*31, Povitroflotskyave., Kyiv, Ukraine, 03680*

DOI: 10.32347/2410-2547.2021.107.3-19

Molding processes are among the most important in the manufacture of reinforced concrete structures. Vibration and shock-vibration technologies for concrete mixtures compaction and concrete products molding have the greatest distribution in the construction industry. Therefore, the issues of optimizing vibration modes, correct choice of vibration equipment do not lose their relevance. The article discusses the dynamical behavior of a shock-vibrational low-frequency resonant machine. Its mathematical model corresponds to a two-body 2-DOF vibro-impact system with a soft impact, which is simulated by a nonlinear interactive contact force in accordance with Hertz's quasi-static contact theory. Changing the control parameters can, on the one hand, improve the compaction process, but, on the other hand, lead to unwanted vibrational modes. The article discusses such control parameters as the exciting frequency, the technological mass of the mold with concrete, and the stiffness parameters of elastic elements. Decreasing the exciting frequency, the mold mass, the vibro-isolating spring stiffness and increasing the Young's modulus of elasticity of the rubber gasket provide an increase in impact acceleration, which improves the compaction process. However, with such changes in the parameters, coexisting regimes arise, many of which are undesirable. These are modes with a large periodicity and several impacts per cycle, chaotic modes, and transient chaos. The regime diagnostics is performed by traditional numerical means, namely, by constructing time series, phase trajectories, Poincaré maps, Fourier spectra, and the largest Lyapunov exponent. We hope that this analysis can help avoid unwanted platform-vibrator behaviour during design and operation. The presentation is accompanied by many graphs and a table.

Keywords: platform-vibrator, vibro-impact, mold with concrete, technological mass, coexisting modes, control parameter, stiffness parameters

## 1. Introduction

Molding processes are among the most important in the manufacture of reinforced concrete structures. Vibration and shock-vibration technologies for concrete mixtures compaction and concrete products molding have the greatest distribution in the construction industry. This priority is likely to continue in the future. Therefore, the issues of optimizing vibration modes, correct choice of vibration equipment do not lose their relevance [1].

Nowadays, the opinion has been established that low-frequency compaction modes have undoubted advantages; it is they that make it possible to obtain high-density concrete with a shorter compaction time. The low-frequency resonant platform-vibrator with shock use this technology. Their employment is quite effective; it significantly improves the quality of the products front surfaces and the degree of their factory readiness. The

© Bazhenov V.A., Pogorelova O.S., Postnikova T.G.

efficiency of the concrete mixture compaction in machines with vertical vibrations is achieved by the shocks on the mold directed upwards.

Despite the wide application of the already developed platform-vibrators, the increase of their operational efficiency, the choice of parameters, and the effect on the machine dynamics of the concrete mix (first liquid and then gradually hardening) and other problems are still being discussed at present [2-4]. The efficiency of the vibrational molding of concrete products depends on the rational vibration modes and the selected parameters of the equipment. Effective compaction modes can be realized by choosing the parameters of the oscillating system "working body – elastic element – mold with concrete" [2]. The gasket stiffness is one of the most important parameters of this system. It is determined by the shape, sizes and elasticity modulus of the gasket material [5, 6]. In [2], the influence of the gasket stiffness on the system dynamics was experimentally investigated in a particular case of a shock-vibrational machine. In [7], the author considers the stiffness of the vibro-isolating spring as the most "convenient" parameter for creating a poly-frequency oscillatory mode. A complex process of interaction between the concrete mixture particles takes place under vibration influence. Many aspects of this process are not well understood. The proposed models and the corresponding equations of the concrete mixture state, the criteria for the compaction effectiveness and the front surfaces quality remain debatable [8]. Many experiments have been carried out to study various aspects of the concrete compaction process. In [9], the interaction of a building concrete mixture and a working body of a shock-vibrational machine during compaction is studied.

Thus, the investigation of the influence of both its parameters and the parameters of external excitation on the machine dynamics is relevant.

We have created a mathematical model of a platform-vibrator with shock. It is the two-body 2-DOF vibro-impact system. It is strongly nonlinear non-smooth discontinuous system. The mold with concrete is the upper body, the platform table with an attached rubber gasket is the lower body. The electric motors are under table. The mold with concrete, which has a huge mass $m_2$, is not fastened. When the motors start their work, it breaks off the limiters, and then collides with blocks in oncoming motion. Because of this, accelerations of different magnitudes arise when the mold moves up and down, that is, the accelerations are asymmetric. The mold acceleration in the uppermost position is the upper acceleration $w_U$, the mold acceleration in the lowest position is the lower acceleration $w_L$. Their ratio $w_L/w_U$ is the coefficient of the asymmetry. Exactly the lower acceleration $w_L$ is considered as acceleration that realizes the mix compaction. The prevalence of $w_L$ over $w_U$ accelerates the compaction process. The maximum acceleration of the mold with concrete in the lowest position $w_L$, that is, at the moment of collision with the platform table, is one of the main criteria for the technical assessment of the vibration machine efficiency. The asymmetric vibrations use makes it possible to increase the value of this compaction acceleration up to several $g$ (2…4…6$g$);

$g$ is the acceleration due the gravity. The process of concrete mixture compaction is intensified due to such asymmetric vertical mold vibrations. Accelerations $w_U$ that tear off mixture from the form pallet become smaller, and the pressing accelerations $w_L$ become larger with such oscillations. These asymmetric vibrations can be obtained precisely in shock-vibration compaction machines [10, 11].

Fig. 1 (a)-(c), (e)-(g) show that the impact acceleration $w_L$ increases with a decrease in the exciting frequency $\omega$, the technological mass $m_2$, the stiffness of the vibro-isolating spring, which improves the compaction process [12]. Fig. 1(d, h) show that it also increases with increasing Young's modulus of elasticity of the rubber gasket.

However, in these cases, other, possibly unwanted modes arise. In particular, with such a change in the control parameters, coexisting regimes occur under different initial conditions. This should be borne in mind when operating the platform-vibrator.

The model exhibits coexisting regimes with different initial conditions when the control parameter is varied. This phenomenon is observed with different control parameters, namely, exciting frequency, technological mass, and stiffness parameters of vibro-isolating spring and rubber gasket. The zone of coexisting regimes, i.e., the hysteresis effect (jump phenomenon) is defined as follows. The dynamical systems in general and nonlinear systems in particular may typically have the coexisting solutions at certain fixed parameter values. A jump phenomenon is simple example of crisis or saddle-note bifurcation, while the process of different patterns of response for increasing and decreasing parameters is called hysteresis [13].

The goal of this article is to show the emergence of coexisting modes for different initial conditions when the control parameters change. Some of these regimes may be undesirable.

## 2. Brief model description

The creation of mathematical model for platform-vibrator with shock was described in detail in [14]. A detailed description of the model and its verification were made in [12, 15, 16]. Therefore, only a brief model description is given here in order to understand the analysis of its dynamic behavior.

The accepted simplified design scheme of the platform-vibrator with shock is shown in Fig. 2.

The platform table with mass $m_1$ is attached to the base by linear vibration isolating spring of stiffness $k_1$ and a linear dashpot with damping factor $c_1$. Exciting external periodic force $F(t)$ is generated by electric motors (vibration exciters) mounted under the table. Elastic rubber gasket with thickness $h$ and stiffness $k_0$ is attached to the table. A linear dashpot with damping factor $c_0$ is placed between the table and the mold. The mold with concrete with mass $m_2$ is placed on the gasket but is not fastened either to the gasket or to the table. The platform table is equipped with limiters that prevent the mold from sliding and rotating; therefore, the movement is only vertical. For volumetric compaction, this machine uses vertically directed mold vibrations.

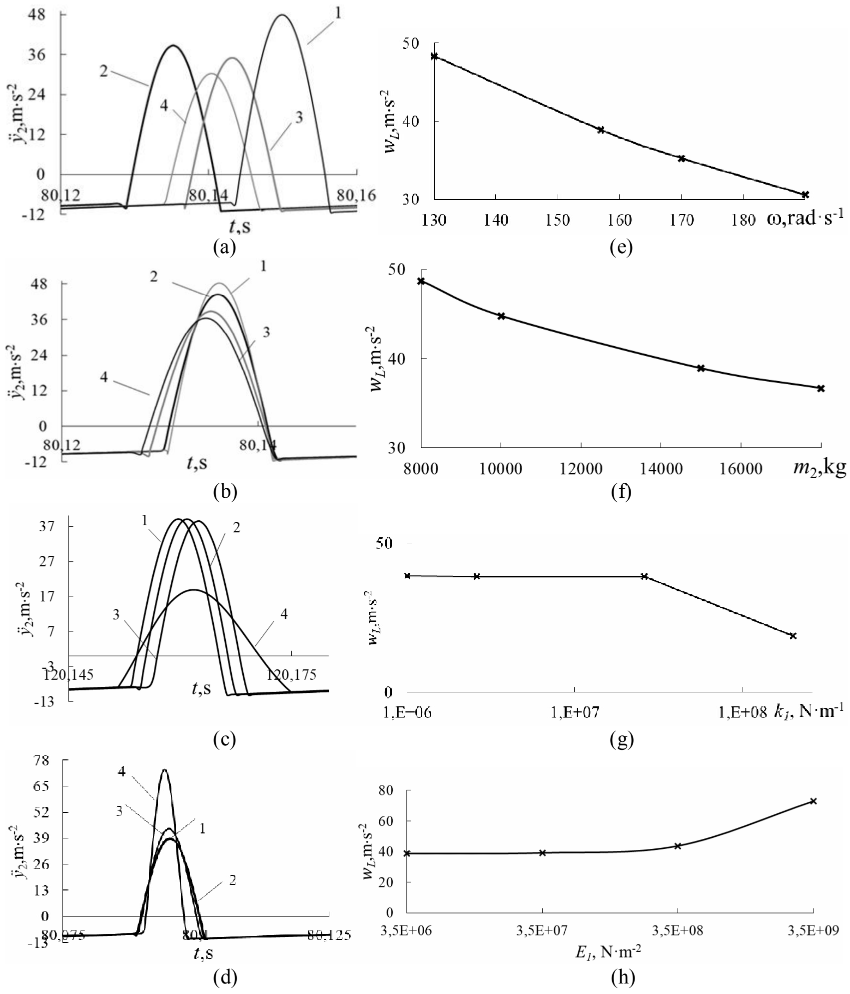


Fig. 1. Acceleration of the mold with concrete for different values of (a) the exciting frequency $\omega$ = (**1** – 130, **2** – 157, **3** – 170, **4** – 190) rad·s$^{-1}$; (b) the technological mass of the mold with concrete $m_2$ =(**1** – 8000, **2** – 10000, **3** – 15000, **4** - 18000) kg; (c) the vibro-isolating spring stiffness $k_1$ = (**1** – 1.0·10$^6$, **2** – 2.6·10$^6$, **3** – 2.6·10$^7$, **4** – 2.0·10$^8$) N·m$^{-1}$; (d) Young's modulus of elasticity of the rubber gasket $E_1$ =(**1** – 3.5·10$^6$, **2** – 3.5·10$^7$, **3** – 3.5·10$^8$, **4** – 3.5·10$^9$) N·m$^{-2}$. Dependence of impact acceleration $w_L$ on (e) the exciting frequency $\omega$; (f) the technological mass of the mold with concrete $m_2$ ; (g) the vibro-isolating spring stiffness $k_1$ ; (h) the elastic modulus of the rubber gasket. The impact acceleration $w_L$ increases with decreasing the control parameter in (e), (g), (f) and with increasing the elastic modulus of the rubber gasket in (h)

The machine starts their movement when the electric motors begin their work. First, the table and the mold move vertically together. Then the mold with a huge mass “bounce”, that is, comes off from the gasket for a very short distance. The table and the mold are moving separately until the mold falls down onto the rubber gasket. An impact occurs; it is soft due the softness and flexibility of the rubber gasket. The bodies move together again until the mold comes off the gasket and so on.

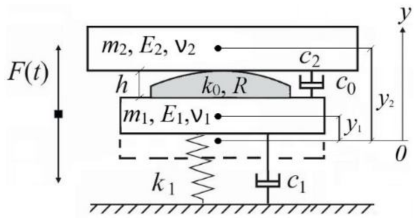

Fig.2. Design scheme for platform-vibrator with shock. Platform table with attached rubber gasket is attached to the base with a linear vibro-isolating spring. The mold with concrete is installed on the gasket without fastening. The platform table is equipped with limiters that prevent the mold from sliding and rotating

The calculation schemes of resonant vibration machines are based on assumptions that are common for most applied problems in vibration theory. The main moving masses are assumed to be absolutely rigid. The masses of elastic bonds are not taken into account due to their relative smallness. The conditions guaranteeing single-axis motion are also fulfilled. Such assumptions turn out to be quite acceptable and do not introduce significant errors into the final results of resonant vibratory machines calculating.

This model of the shock-and-vibration machine corresponds to the two-body 2-DOF vibro-impact system. In the two-body model, the masses are concentrated in the mass centers of both bodies. The parameters $y_1$ and $y_2$ represent the coordinates of these centers for the lower body (a platform table) and the upper body (a mold with concrete) respectively in the selected coordinate system. The origin of $y$ coordinate is chosen in the table center in a state of static equilibrium.

Vibro-impact movement of the platform includes both joint movement during impact and separate motion between impacts. The equations of this movement are:

$$\ddot{y}_1 = g\chi - \omega_1^2 y_1 - 2\xi_1\omega_1\dot{y}_1 + \frac{1}{m_1}F(t) +$$
$$+H(z)\left\{2\xi_0\omega_2\chi\dot{y}_1 - \omega_2^2\chi\left[h-(y_2-y_1)\right] - \frac{1}{m_1}F_{con}(z)\right\},$$
$$\ddot{y}_2 = -g - 2\xi_2\omega_2\dot{y}_2 + \tag{1}$$
$$+H(z)\left\{\omega_2^2\left[h-(y_2-y_1)\right] - 2\xi_0\omega_2\dot{y}_1 + \frac{1}{m_2}F_{con}(z)\right\}.$$

The exciting force is periodic $F(t) = P\cos(\omega t + \varphi_0)$; its period is $T = 2\pi/\omega$. The initial conditions are:

At $t = 0$ we have

$$\varphi_0 = 0,\ y_1 = 0,\ \dot{y}_1 = 0,\ y_2 = h - \lambda_0,\ \dot{y}_2 = 0. \tag{2}$$

The static deformation of the gasket is: $\lambda_0 = m_2 g / k_0$, $g$ is the acceleration due to gravity.

Here the standard notations are introduced:

$$\frac{k_1}{m_1} = \omega_1^2, \ \frac{k_0}{m_2} = \omega_2^2, \ \frac{c_0}{m_2} = 2\xi_0\omega_2, \ \frac{c_1}{m_1} = 2\xi_1\omega_1, \ \frac{c_2}{m_2} = 2\xi_2\omega_2, \ \frac{m_2}{m_1} = \chi. \quad (3)$$

$H(z)$ is Heaviside step function relatively bodies' rapprochement $z = h - (y_2 - y_1)$. $F_{con}(z)$ is contact interactive force that simulates an impact and acts only during an impact.

The damping forces are taken to be proportional to the first degree of velocity: in the rubber gasket $F_{damp\,0} = c_0\dot{y}_1$, in the vibro-isolating spring $F_{damp\,1} = c_1\dot{y}_1$. The influence of the concrete mixture can be taken into account as some additional damping $F_{damp\,2} = c_2\dot{y}_2$.

The interactive contact force $F_{con}(z)$ simulates a soft impact and is taken as a nonlinear contact Hertzian force in accordance with the quasistatic contact Hertz's theory [17, 18].

$$F_{con}(z) = K[z(t)]^{3/2}, \ K = \frac{4}{3}\frac{q}{(\delta_1 + \delta_2)\sqrt{A+B}}, \ \delta_1 = \frac{1-\nu_1^2}{E_1\pi}, \quad \delta_2 = \frac{1-\nu_2^2}{E_2\pi}. \quad (4)$$

Here $z(t)$ is the rapprochement of the bodies, as before, $z = (y_2 - y_1) - h$, when $(y_2 - y_1) \le h$; $\nu_i$ and $E_i$ − Poisson's ratios and Young's moduli of elasticity for both bodies; $A$, $B$, $q$ − are constants characterizing the local geometry of the contact zone. The gasket surface is flat, but it is expediently to consider it as a sphere of the large radius $R$. Then in the collision of a plane (mold) and a sphere (rubber gasket) $A = B = 1/2R$, $q$=0.318.

The model numerical parameters are listed in Table 1.

Table 1

Numerical parameters of platform-vibrator with shock

| | | | |
|---|---|---|---|
| Mass of table $m_1$, kg | 7400 | Damping ratio of dashpot in spring $\xi_1$ | 0.5 |
| Mass of mold with con. $m_2$, kg | 15000 | Damping ratio of dashpot in gasket $\xi_0$ | 0.02 |
| Stiffness of gasket $k_0$, N·m$^{-1}$ | $3.0\cdot10^8$ | Damping ratio in concrete mixture $\xi_2$ | 0.03 |
| Stiffness of spring $k_2$, N·m$^{-1}$ | $2.6\cdot10^7$ | Elastic modulus of mold $E_2$, N·m$^{-2}$ | $2\cdot10^{11}$ |
| Poisson's ratio of gasket $\nu_0$ | 0.4 | Elastic modulus of gasket $E_1$, N·m$^{-2}$ | $3.5\cdot10^6$ |
| Poisson's ratio of mold $\nu_2$ | 0.3 | Amplitude of exciting force $P$, N | $2.44\cdot10^5$ |
| Thickness of gasket $h$, m | 0.0275 | Frequency of exciting force $\omega$, Hz | 25 |
| Radius of gasket $R$, m | 5 | | |

### 3. Coexisting regimes with different initial conditions

### 3.1. Exciting frequency ω is a control parameter

When the exciting frequency changes, the amplitude-frequency responses are constructed. They show the dependence of vibration amplitudes of both bodies on the exciting frequency. Amplitude is half the peak-to-peak distance on the displacement plot.

After direct numerical integration the movement equations (1) the oscillatory amplitude for non-harmonic vibrations is calculated by the simple formula $A_{\max} = \dfrac{y_{\max} - y_{\min}}{2}$. The amplitude-frequency responses for the platform table (Fig. 3 (a)) and for the mold with concrete (Fig. 3 (b)) are depicted in Fig. 3. The curves $AC$ ($A'C'$) and $BD$ ($B'D'$) are obtained for different initial conditions. The coexisting modes occur in range between $B$ and $C$. It is marked with vertical dashed lines with arrows. The dynamical system at these points "jumps" from one regime to another with a further change in the control parameter.

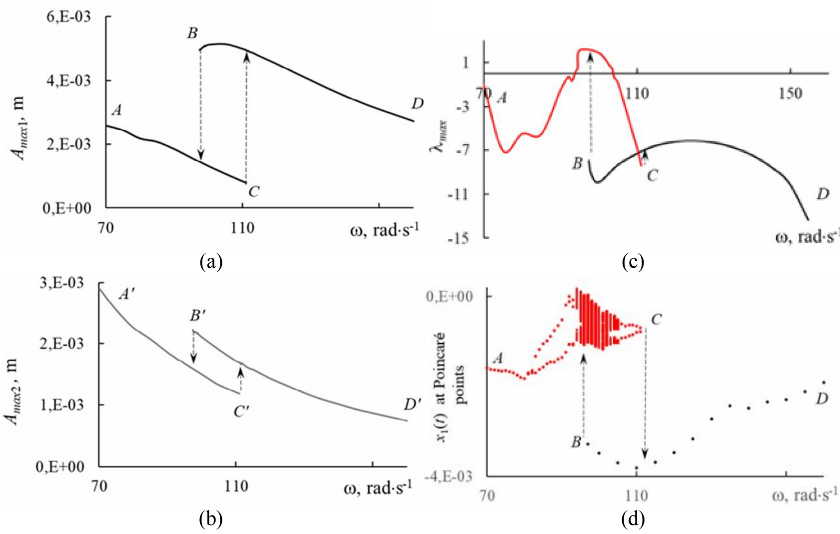


Fig.3. Amplitude-frequency responses for: (a) the platform tableand (b)the mold with concrete; (c)the dependence of the largest Lyapunov exponent $\lambda_{\max}$ on the exciting frequency $\omega$; (d)bifurcation diagram for the platform table

The graph of the largest Lyapunov exponent $\lambda_{\max}$ (Fig. 3 (c))and bifurcation diagram (Fig. 3 (d))confirm the presence of coexisting regimes in this range. The negative sign of $\lambda_{\max}$ corresponds to the periodic modes, and its positive sign hints at chaotic dynamics. This means that chaotic regimes probably exist in a narrow range of the control parameter (the exciting frequency). The bifurcation diagram also determines the mode type – it shows regime periodicity. One point (black or red) corresponds to $T$-periodic regime, two points on the same vertical – $2T$-periodic one, solid vertical line – to chaotic mode. These graphs show that chaotic motion may be realized in the frequency range 94 rad·s$^{-1}$ ≤ $\omega$ ≤ 103.5 rad·s$^{-1}$. Chaotic motion in the frequency range 98 rad·s$^{-1}$ ≤ $\omega$ ≤ 103.5 rad·s$^{-1}$ can be realized in the zone of hysteresis along with periodic (1,1)-regime, when the initial conditions are different.

**Note.** The notation $(n, m)$-regime means that regime is $nT$-periodic with $m$ impacts per cycle.

The chaotic movement at the exciting frequency $\omega$ = 100 rad·s$^{-1}$ (15.9 Hz) with $\lambda_{max}$=+1.88 is shown in detail in Fig. 4.

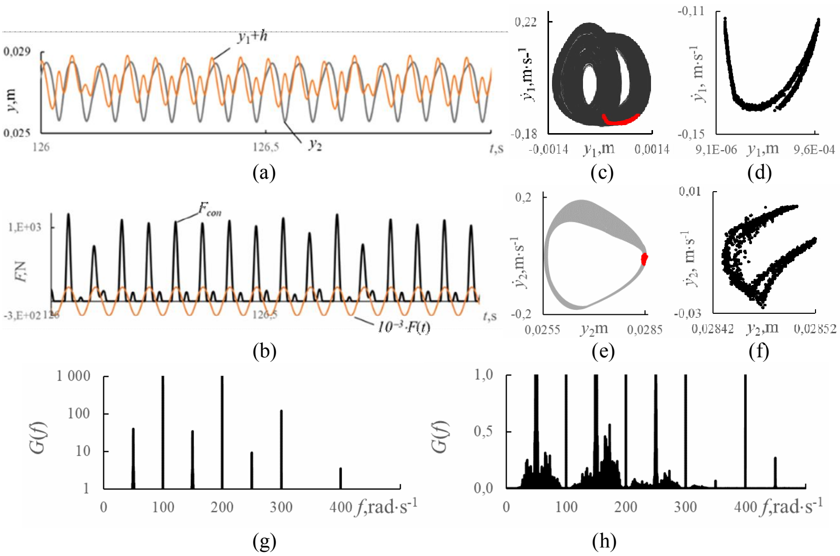


Fig. 4. The movement picture of chaotic regime for $\omega$=100 rad·s$^{-1}$, $\lambda_{max}$=+1.88. (a) Time series for both bodies. Their penetration into each other is very large due a soft impact. (b) Graph of Hertz's contact force and exciting force. (c), (e) Phase trajectories with Poincaré maps in red for (c)platform table and (e) mold with concrete; (d), (f) Poincaré maps in a larger scale for (d)platform table and (f) mold with concrete; (g) Fourier spectrum in logarithmic scale; (h) the lower part of spectrum on a large scale shows that it is broad and continuous

The right border of the hysteresis corresponds to the frequency $\omega$=111rad·s$^{-1}$ (17.6 Hz). The characteristics of the regime implemented at this frequency are presented in Fig. 5. Time histories and contact force are shown in Fig. 5 (a), (b). The large penetration of bodies into each other due to a very soft impact is clearly visible. The graph of contact force and exciting periodic force shows 4 impacts per cycle. Phase trajectories with Poincaré maps for platform table and mold with concrete are given in Fig. 5 (c), (d). The period of this movement is $2T$: the phase trajectory for one period of the external load is not closed; it becomes closed only for two periods. But the movement in each half of this $2T$ is very similar. The two dots on the Poincaré maps have almost merged and look like a cloudlet. The Fourier spectrum in Fig. 5 (e) is typical for periodic movement. It shows the main frequency $\omega$=111 rad·s$^{-1}$, superharmonics $2\omega$, $3\omega$, and harmonics that are multiples of $\omega/2$, which confirms $2T$-periodicity.

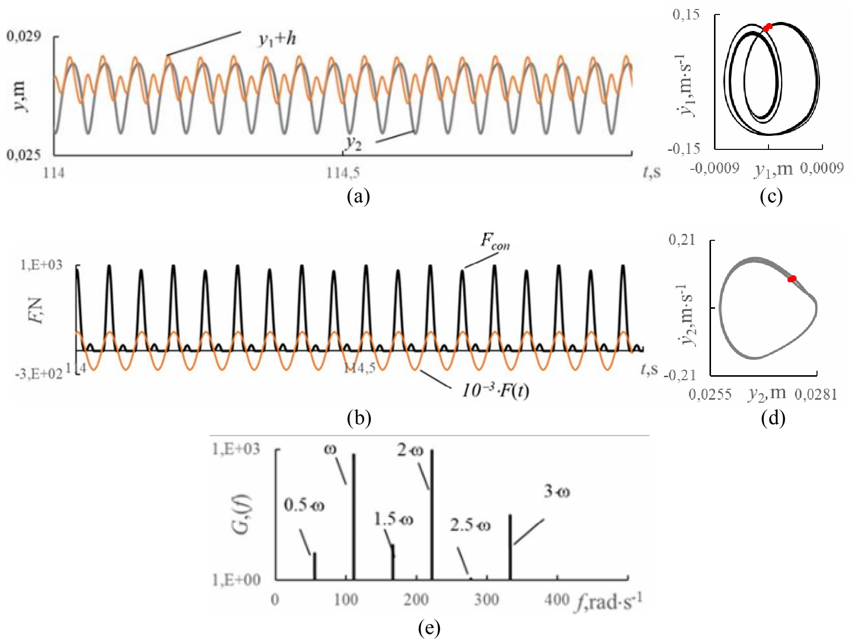


Fig. 5. The movement picture of periodic (2,4)-regime for $\omega$=111 rad·s$^{-1}$, $\lambda_{max}$=-8.37. (a) Time series for both bodies. Their penetration into each other is very large due a soft impact. (b) Graph of Hertz's contact force and exciting force shows four impacts per cycle. (c), (d) Phase trajectories with Poincaré maps for (c)platform table and (d) mold with concrete; (e) Fourier spectrum shows the main frequency $\omega$=111 rad·s$^{-1}$, superharmonics $2\omega$, $3\omega$, and harmonics that are multiples of $\omega/2$, which confirms $2T$-periodicity

Thus, oscillatory regime at $\omega$=111 rad·s$^{-1}$with $\lambda_{max}$=-8.37 is a periodic (2,4)-regime with a period of $2T$ and 4 impacts per cycle.

### 3.2. Technological mass of the mold with concrete $m_2$ is a control parameter

The picture of movement when the control parameter is the technological mass of the mold with concrete and it varies is shown in Fig. 6. The curves *AD* ($A'D'$) and *BC* ($B'C'$) are obtained for different initial conditions. The coexisting modes occur in range between *B* and *C*. The zone of hysteresis (jump phenomenon) is extending in the narrow range of the control parameter 6400 kg ≥ $m_2$ ≥ 5550 kg. These different regimes are realized in the hysteresis zone when the control parameter is kept constant, but initial conditions are different.

Fig. 6 (c) and (d) show that the kinds of regimes obtained with the same initial conditions along the *AD* ($A'D'$) curve are different. Among them there are periodic modes with different periodicity and chaotic ones. The negative sign of the largest Lyapunov exponent $\lambda_{max}$ indicates a periodic regime, and its positive sign hints at a chaotic one. The number of points on the same vertical on the bifurcation diagram determines the regime periodicity. Four dots (or two dots) on the same vertical indicate periodicity 4*T* (or 2*T*). And only for large values of mold mass $m_2$ ($m_2 \geq 7500$kg) *T*-periodic regime becomes stable and steady-state. This fact should be known when light molds can be used to better concrete compaction.

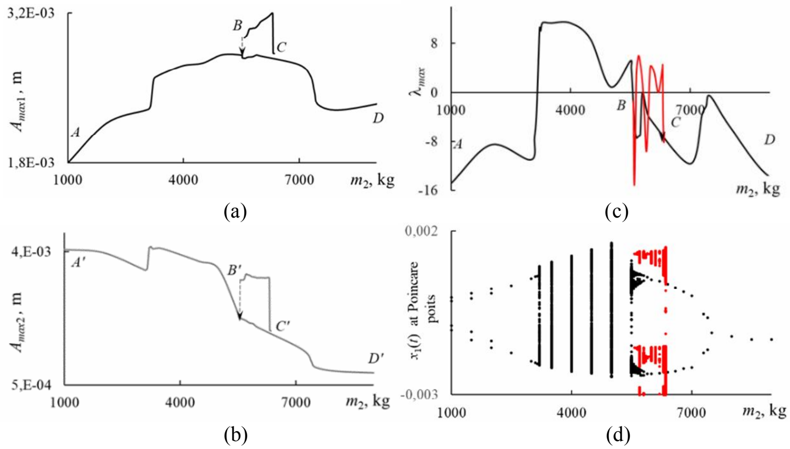


Fig. 6. Dependence on the mold mass $m_2$: the oscillatory amplitudes $A_{max}$ for (a) the platform table and (b) the mold with concrete. The curves *BC* and *B*′*C*′ correspond to coexisting modes; (c) the largest Lyapunov exponent $\lambda_{max}$; (d) bifurcation diagram for the platform table. Red curves and lines in (c) and (d) show the characteristics of coexisting regimes

Fig. 6 (c) shows a frequent change in the sign of the largest Lyapunov exponent $\lambda_{max}$ in coexisting regimes (the red curve). That is, the modes alternate many times in this narrow range of the control parameter. The alternation of coexisting regimes in this zone is shown in detail in Table 2.

Table 2

Alternation of the coexisting regimes in hysteresis zone

| Mass $m_2$, kg | 5550 | 5575-5600 | 5650 - 5750 | 5800 - 5850 | 5900 - 5950 | 6000 - 6350 | 6400 |
|---|---|---|---|---|---|---|---|
| Regime | (8,8) | (3,2) | chaos | (6,4) | (3,2) | chaos | (2,2) |

Fig. 7 shows the characteristics of coexisting modes, which are implemented at the same control parameter value $m_2$=5700 kg, but under different initial conditions. The periodic (4,4)-regime is realized when the initial conditions correspond to the *AD* curve, the chaotic regime is obtained with the initial conditions corresponding to the *BC* curve.

A broad continuous spectrum on the right side of Fig. 7(c) and the undefined set of dots on the Poincaré map on the right side of Fig. 7(d) correspond to a chaotic regime.

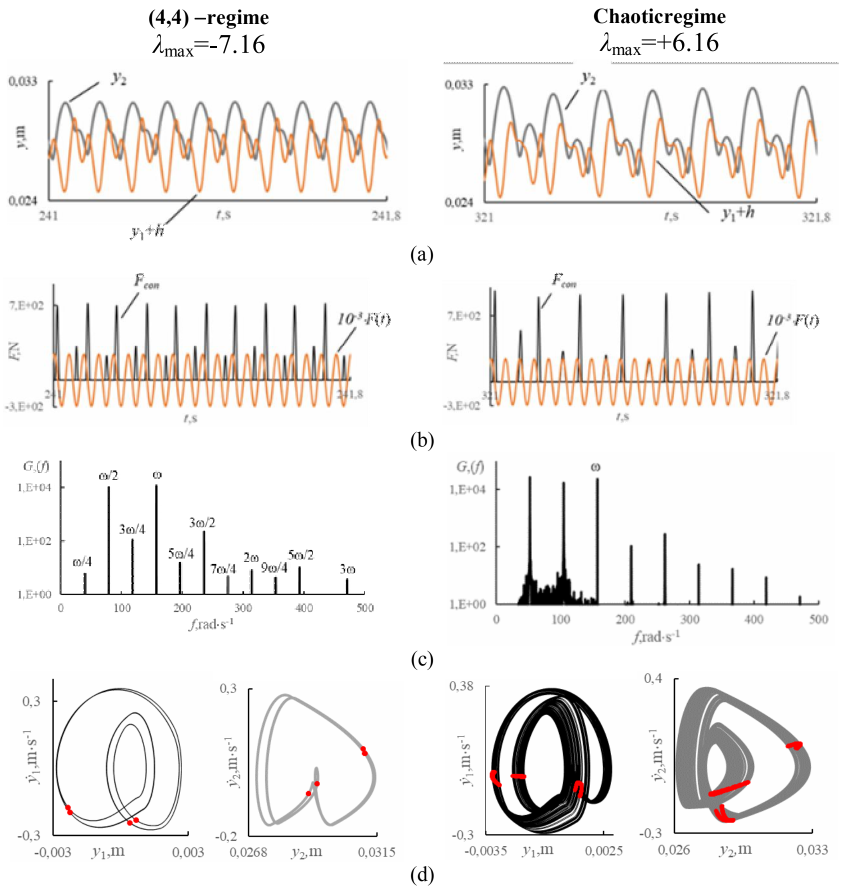


Fig. 7. The characteristics of two coexisting regimes at the same control parameter value $m_2$ =5700 kg, but under different initial conditions; (a) time histories; (b) Hertz’scontact force; (c) Fourier spectra; a broad continuous spectrum for chaotic mode; (d) phase trajectories with Poincaré maps in red; the undefined sets of dots (smears) for chaotic mode

### 3.3. Stiffness parameters are the control parameters

The parameters of the stiffness strongly affect the platform-vibrator dynamic behavior. The stiffness of vibro-isolating spring $k_1$ and Young’s modulus of elasticity of the rubber gasket $E_1$ are those stiffness parameters, the variation of which allowed observing the coexisting modes in the hysteresis zone.

**Stiffness of vibro-isolating spring $k_1$ is a control parameter**

The stiffness of the vibro-isolating spring $k_1$ determines the partial frequency $\omega_1^2$ (3) and enters with it into the motion equations (1).

Four branches of coexisting regimes in hysteresis zone were obtained at very low values of the spring stiffness under different initial conditions (Fig. 8). In Fig. 8 (c) and (d), the black curve, lines and points correspond to the branch *A*, the red ones – to the branch *B*, the blue – to the branch *C*, the green – to the branch *D*. Some curves in Fig. 8(c) practically coincide. Fig.8 (d) shows that only *T*-periodic regime without coexisting modes is established only at $k_1 \geq 3.7 \cdot 10^6$ N·m$^{-1}$. The largest Lyapunov exponent $\lambda_{max}$ is positive in a very narrow range of small control parameter values; a chaotic motion may occur in this range.

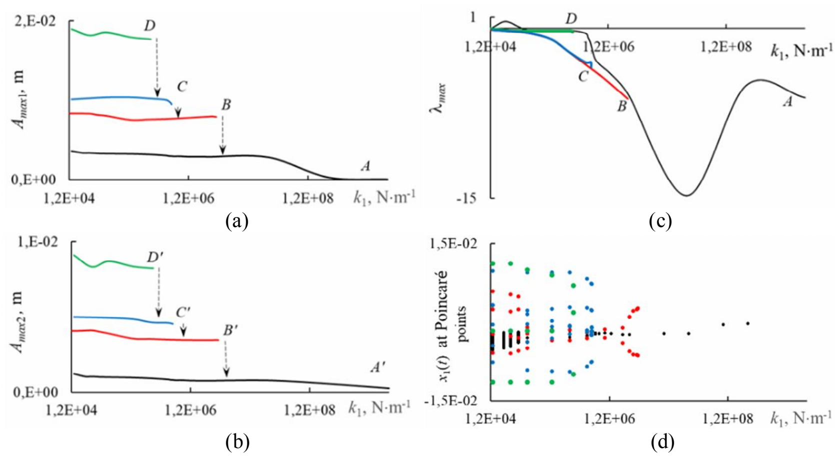


Fig. 8. Dependence on the stiffness of vibro-isolating spring $k_1$ in four*A*, *B*, *C*, *D* branches of coexisting regimes: the oscillatory amplitudes $A_{max}$ for (a) the platform tableand (b) the mold with concrete; (c) the largest Lyapunov exponent $\lambda_{max}$; (d) bifurcation diagram for the platform table. The black curve, lines and points in (c) and (d) correspond to the branch *A*, the red ones – to the branch *B*, the blue – to the branch *C*, the green – to the branch *D*

The arrows in Fig. 8 (a), (b) show that dynamical system at this point "jumps" from one regime to another with a further increase in the control parameter.

As an example, four different regimes for small value $k_1 = 2.6 \cdot 10^4$ N·m$^{-1}$ in *A*, *B*, *C*, *D* branches are shown in Fig. 9. The phase trajectories are very close one to another at each period of the external force and almost merge in the (3,1)-regime in the *D* branch. But the contact force graph clearly shows that the regime has a periodicity of 3*T* and 1 impact per cycle. The external force $F(t)$ is shown on a reduced scale. The red dotes on the phase trajectories are Poincaré sections: *n* dots for an *nT*-periodic mode, and an undefined set of dots (smear) for a chaotic signal. Fourier spectra have frequencies that are multiples of $\omega/n$ for *nT*-periodic regime. A chaotic signal produces a broad continuous spectrum.

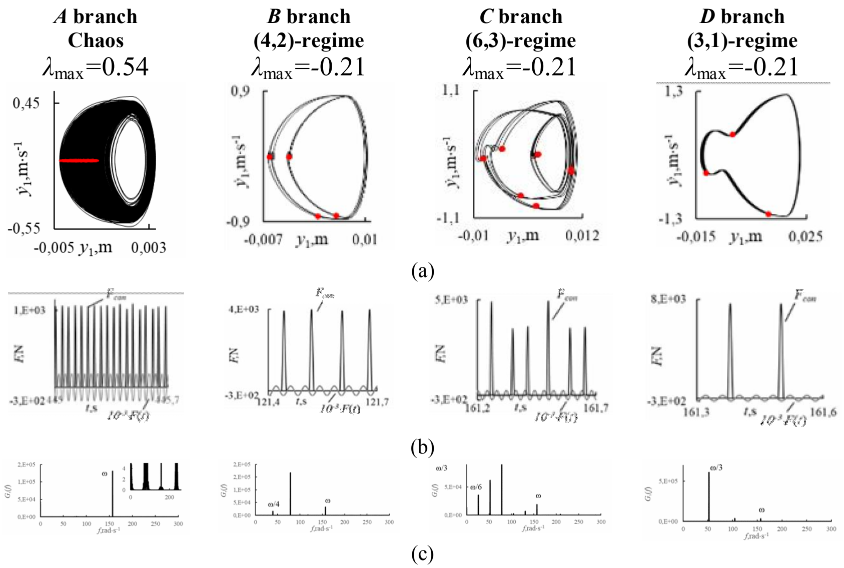


Fig. 9. Characteristicsof4 different coexisting regimesin *A*, *B*, *C*, *D* branches obtained at small valueof spring stiffness $k_1 = 2.6 \cdot 10^4$ N·m$^{-1}$ under different initial conditions: (a) phase trajectories with Poincaré maps in red; *n* dots for an $nT$-periodic mode, and an undefined set of dots (smear) for a chaotic signal; (b)graphs of Hertz'scontact force show the impact numbers per cycle; (c) Fourier spectra have frequencies that are multiples of $\omega/n$ for $nT$-periodic regime. A chaotic signal produces a broad continuous spectrum

## Young's modulus of elasticity for rubber gasket $E_1$ is a control parameter

Fig. 1 (g, h) shows an increase in the impact acceleration $w_L$ with an increase in the elastic modulus of the rubber gasket. However, an increase in the elastic modulus may lead to hysteresis phenomenon, where some of coexisting regimes can be undesirable.

Fig. 10 shows a general movement picture with a change in the elastic modulus of the rubber gasket.

The curves $AB$ ($A'B'$) and $CD$ ($C'D'$) are obtained for different initial conditions**.** Coexisting regimes occur in a very narrow range of the control parameter. In points $B$($B'$) and $C$ ($C'$) the dynamical system "jumps" from one regime to another with a further increase in the control parameter. The $CD$-curve modes that occur when the control parameter is increased are likely to be undesirable. Fig. 10 (c) shows that they all have the positive largest Lyapunov exponent, that is, they are chaotic. The bifurcation diagram in Fig. 10(d) confirms this fact. The amplitude of the platform table vibrations decreases but the oscillatory amplitude of the mold with concrete is greatly increased.

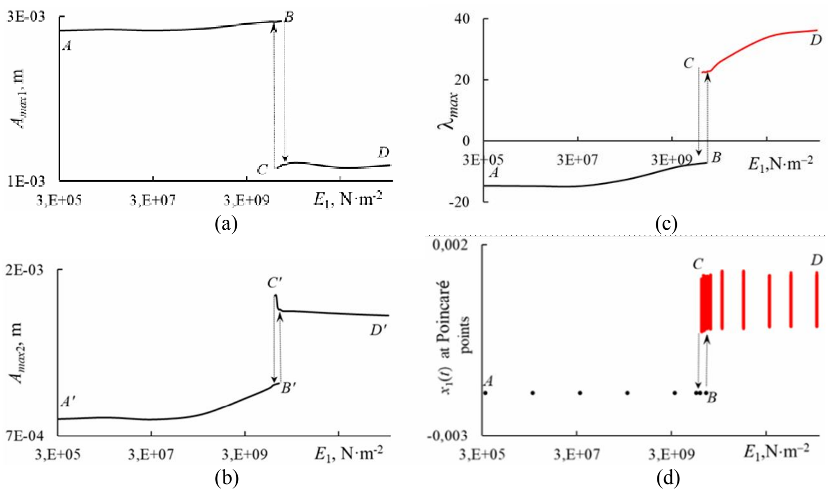


Fig. 10. Dependence on the elastic modulus of the rubber gasket $E_1$ the oscillatory amplitudes $A_{max}$ for (a) platform tableand (b) mold with concrete; (c) the largest Lyapunov exponent $\lambda_{max}$; (d) bifurcation diagram for platform table

In the hysteresis zone between points *B* and *C* at $E_1 = 1.2 \cdot 10^{10}$ N·m$^{-2}$, there is a*T*-periodic regime on the *AB* branch, when zero initial conditions are taken from the resting state. On the *CD* branch there is a chaotic mode, more precisely, transient chaos. Its lifetime depends on the initial conditions. Fig. 11 shows these modes for the platform table.

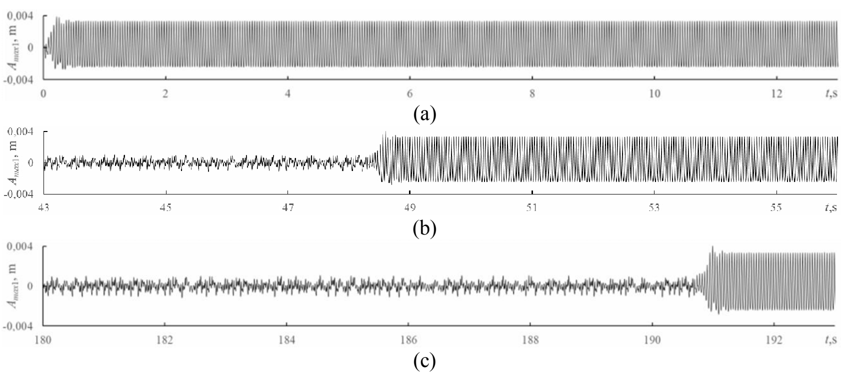


Fig. 11. Coexistingregimes in hysteresis zone at $E_1 = 1.2 \cdot 10^{10}$ N·m$^{-2}$. Time series for platform table: (a) *T*-periodic regime when zero initial conditions are taken in resting state; (b) short transient chaos when initial conditions are taken in chaotic motion at $E_1 = 1.7 \cdot 10^{10}$ N·m$^{-2}$; (c) long transient chaos when initial conditions are taken in chaotic motion at $E_1 = 1.3 \cdot 10^{10}$ N·m$^{-2}$

The transient chaosis a very interesting phenomenon. In [15], we described it in detail. When a transient chaos occurs, a dynamical system that was in a chaotic movement abruptly turns into a periodic one with the same value of the parameter! (Or, on the contrary, it suddenly goes from the periodic movement to a chaotic one.)The lifetime of transient chaos depends both on the control parameter value and on the initial conditions [12, 15, 16].

**4. Conclusions**

The mathematical model of a platform-vibrator with shock corresponds to two-body 2-DOF nonlinear non-smooth discontinuous vibro-impact system with soft impact. It exhibits coexisting regimes when changing the control parameters, which were the exciting frequency, the technological mass of the mold with concrete, and the stiffness parameters of elastic elements. On the one hand, a decrease in the exciting frequency, the mold mass, the vibro-isolating spring stiffness and an increase in Young's modulus of elasticity of the rubber gasket provide an increase in impact acceleration, which improves the compaction process. On the other hand, such changes in the parameters lead to arising of the coexisting regimes, many of which are undesirable. These are modes with a large periodicity and several impacts per cycle, chaotic modes, and transient chaos. Both permanent and transient chaos may often be dangerous and unwanted states. Therefore, when operating the equipment, it is desirable to avoid the control parameter range in which these states can occur.

REFERENCES

1. Nazarenko, I. I. Applied problems of the vibration systems theory: Textbook (2nd edition). Kyiv. Publishing House "Word".2010. (in Ukrainian)
2. Vasiliev, V.G. Vyibor optimalnyih parametrov vibratsionnogo formovanii Zhelezobetonnyih izdeliy (Selection of optimal parameters of vibration molding of reinforced concrete products). Dig. J. Technique and Technology of Transport, S13. 2019. (in Russian).
3. Nazarenko, I.I., et al. Investigation of vibration machine movement with a multimode oscillation spectrum. Eastern-European Journal of Enterprise Technologies.2017. 6 (1), 28-36.
4. Nazarenko, I.I., et al. Development of energy-efficient vibration machines for the building-and-contruction industry. Przeglad Elektrotechniczny. 2019. 1(4), 55-61.
5. Gusev, B.V., Fayvusovich A.S. Technological mechanics of vibrating concrete mixes. M. 2002. 252 c. (in Russian)
6. Sharapov, R., &Vasiliev, V. Analysis of the spectrum distribution of oscillation amplitudes of the concrete mix at shock vibration molding. In MATEC Web of Conferences (Vol. 117, p. 00152). EDP Sciences.2017. (in Russian)
7. Basarab V.A. Investigation of the poly-frequency mode of oscillations of the electromagnetic shock-vibration system. Scientific Bulletin of the National University of Life and Environmental Sciences of Ukraine. Series: Technology and energy of agro-industrial complex. (241), 2016, P.101-110. (in Ukrainian)
8. Gusev, B.V., &Zazimko, V.G. Vibration Technology of Concrete. Budivelnik, Kiev. (1991). (in Russian)
9. Basarab, V.A. Investigation of the dynamic parameters of a vibration machine for building mixes compaction. Int Appl Mech 56. 2020. P.750–761
10. Borshchevsky, A. A., &Ilyin, A. S. Mechanical equipment of enterprises for the production of building materials and products. Moscow, Alliance. 2009. (in Russian)
11. Gusev, B. V., et al.. Recommendations on Vibration Forming of Reinforced Concrete.(1986) (in Russian)
12. Bazhenov, V. A., Pogorelova, O. S., &Postnikova, T. G. Nonlinear Events in Dynamic Behavior of Unusual Vibro-impact System: Numerical studies of the dynamic behavior of the

platform-vibrator with shock, LAP LAMBERT Academic Publ. GmbH and Co. KG Dudweiler, Germany. 2021.

13. Kapitaniak T., Bishop S. R. The illustrated dictionary of nonlinear dynamics and chaos. – Wiley, 1999.
14. Bazhenov V., Pogorelova O., Postnikova T.G. Creation of mathematical model of platform-vibrator with shock. designed for concrete products compaction and molding //Strength of Materials and Theory of Structures: Scientific-and-technical collected articles. – 2020. – №. 104. – С. 103-116.
15. Bazhenov V.A., Pogorelova O.S., Postnikova T.G. Transient Chaos in Platform-vibrator with Shock // Strength of Materials and Theory of Structures: Scientific-and-technical collected articles. – K.: KNUCA, 2021. – Issue 106. – P 22-40.
16. Bazhenov V.A., Pogorelova O.S., Postnikova T.G. Crisis-induced Intermittency and Other Nonlinear Dynamics Phenomena in Vibro-impact System with Soft Impact. 11 Chapter in book "Nonlinear Mechanics of Complex Structures: From Theory to Engineering Applications" (Edited by Prof. Altenbach H., Prof. Amabili M., Prof. Mikhlin Yu.) in the Springer Book Series "Advanced Structured Materials". 2021.Book 157. Springer International Publishing. ISBN: 978-3-030-75889-9 (print), 978-3-030-75890-5 (eBook) DOI 10.1007/978-3-030-75890-5
17. Goldsmith W. Impact: The Theory and Physical Behavior of Colliding Solids. Edward Arnold Ltd. – 1960.
18. Johnson K. L. Contact mechanics.Cambridgeuniv //Press. Cambridge. – 1985. – Т. 95. – С. 365.

*Стаття надійшла 05.10.2021*

*Баженов В.А., Погорелова О.С.,Постнікова Т.Г.*

**СПІВІСНУЮЧІ РЕЖИМИ В ЗОНАХ ГІСТЕРЕЗІСА У ВІБРОУДАРНОМУ МАЙДАНЧИКУ**

Процеси формування є одними з найважливіших у виробництві залізобетонних конструкцій. Вібраційні та ударно-вібраційні технології ущільнення бетонних сумішей та формування бетонних виробів мають найбільше поширення у будівельній промисловості. Тому питання оптимізації режимів вібрації, правильного вибору вібраційного обладнання не втрачають своєї актуальності. У статті обговорюється динамічна поведінка ударно-вібраційної низькочастотної резонансної машини – віброударного майданчика. Його математична модель відповідає двох масовій системі з двома ступнями вільності з м'яким ударом, який моделюється нелінійною інтерактивною контактною силою відповідно до квазістатичної контактної теорії Герца. Зміна провідних параметрів може, з одного боку, покращити процес ущільнення, але, з іншого боку, привести до небажаних коливальних режимів. У статті обговорюються такі провідні параметри, як частота збудження, технологічна маса форми з бетоном та параметри жорсткості пружних елементів. Зменшення частоти збудження, маси форми, жорсткості віброізолюючої пружини та збільшення модуля пружності Юнга гумової прокладки забезпечують збільшення ударного прискорення, що покращує процес ущільнення. Однак при таких змінах параметрів виникають співіснуючі режими, багато з яких є небажаними. Це є режими з великою періодичністю та кількома ударами за цикл, хаотичні режими та перехідний хаос. Діагностика режиму проводиться традиційними чисельними засобами, а саме побудовою часових рядів (реалізацій сигналу), фазових траєкторій, перерізів Пуанкаре, спектрів Фур'є та обчисленням найбільшого показника Ляпунова. Сподіваємось, що цей аналіз може допомогти уникнути небажаної поведінки віброударного майданчика під час проєктування та експлуатації. Виклад супроводжується багатьма графіками та таблицею.

**Ключові слова:**віброударниймайданчик,форма з бетоном,гумова прокладка, частота збудження,технологічна маса,параметри жорсткості,співіснуючі режими.

УДК 539.3
*Баженов В.А., Погорелова О.С., Постнікова Т.Г.* **Співіснуючі режими в зонах гістерезіса в ударно-вібраційному майданчику**// Опір матеріалів і теорія споруд: наук.-тех. збірн. – К.: КНУБА.2021. – Вип. 107. – С. 3-19. – Англ.
*Математична модель ударно-вібраційного майданчика, що широко застосовується у будівельній галузі для ущільнення та формування бетонних виробів, при зміні контрольних параметрів демонструє низку нелінійних явищ, зокрема таке цікаве та "примхливе" явище, як перехідний хаос.*
Табл. 2. Рис. 11. Бібліогр. 18 назв.

UDC 539.3
*Bazhenov V.A.,Pogorelova O.S.,Postnikova T.G.*
**Coexisting Regimes in Hysteresis Zone in Platform-Vibrator with Shock**// Strength of Materials and Theory of Structures: Scientific-and-technical collected articles. – K.: KNUBA. 2021. – Issue107. – P. 3-19.
*The article discusses the dynamical behavior of a shock-vibrational low-frequency resonant machine, which is widely used in the construction industry for compacting and molding concrete products.Its mathematical model corresponds to a strongly nonlinear nonsmooth discontinuoustwo-body 2-DOF vibro-impact system with a soft impact.When changing the control parameters, coexisting oscillatory regimeswere observed in the hysteresis zone, many of which may be undesirable and sometimes dangerous. These are modes with a large periodicity and several impacts per cycle, chaotic modes, and transient chaos.*
Tabl. 2. Fig. 11. Ref. 18.

**Автор (вчена ступень, вчене звання, посада)**: *доктор технічних наук, професор, БАЖЕНОВ Віктор Андрійович*
**ORCIDID:** https//orcid/org/0000-0002-5802-9848

**Автор (вчена ступень, вчене звання, посада)**: *кандидат фізико-математичних наук, старший науковий співробітник, провідний науковий співробітник НДІ будівельної механіки ПОГОРЕЛОВА Ольга Семенівна*
**Адреса робоча:** *03680 Україна, м. Київ. Повітрофлотський проспект 31, Київський національний університет будівництва і архітектури*
**Робочий тел.:** *+38(044) 245-48-29*
**Мобільний тел.:** *+38(067) 606-03-00*
**E-mail:** pogos13@ukr.net
**ORCID ID:** http://orcid.org/0000-0002-5522-3995

**Автор (вчена ступень, вчене звання, посада)**: *кандидат технічних наук, старший науковий співробітник, старший науковий співробітник НДІ будівельної механіки ПОСТНІКОВА Тетяна Георгіївна*
**Адреса робоча:** *03680 Україна, м. Київ, Повітрофлотський проспект 31,Київський національний університет будівництва і архітектури*
**Робочий тел.:** *+38(044) 245-48-29*
**Мобільний тел.:** *+38(050) 353-47-19*
**E-mail:** postnikova.tg@knuba.edu.ua
**ORCID ID:** https://orcid.org/0000-0002-6677-4127