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***Research paper***

# Estimating the Motion of Shock and Vibration System and Performance of Oscillation Limiters Based on Time and Shape of Shock Pulse of the Shock and Vibration Machine

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**Abstract**

The paper describes an analytic dependence for determining the amplitude of oscillations on a fundamental frequency with the definition of the limit on the amplitude of the super resonance harmonic. In the article the conditions are formulated and dependences for a system moving in shock and up to shock mode: time of impact, deformation of limiters, recovery factor, velocity after the end of interaction are defined.

***Keywords****: concrete mix compaction, equation of motion, impact pulse, oscillation limiters, shock and vibration machine.*

## 1. Introduction

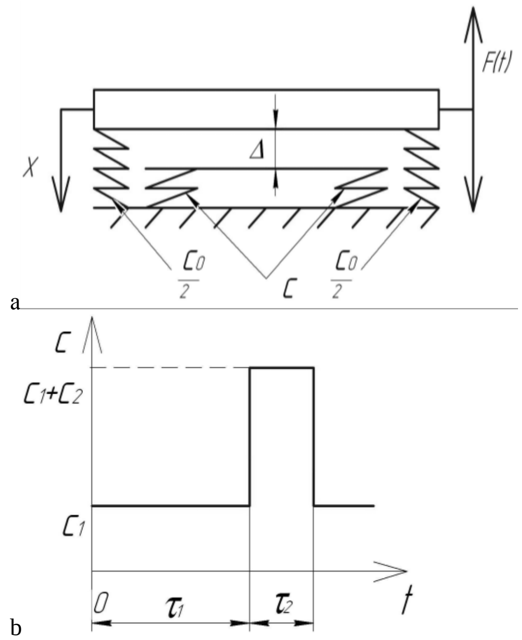
Taking into account current trends in thermal modernization and reconstruction of existing buildings and structures, there is a need for building materials that could meet the regulatory requirements for strength and thermal conductivity. Such materials can include lightweight concrete products: arbolit, ceramsite, concrete, polystyrene concrete and other products with artificial and natural fillers.

It is proved [1-5] that it is expedient to use shock and vibration machines for making lightweight concrete products. The scientific studies and basic requirements for vibration machines for the formation of concrete products, given in works [2, 6-9] is a theoretical basis for generation of equation of shock and vibration system motion and determination of the basic parameters of shock and vibration machines [10-14] and estimation of oscillation limiters performance based on time and shape of a shock impulse.

## 2. The statement of basic materials

Generation of the equation of shock vibration systems motion can not be imagined without the formulation of preconditions and assumptions: a mixed discrete-continual model of the system is taken into account, the equation of motion includes acceleration of a contact area, a processed environment - a system with distributed parameters..

As an analytical, the installation scheme (Fig. 1, a) is taken into account, in which a stiffness coefficient varies according to the law (Fig. 1, b). The main interest is the determination supports elasticity on which falls the mass of forms with a compacted mixture at the kinematic excitation of oscillations.




a - ; b - the law of stiffness change.

**Fig. 1:** General scheme of research facility:

In the analytical scheme (Fig. 1, a) is meant the reduced mass of the vibration system, which contains the mass of the machine that vibrates and the reactive resistance of the medium. Time intervals (Fig. 1, b) $\tau_1$ and $\tau_2$ show the time of mass movement without contact with elastic oscillation limiters, stiffness $C$ in contact with these elements. Obviously, that $T = \tau_1 + \tau_2$.

Let's take a look at the approach, the essence of which is to estimate the average stiffness for the period:

$$C=\frac{1}{T}\int_0^T c(t)dt=\frac{1}{T}\left\{\int_0^T (c_1+c_2)dt+\int_0^T c_1 dt\right\}=c_1+c_2\frac{\tau_2}{T}\ . \qquad (1)$$

Here, the countdown is taken from the moment of contact between two mutually active masses (see Fig. 1, a). The approach written in the equation allows to approximate the given laws by the function:

$$c(t)=c_1+c_x\cos(\frac{\pi}{2\tau_2}t)\ . \qquad (2)$$

The accepted record is substantiated by the fact that a "rectangular pulse" $C(t)$ (Fig. 1, b) on the interval $0\le t\le\tau_2$ can be described by cosinusoidal function and when $\cos\omega t\to 0$ at $t=\frac{1}{4}T$, then we choose $\tau_2=\frac{1}{4}T$, and obtain $\omega=\frac{2\pi}{T}=\frac{2\pi}{4\tau_2}=\frac{\pi}{2\tau_2}$.

To determine the dependence for $c_x$ we'll assume the identity (1) and (2) having stiffness changes $c(t)$ as the average value for the period $T$:

$$\frac{1}{T}\int_0^T\left[c_1+c_x\cos(\frac{\pi}{2\tau_2}t)\right]dt=c_1+c_2\frac{\tau_2}{T}\ . \qquad (3)$$

Having solved the equation (3), we obtain

$$c_x=-\frac{\pi c_2}{2\sin(\frac{\pi}{2\tau_2}T)}\ . \qquad (4)$$

The sign "-" indicates that the considered sinus value is in the 3rd and 4th quarters $(\frac{\pi}{2}\frac{T}{\tau_2}>\pi)$, consequently $c_x>0$. Using experimental data [1] we obtain $\frac{\tau_2}{T}=\frac{\tau_k}{T}=\frac{1}{3}$. Then $\frac{\tau_2}{T}=\frac{1}{3}$; $c_x=\frac{\pi}{2}c_2$.

Now write of oscillation system equation (Fig. 2., a)

$$m\ddot{x}+\left[c_1+c_x(\frac{\pi}{2\tau_2}t)\right]x+b\dot{x}=F_0\sin(\omega t+\varphi)\ , \qquad (5)$$

where

$$m=m_c+m_c(a_1+a_1^*\frac{\tau_2}{T})\ , \qquad (6)$$

$$b=b_0+m_c(\omega d_1+\frac{\omega^*}{2}d_1^*\frac{\tau_2}{T})\ , \qquad (7)$$

where $a_1^*$ and $d_1^*$ – the influence coefficient of a reactive and active forces of resistance at frequency $\omega^*/2$;

$a_1$ and $d_1$ – the influence coefficient of a reactive and active forces of resistance on the main frequency $\omega$;

$\tau_2$ – contact time with з $c_2$;

$T$ – the period of stiffness change; $\omega=\frac{2\pi}{T}$; $\omega^*=\omega$.

Let's consider free oscillations of the installation without consideration of energy dissipation with the following analysis of the equation (5).

The consideration of free oscillations is due to the fact that in such a regime it is possible to determine the influence of inertial and elastic forces and, on this basis, to obtain analytical dependencies for the determination of elastic characteristics, to take into account the contribution of higher harmonics that may occur during the impact of form with a mixture of a oscillation limiter.

Take $b\equiv 0$ and $F_0=0$, then equation (5) will take the form

$$m\ddot{x}+\left[c_1+c_x\cos(\frac{\pi}{2\tau_2}t)\right]x=0\ . \qquad (8)$$

According to the structure, this is Mathieu's equation, but the difference lies in the consideration of wave processes.

The nature of its solution depends on two nondimensional factors.

Putting in nondimensional time $\theta=\frac{\pi}{2\tau_2}t\cdot\frac{1}{2}$, rearrange of the equation

$$\frac{d^2x}{d\theta^2}+(\varepsilon+2q\cos 2\theta)x=0 \qquad (9)$$

where

$$\varepsilon=\frac{4c_1}{m(\frac{\pi}{2\tau_2})^2}\ ;\quad q=\frac{2c_x}{m(\frac{\pi}{2\tau_2})^2}\ . \qquad (10)$$

Determine the system oscillations, taking into account the higher harmonics: $\frac{\pi}{2\tau_2}=\omega=2n\omega$, where $n$ – number, close to two.

Contact time at that $\tau_2=\frac{\pi}{2\cdot 2n\omega}=\frac{\pi}{4n}\frac{T}{2\pi}=\frac{T}{8n}$.

It should be noted that $n\ne 2$, because $c_x\to\infty$ according to (4), so we adopt $n=1{,}9;1{,}95;1{,}975;1{,}99$.

Thus, the formulas for the determination $\varepsilon$, $q$, $c_x$ will be the following:

$$\varepsilon=\frac{c_1}{mn^2\omega^2}\ ;\ q=\frac{c_x}{2mn^2\omega^2}\ ;\ c_x=-\frac{\pi c_2}{2\sin 4n\pi}\ . \qquad (11)$$

After substitution $q$, $c_x$ we obtain

$$\varepsilon=\frac{c_1}{mn^2\omega^2}\ ;\ q=-\frac{\pi c_2}{4mn^2\omega^2\sin(4\pi n)}\ . \qquad (12)$$

The coefficient (characterizing the ratio of the intrinsic frequency of the system with the average parameter value to the frequency of of shiftness parameter change) and the coefficient (characterizing the degree of shiftness parameter change) completely determines the stability of the work. Plane of parameters variation, fall into a zone of stability, then periodic solutions are possible (8). In this case, the period of motion must be twice as much as the length of a parameter change. In this case, the period of motion must be twice as much as the period of parameter change. If the change in stiffness is proportional $4\omega$ to the system, then the motion is proportional to the double frequency of the system and we $2\omega$ obtain a superharmonic component in a stability zone.

Now we take into account the dissipation of energy in the system, that is $b \neq 0$. Then the condition for the formation of super resonance will be under the condition

$$(\varepsilon-1)^2 - q^2 - \alpha_1^2 < 0 . \qquad (13)$$

From here it follows that the coefficient

$$q > \sqrt{(\varepsilon-1)^2 + \alpha_1^2}\ ;\ \alpha_1 = b\frac{\omega^*}{2m} . \qquad (14)$$

Accordingly, while at the absence of friction super resonance occurred at $q > (1-\varepsilon) \approx 1$, then $q$ grows and equation (13) takes the form:

$$\frac{-\pi c_2}{4mn^2\omega^2 \sin(4\pi n)} > \sqrt{(1-\frac{c_1}{mn^2\omega^2})^2 + (\frac{b\pi}{4m\tau_2})^2} . \qquad (15)$$

It becomes obvious that the change of contact time $\tau_2$ causes the parameter change $q$. Since this system is discrete-continuum, according to (5), then the coefficient $m$ has a mass dimension, determines a reactive resistance and depends on frequency.
In accordance with the initial equation (5), consider the most general case of the studied system motion (Fig 1, a). In a similar way, when we obtain the equation (11), and record

$$\ddot{\varepsilon} + \alpha_1\dot{\varepsilon} + (\varepsilon + 2q\cos 2\theta)\varepsilon = 0 . \qquad (16)$$

Stability condition, as in (13), is the equation $(\varepsilon-1)^2 + q^2 + \alpha_1^2 < 0$, that is, coercive force did not change the zone of stability and instability of the studied parametric oscillations.
We estimate the region of oscillation regimes in coordinates $\omega$, $x_0$. Assume that $x_{01}$ – amplitude at frequency $\omega$, and $x_{02}$ – the amplitude at frequency $2\omega$ (super resonance). Coercive force has the amplitude $F_0$ at the frequency $\omega$:

$$x = x_{01}\sin\omega t + B_1\cos\omega t + x_{02}\sin 2\omega t + B_2\cos 2\omega t . \qquad (17)$$

Now determine the work of external and internal forces of the system.
The work of external force for the cycle of oscillations is

$$A = \int_0^{2\pi/\omega} F(t)\dot{x}(t)dt = \pi F_0 x_0 \sin\varphi . \qquad (18)$$

since the work of external force $F(t)$ over super harmonics gives a zero-point effect.
Work of internal forces (forces of friction) during the period of oscillations

$$W = \int_0^{2\pi/\omega} b_1\dot{x}^2 dt = (\pi x_{01}^2\omega + 4\pi x_{02}^2\omega)b_1 . \qquad (19)$$

Provided that energy balance $A = W$ we obtain

$$\pi F_0 x_{01}\sin\varphi = \pi b_1\omega(x_{01}^2 + 4x_{02}^2) , \qquad (20)$$

from here it follows that $\sin\varphi = \frac{b_1\omega(x_{01}^2 + 4x_{02}^2)}{F_0 x_{01}}$, as $\sin\varphi \le 1$, then

$$\frac{b_1\omega(x_{01}^2 + 4x_{02}^2)}{F_0 x_{01}} \le 1 . \qquad (21)$$

From the equation we obtain

$$x_{01} \le \frac{1}{2}\sqrt{\frac{F_0 x_{01}}{b_1\omega} - x_{01}^2} . \qquad (22)$$

To increase the super harmonics $x_{02}$ it is necessary to increase the forces with simultaneous decreasing of frictional forces $b_1$ and frequency $\omega$.
Dependency $x_{02}$ on $x_{01}$ will have a small upper possible bound.
If $\frac{F_0 x_{01}}{(b\omega) - x_{01}^2} = \tilde{f}(x_{01})$, then the required equation will be valid at $\left[F_0 x_{01}\right]_{x_{01}}' = 0$.
Then $\frac{F_0}{(b\omega) - 2x_{01}} = 0$ and $x_{01} = \frac{F_0}{2b_1\omega}$, $x_{01}$ – the determined amplitude.
At the same time, the value of the amplitude

$$x_{02} \le \frac{1}{2}\sqrt{2x_{01}^2 - x_{01}^2} \le \frac{1}{2}x_{01} . \qquad (23)$$

With the adopted approach will be obtained $x_{02} \le 0{,}5x_{01}$.
Knowing that $x_{01} = \frac{F_0}{2b_1\omega}$, it is possible to get a condition to determine the amplitude

$$x_{02} = \frac{F_0}{4b_1\omega} . \qquad (24)$$

The presence of a coercive force in our assumption does not change the stability map, but imposes a restriction on top of the amplitude of the super resonance harmonic.
Thus, engineering formulas (10), (11), (24) allow to determine the necessary parameters of the vibration system for the implementation of superresonance mode of operation, taking into account the wave processes in the sealing medium.
The equation of motion of the studied system (Fig. 1, a) will have the following form for each stage:
at $0 \le t \le \tau_1$

$$m\ddot{x}^{(-)} + b_1\dot{x}^{(-)} + c_1 x^{(-)} = F_0 \sin\omega t , \qquad (25)$$

at $\tau_1 \le t \le T$

$$m\ddot{x}^{(+)} + (b_1 + b)\dot{x}^{(+)} + (c_1 + c_2)x^{(+)} = F_0 \sin\omega(t - t_0) . \qquad (26)$$

The solution of equation (25) relative to displacement can be represented as a sum of own and stationary vibrations [1]:

$$x^{(-)} = e^{-\tilde{b}_1 t}\left[A_1\cos(\tilde{p}_1 t) + A_2\sin(p_1 t) + \frac{F_0(\sin)(\omega t - \varphi)}{\sqrt{(p_1^2 - \omega^2)^2 + 4\tilde{b}_1^2\omega^2}}\right], \qquad (27)$$

where $\tilde{b}_1 = \frac{b_1}{2m_{np}}$, $\tilde{p}_1 = \sqrt{p_1^2 - \tilde{b}_1^2}$, $p_1^2 = \frac{c_1}{m_{np}}$; $\varphi = arctg\left\{\frac{2\tilde{b}_1\omega}{p_q^2 - \omega^2}\right\}$.

Vibration velocity:

$$\dot{x}^{(-)}\Big|_{t=t_1} = -b_1 e^{-b_1 t_1}\left[A_1\cos(\tilde{p}_1 t_1) + A_2\sin(p_1 t)\right] + $$
$$+e^{-\tilde{b}_1 t_1}\left[-\tilde{p}_1 A_1\sin(\tilde{p}_1 t_1) + \tilde{p}_1 A_2\cos(\tilde{p}_1 t_1)\right] + \frac{2F_0\omega\cos(\omega t_1-\varphi)}{\sqrt{(p_1^2-\omega^2)^2+4\tilde{b}_1^2\omega^2}} , \quad (28)$$

where

$$A_1=\frac{\Delta A_1}{\Delta}\,;\; A_2=\frac{\Delta A_2}{\Delta}\,;\; \Delta=(\tilde{b}_1^2+\tilde{p}_1^2)^2\cdot\sin(\tilde{p}_1 t_1)\,;$$
$$\Delta A_1 = G_c\left\{(\tilde{b}_1^2+\tilde{p}_1^2)\sin(\tilde{p}_1 t_1) - 2\tilde{b}_1\tilde{p}_1\cos(\tilde{p}_1 t_1)\right\} + G_k 2\tilde{b}_1\tilde{p}_1 e^{-\tilde{b}_1 t_1}\;; \quad (29)$$
$$\Delta A_2 = G_k e^{b_1 t_1}(\tilde{b}_1^2+\tilde{p}_1^2) - G_k\left\{(\tilde{b}_1^2+\tilde{p}_1^2)\cos(\tilde{p}_1 t_1) + 2\tilde{b}_1\tilde{p}_1\sin(\tilde{p}_1 t_1)\right\}$$

Let's denote $\dot{x}^{(-)}\Big|_{t=t_1} = v$ .

Assuming that $\dot{x}^{(+)}\Big|_{t'=0} = v$ ; $t' = t - t_1$ ; $x^{(+)}\Big|_{t'=0} = v$ .

The vibration velocity for the equation (27) is similar to (28)

$$v = -\tilde{b}_1 e^{-\tilde{b}_1 t_1}\left[A_1\cos(\tilde{p}_1 t_1) - A_2\sin(\tilde{p}_1 t_1)\right] +$$
$$+e^{-\tilde{b}_1 t_1}\left[-\tilde{p}_1 A_1\sin(\tilde{p}_1 t_1) + \tilde{p}_1 A_2\cos(\tilde{p}_1 t_1)\right] + . \quad (30)$$
$$+\frac{F_0\omega\sin(\omega t_1-\varphi)}{\sqrt{(p_1^2-\omega^2)^2+4\tilde{b}_1^2\omega^2}}$$

We introduce a notation that allows us to proceed to the conrtol in a dimensionless form:

$$m = m_{np}\,;\; b = b_1 + b_0\,;\; c = c_1 + c_0\,;\; F(t') = F_0(\omega t')\,;\; \Omega = \frac{F_0}{mv}\,;$$
$$\tau = \Omega t' = \Omega(t-t_1)\,;\; \varepsilon = \frac{mv^2}{F_0}\,;\; z = \frac{x^{(+)}}{\varepsilon}\,;$$
$$k = \frac{1}{\Omega}\sqrt{\frac{c_1+c_0}{m}}\,;\; \delta = \frac{b}{2\sqrt{(c_1+c)m}\cdot t}\,;\; f(\tau) = \frac{F_0\cos(\frac{\omega}{\Omega}\tau)}{m\varepsilon\Omega^2}\,;$$
$$f(0) = \frac{F_0}{m\varepsilon\Omega^2} . \quad (31)$$

Thus,the equation (25) takes the form:

$$z'' + 2\delta k z' + k^2 z = f . \quad (32)$$

Initial conditions:

$$\tau = 0\,;\; z = 0\,;\; z' = v = \frac{v}{\varepsilon\Omega} > 0 . \quad (33)$$

As a result, we obtain a system of parameters characterizing the considered process of interaction of a form with a mixture and vibration limiters.

The time of the process during which the maximum deformation of the limiter is achieved,

$$\tau_* = \frac{\arccos\delta}{k\sqrt{1-\delta^2}} + \frac{f(0)}{k^2 v} + \frac{1}{k^2 v}\left[\frac{\delta}{v} f^2(0)\right] . \quad (34)$$

You can also note that effective time is $t_*$ , during which the maximum deformation of the oscillation limiter occurs, which depends on $\tau_*$ dependence

$$t_* = (\frac{\tau_*}{\Omega} + t_1) . \quad (35)$$

The value of a limiter maximum deformation

$$a = \exp(-\delta k\tau_*)\left[c_1\cos(k_1\tau_*) + c_2\sin(k_1\tau_*)\right] + \frac{f(\tau_*)}{k^2} . \quad (36)$$

Consequently

$$k_1 = k\sqrt{1-\delta^2}\,;\; c_1 = -\frac{f(0)}{k^2}\,;$$
$$c_2 = \frac{v}{k\sqrt{1-\delta^2}} + \frac{\delta f(0)}{k^2\sqrt{1-\delta^2}}\,;\; c_2 \ge c_1 . \quad (37)$$

Actual deformation:

$$x_{\max} = \varepsilon_a . \quad (38)$$

Shock duration:

$$\tau_{y\partial} = \frac{\pi}{k\sqrt{1-\delta^2}} + \frac{1+\exp(\pi\delta/\sqrt{1-\delta^2})}{k^2 v} f(0) +$$
$$+\frac{1}{k^2}\left\{\frac{f^2(0)}{v^2}\delta\left[1+\exp(\frac{\pi\delta}{\sqrt{1-\delta^2}})\right]\right\}; \quad (39)$$
$$t_{y\partial} = \frac{\tau_{y\partial}}{\Omega} .$$

The coefficient of restitution:

$$R = \exp\left(-\frac{\pi\delta}{\sqrt{1-\delta^2}}\right) + \frac{1}{k}\frac{2f(0)(1+R_0)\ln R_0}{v\sqrt{\pi^2+\ln^2 R_0}} +$$
$$+\frac{1}{k^2}\frac{f^2(0)}{2v^2}\left(\frac{1}{R_0} - R_0\right) ; \quad (40)$$
$$t_{y\partial} = \frac{\tau_{y\partial}}{\Omega} .$$

Consequently,

$$R_0 = \exp\left(-\frac{\pi\delta}{\sqrt{1-\delta^2}}\right) . \quad (41)$$

Velocity after the end of shock interaction:

$$V(t) = -R_0 V + \frac{2\delta}{k^2}(1+R_0)f(0) + \exp\left(-\frac{\pi\delta}{\sqrt{1-\delta^2}}\right) +$$
$$+\frac{f^2(0)}{v}\frac{1}{k^2}\left(\frac{1-R_0}{R_0}\right) . \quad (42)$$

Effective velocity

$$V_+ = \varepsilon\Omega v_+ . \quad (43)$$

Thus, the obtained analytic dependences (33) - (42) determine the basic parameters of a shock process of the system "form with a mixture - a limiter of oscillations".

## 3. Conclusions

As a result of the theoretical studies, an analytical dependence was obtained for determining the amplitude of the oscillations at fundamental frequency with the definition of the limit on the ampli-

tude of the super resonance harmonic. The conditions and defined dependences for a system motion in shock and up to shock mode: time of impact, deformation of limiters, coefficient of restitution, velocity after the end of interaction are formulated.
The proposed dependencies can be used in the future to calculate the numerical values of the parameters of a shock process, which will be the source information for the development of the method for calculating and improving the existing designs of shock and vibration installation.

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