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DYNAMICS OF PRIMARY STRUCTURE COUPLEDWITH SINGLE-SIDED VIBRO-IMPACT NONLINEAR ENERGY SINK

P.P. Lizunov,

O.S. Pogorelova,

T.G. Postnikova

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

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In this paper, we consider a two-mass 2-DOF vibro-impact system, consisting of a linear oscillator, called the primary structure, and an impact damper attached to it. A damper with a small mass hits a wall rigidly connected to the primary structure. This scheme corresponds to the scheme of single-sided vibro-impact nonlinear energy sink – SSVI NES. It is shown that even a light damper can reduce the amplitude and velocity of the primary structure oscillatory movement, that is, decrease its energy. Further optimization of damper parameters should improve this effect. The impact simulation using Hertz's nonlinear contact force makes it possible to take into account the mechanical characteristics of all colliding surfaces in more detail. The introduction of the initial distance between the primary structure and the damper into the calculation scheme makes it possible to take into account the impact between bodies and see when this impact is absent.
Keywords: vibro-impact,primary structure, damper, nonlinear energy sink.

1. Introduction

Vibration reduction in engineering in general and in the construction of high-rise structures in particular has always aroused great interest among engineers and scientists. Two decades ago, a proposal appeared to use special dampers for this – nonlinear energy sinks (NESs). Nonlinear energy sinks have been proposed as a practical and robust means of passively protecting buildings structures subjected to extreme transient loads. Recently there has been a significant growth in the field of NES. Various types of NESs have been introduced for vibration mitigation in variety of dynamical and structural engineering systems and have been described in the scientific literature and in particular in the most recent articles. In [1], the authors compare the different types of NESs. They consider the single-sided vibro-impact (SSVI) NES to be the most effective and efficient type among the common ones. The coefficient of restitution is discussed, since in the vast majority of investigations the impact is simulated by recalculation of the velocity reversal at the impact moment. The authors consider that using the restitution coefficient 0.45 instead of the commonly used 0.7 (steel-to-steel impact) may significantly improve the SSVI NES performance. In [2], a new vibro-impact bistable nonlinear energy sink with relatively light weight attached to a damped linear oscillator is proposed to form a two-degree-of-freedom nonlinear mechanical system with bilateral rigid constraints. The state of the system after instantaneous impact is described by the simplified shock theory and the momentum conservation. In [3], the authors' attention is focused on the vibration reduction of a beam using a vibro-impact absorber with adjustable clearance. The response of the beam under harmonic excitation demonstrates the existence of an optimal clearance that leads to the lowest level of vibration of the beam. The article [4] addresses the effect of gravity and sliding friction on the dynamics around targeted energy transfer of an inclined VI NES. The authors believe that the results open a door for appropriately taking advantage of the gravity into the VI NES design to improve its damping performance. The analysis performed in [5] shows that the energy in the system can be redistributed between the different impact modes. A new evaluation criterion called the vibro-impact vibration reduction factor is proposed in order to better evaluate the energy dissipation performance of the SSVI NES. The relationship between this factor and the energy free impact mode coefficient is investigated using the Hilbert transform. The effect of the SSVI NES parameters on the energy dissipation performance under various initial conditions is discussed. A satisfactory region for the SSVI NES design, which is identified via numerical simulation, is proposed. In [6], the authors argue that a properly designed VI NES, working with 1–2 impacts per cycle, is capable for effective broadband energy harvesting over a wide amplitude and frequency range. The performed in [7] asymptotic analysis reveals that the system with attached NES may have simultaneous stable attractors. Numerical simulations highlights a possible competition between stable attractors and allows us to investigate their basins of attraction. The work [8] treats the dynamics of hybrid vibro-impact NES attached to a linear primary structure as a passive energy absorber. The NES exhibits rich dynamics, consisting of sustained linear oscillations, sustained impacts of various frequencies, and alternating transition between both regimes. The analytical results are supported by numerical verifications. The paper [9] proposes an approach for the optimal design of NESs installed in structures subjected to stochastic excitation. Parametric optimization of an NES installed at the top of a shear building structure is performed to illustrate the proposed methodology. The paper [10] presents a comprehensive study on seismic response mitigation of building structures enabled by a novel vibro-impact dual-mass damper. It consists of a linear oscillator and a nonlinear oscillator with impact surfaces between these two oscillators. Its experimental studies are carried out on a three-story steel frame structure with different column layouts. The authors believe that this damper demonstrates great potential as an effective control strategy for seismic response mitigation of building structures. The paper [11] presents a track NES and a SSVI track NES as effective control strategies to mitigate the seismic response of high-rise buildings. The performance of these devices is evaluated comprehensively when attached to a representative 32-story high-rise building. Numerical results show that the SSVI track NES exhibits strong robustness against changes in the structural stiffness and the input energy level. The cost-effectiveness of the SSVI track NES is also demonstrated on a 20-story shear-frame building. The seismic performance of the SSVI track NES can be further improved by adjusting the position of the impact surface. The authors believe that the track NES and, more so, the SSVI track NES can be designed as highly cost-effective control strategies and offer a promising solution for seismic response mitigation of high-rise buildings.

In [12], we have indicated some of NES types and described the chosen model – vibro-impact NES. The article [12] contains a mini-review and the bibliography of the works on NESs. Now, we study some dynamics aspects of single-sided vibro-impact nonlinear energy sink – SSVI NES. It is recommended to use low-mass dampers as NES (about 1% from the primary structure mass). The study of impact processes in vibro-impact systems is associated with subtle dynamic effects accompanying impacts between bodies. We want to emphasize two things. First, we take into account the impacts between the primary structure and the damper. This impact is absent when the exciting force is not large. However, with an increase in the exciting force, these impacts exist and affect the system dynamics. The introduction of the initial distance between the primary structure and the damper into the calculation scheme makes it possible to find cases where these impacts are absent, while according to the motion equations without this distance, these impacts always exist. Secondly, the impact simulation using the nonlinear Hertz's contact force allows us to take into account the mechanical characteristics of the colliding surfaces in more detail. The choice of suitable Young's moduli of elasticity can be useful instead of the restitution coefficient choice.

Thus, the goals of this paper are:

• to show a decrease in the primary structure amplitude and velocity during its oscillatory motion when a low-mass damper is attached to it;

• to show this reduction for various damper masses and different amplitudes of the harmonic exciting force.

2. Mathematical model

The system under consideration is a two-body 2-DOF vibro-impact system. A linear elastic spring with a stiffness k_1 and a damper with a damping coefficient $c_1$attaches its main body of mass m_1, called the primary structure, to a fixed wall. It moves along the base without friction. An absorber of much smaller mass m_2 is connected to the primary structure by a linear elastic spring with a stiffness k_2 and a damper with a damping coefficient c_1. The harmonic force $F(t)$ acting on the primary structure causes an oscillatory motion in which the shock absorber hits a wall rigidly connected to the primary structure. The bodies coordinates are x_1 and x_2; the zero mark of the x-axis at the primary structure mass center in an equilibrium state when all springs are not deformed. The initial distance between the bodies, that is, the length of the undeformed right spring, is equal to D. The distance to the right movable wall is C; this distance defines the clearance. We emphasize that we take into account the distance D and insert it into the motion equations, since this allows us to obtain the movement without impact between bodies m_1 and m_2. Otherwise, this impact

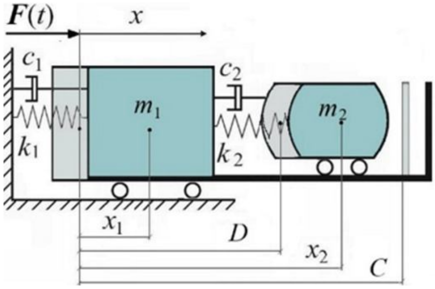

Fig. 1. Calculation scheme of SSVI NES

occurs always and must be taken into account. The calculation scheme of this system is depicted in Fig. 1. It corresponds to scheme of single-sided vibro-impact nonlinear energy sink (SSVI NES) [12,13].

The motion equations for this system are as follows:

$$\begin{aligned} m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 - c_2(\dot{x}_2 - \dot{x}_1) - k_2(x_2 - x_1 - D) = \\ = F(t) - \boldsymbol{H(z)F_{con}(z)} + \boldsymbol{H(z_1)F_{con}(z_1)}, \\ m_2\ddot{x}_2 + c_2(\dot{x}_2 - \dot{x}_1) + k_2(x_2 - x_1 - D) = \\ = +\boldsymbol{H(z)F_{con}(z)} - \boldsymbol{H(z_1)F_{con}(z_1)}. \end{aligned} \quad (1)$$

Exciting harmonic force $F(t) = P\cos(\omega t + \varphi_0)$. Its period $T = {}^{2\pi}/_{\omega}$.

The initial conditions are: at t=0 we have

$$x_1(0) = 0,\ x_2(0) = D,\ \dot{x}_1(0) = 0,\ \dot{x}_2(0) = 0,\ \varphi_0 = 0. \quad (2)$$

Here $H(z)$ is the Heaviside step function $H(z) = \begin{cases} 1, z \geq 0 \\ 0, z < 0 \end{cases}$. $F_{con}(z)$ – the contact interactive force that simulate an impact. It has the following form for impact between bodies, since we are simulating the impact using the Hertzian contact theory [14,15]:

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

and the same form for the impact of the damper onthe right wall, moving along with the primary structure:

$$F_{con}(z_1) = K_1[z_1(t)]^{3/2},$$
$$K_1 = \frac{4}{3}\frac{q_1}{(\delta_3+\delta_4)\sqrt{A_1+B_1}},\quad \delta_3 = \frac{1-\nu_3^2}{E_3\pi},\ \delta_4 = \frac{1-\nu_4^2}{E_4\pi}. \quad (4)$$

Here z and z_1 are the colliding bodies r approchement upon impact, since the Hertz's theory allows local deformations in the contact zone. $\nu_1, \nu_2, \nu_3, \nu_4$ are Poisson's ratios; E_1, E_2, E_3, E_4 are Young's moduli of elasticity for fourth colliding surfaces; A, A_1, B, B_1, q, q_1 are constants characterizing the contact zones geometry. The absorber surfaces, both left and right, are assumed to be spherical with large radii R and R_1; the contact surfaces of the primary structure and the right obstacle are flat. Then $A = B = 1/2R$, $A_1 = B_1 = 1/2R, q = q_1$=0.319 as in the collision of a plane and a sphere.

When an impact between the bodies occurs, then

$x_1 \geq x_2$, that is, $x_1 - x_2 \geq 0$.

There is no impact when $x_1 < x_2$, that is, $x_1 - x_2 < 0$. Then $z = x_1 - x_2$.

The impact of the damper on the right wall, moving together with the primary structure, occurs when

$x_2 = x_1 + C$, that is, $x_2 - x_1 = C$, i.e. $x_2 - x_1 - C = 0$.

During impact $x_2 - x_1 - C \geq 0$.

There is no impact when $x_2 - x_1 - C < 0$. Then $z_1 = x_2 - x_1 - C$.

Numerical parameters of the considered system are listed in Table 1.

Table 1

Numerical parameters of vibro-impact system (SSVI NES)

m_1 =1000 kg	m_2 =50 kg	A = B = 0.5 m^{-1}
k_1 = 3.95·10^4 N·m^{-1}	k_2 = 3.19·10^3 N·m^{-1}	q = 0.319
c_1 = 4.52·10^4 N·s·m^{-1}	c_2 = 4.07·10^4 N· s·m^{-1}	$A_1 = B_1$ = 0.5 m^{-1}
E_1 = 2.1·10^{11} N·m^{-2}	E_2 = 2.1·10^{11} N·m^{-2}	q_1 = 0.319
E_3 = 2.1·10^{11} N·m^{-2}	E_4 = 2.1·10^{11} N·m^{-2}	D = 0.05 m
ν_1 =0.3	ν_2 = 0.3	C = 0.06 m
ν_3 =0.3	ν_4 = 0.3	ω = 7.23 rad·s^{-1}

3. Numerical results

3.1. There is no impact between the bodies, but the damper hits the right wall, which moves along with the primary structure

Two options are considered when the amplitude of exciting force is 200 N and 500 N (Fig. 2 and Fig. 3). The graphs of the both bodies displacements are presented in figures (a); graphs of their velocities are shown in figures (b). The brown curves correspond to characteristics of damper; the black curves correspond to the primary structure. The upper brown sharp peaks on displacement plots clearly show impacts against the obstacle. The brown and black curves on displacement plots do not touch because there is no collision between the bodies. Figures (c) show the difference in displacements $x_2 - x_1$. The upper blue peaks $x_2 - x_1 = 0.06$ m show impacts against an obstacle. In figures (d), the contact force is shown in red along with the exciting force. This is a *T*- periodic vibration mode with one impact per cycle. The impact contact force is much greater than the exciting force. Figures (e) and (f) give the phase trajectories for both bodies. Figures (f) clearly show the velocities reversal when the damper hits an obstacle.

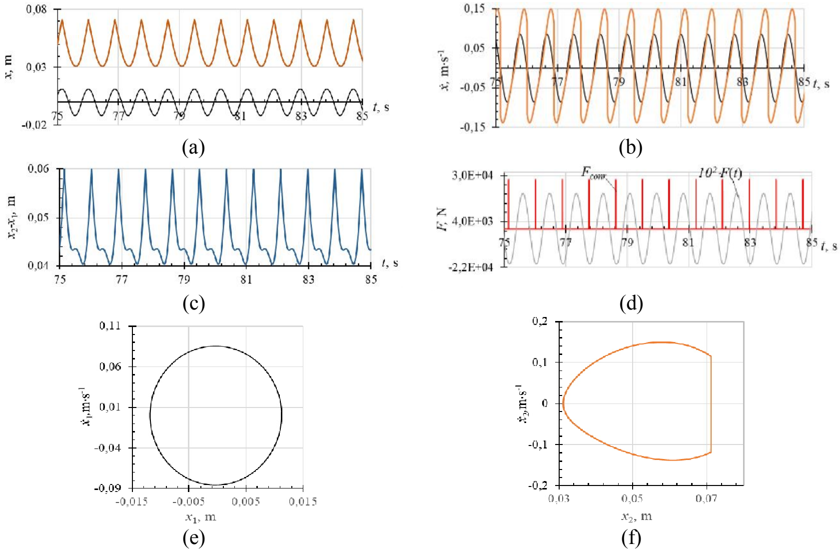

Fig. 2. Characteristics of both bodies oscillatory movement at the amplitude of the exciting force *P*=200 N

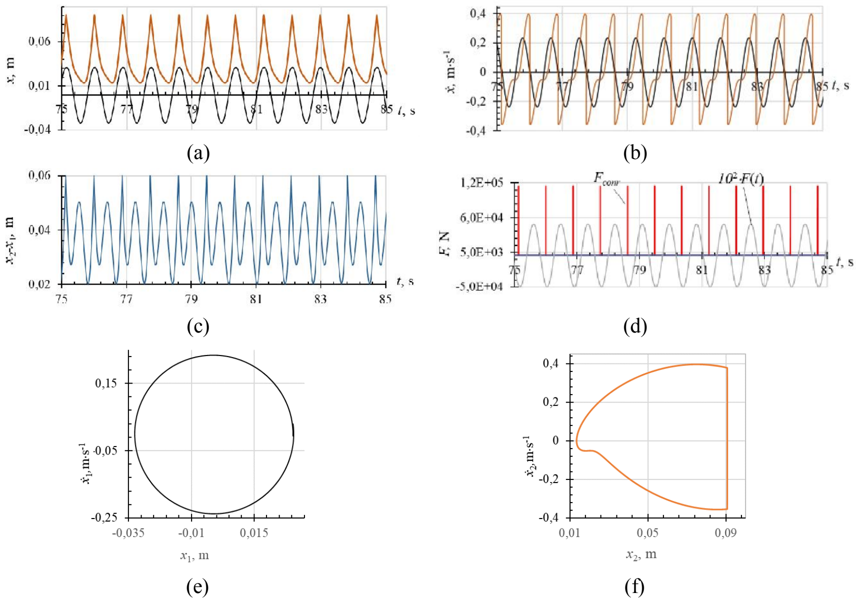

Fig. 3. Characteristics of both bodies oscillatory movement at the amplitude of the exciting force P=500 N

3.2.There are impacts between the bodies and the damper hits the right wall, which moves along with the primary structure

With an increase in the amplitude of the exciting force, the impacts between bodies are added to the impacts of the damper on the right moving wall. The characteristics of this motion at the amplitude value P=800 N are shown in Fig. 4. We see the tangency of the brown and black curves on the bodies displacements plot (a), which correspond to impacts between the bodies. The upper blue peaks in figure (c) at $x_2 - x_1 = 0.06$ m correspond to the impacts of the damper against an obstacle; the lower blue peaks on this plot at $x_2 - x_1 = 0$ show collisions between the bodies. In figure (d), the impact contact forces highlighted in red are the forces when the damper hits the right moving wall; the contact forces highlighted in blue are the forces accompanying impacts between bodies. We see a $3T$-peridic motion with 6 impacts of the damper against obstacle in a $3T$ cycle and 2 impacts between bodies in the same cycle.

The phase trajectories in figures (e) and (f) show the velocities reversals during these impacts; they are small for the primary structure and significant for the absorber.

3.3. Comparative results analysis

Let's take a closer look at the influence of a low-mass impact damper on the motion characteristics of the primary structure, namely, on the oscillatory amplitude and velocity. Table 2 gives their values during the primary structure motion itself without any attached damper and with dampers of two different masses at three exciting force values.

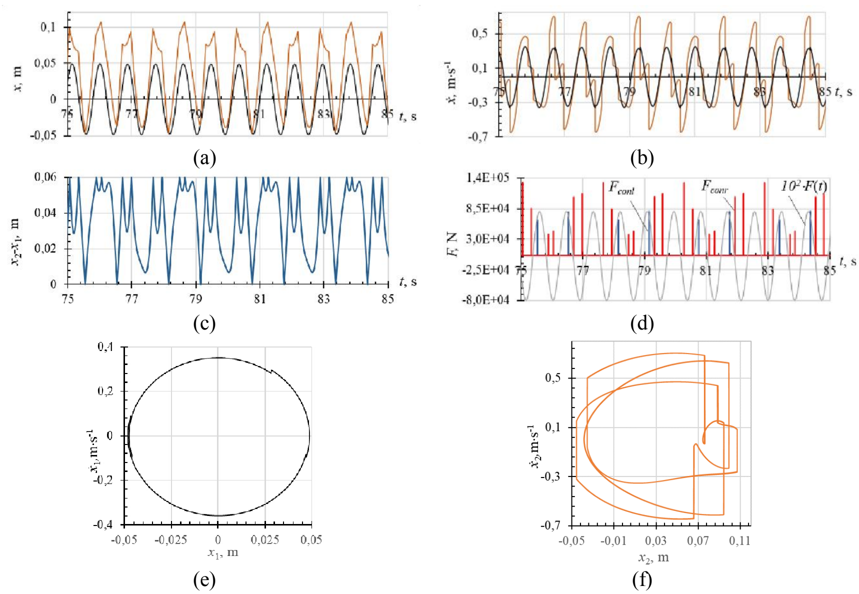

Fig. 4. Characteristics of both bodies oscillatory movement at the amplitude of the exciting force *P*=800 N

Table 2

Amplitudes of displacements and velocities of the primary structure m_1 without any attached damper and with dampers of two different masses

***P*, N**	**200**		**500**		**800**	
Primary structure	A_{max}, 10^{-2}·m	V_{max}, 10^{-1}·m·s^{-1}	A_{max}, 10^{-2}·m	V_{max}, 10^{-1}·m·s^{-1}	A_{max}, 10^{-2}·m	V_{max}, 10^{-1}·m·s^{-1}
without damper	1.51	1.09	3.76	2.72	6.02	4.36
with damper 10 kg	1.44	1.04	3.60	2.61	5.78	4.18
with damper 50 kg	1.15	0.857	3.17	2.36	5.15	3.71

We see that the damper presence decreases the amplitude of both the displacement and the velocity of the primary structure, that is, reduces its energy in accordance with the damper name – energy sink. Fig. 5 graphically demonstrates these results; the colors in the graphs correspond to the colors in Table 2.

A damper with a small mass of 10 kg, that is, 1% of the primary structure mass, slightly reduces its vibration characteristics when choosing damper parameters as in Table 1. A further task arises: to optimize the parameters, that is, to select the damper parameters (mass m_2, stiffness k_2, clearance C) in such a way that the values of the primary structure oscillatory amplitude and velocity are minimal.

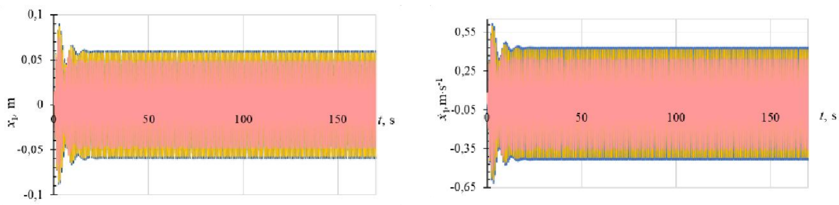

Fig. 5. Time series of displacements and velocities of the primary structure at P=800 N. Blue - without a damper, yellow - with a damper of mass 10 kg, red - with a damper of mass 50 kg.

4. Conclusions

The results obtained allow us to draw the following conclusions.

1. Even a damper with a small mass reduces the amplitude and velocity of the primary structure vibrations.
2. The selection of the optimal damper parameters should to improve this effect.
3. The introduction of the initial distance between the primary structure and the damper into the calculation scheme makes it possible to take into account the impact between them and see when this impact is absent.
4. The damper only hits the obstacle, and there are no impacts between the primary structure and the damper when the exciting force amplitude is small. The impacts between the bodies occur with an increase in the exciting force amplitude.
5. The impact simulation using Hertz's nonlinear contact force makes it possible to take into account the mechanical characteristics of all fourth colliding surfaces in more detail.

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Лізунов П.П., Погорелова О.С., Постнікова Т.Г.
ДИНАМИКА ПЕРВИННОЇ СТРУКТУРИ З'ЄДНАНОЇ З ОДНОБІЧНИМ ВІБРОУДАРНИМ НЕЛІНІЙНИМ ПОГЛИНАЧЕМ ЕНЕРГІЇ

Розглядається двох масова віброударна система з 2 ступнями вільності, яка складається з лінійного осцилятора, що названий первинною структурою, та з'єднаного з нею демпфера. Демпфер малої маси б'ється об стінку, яка жорстко скріплена з первинною структурою. Ця схема відповідає схемі однобічного віброударного нелінійного поглинача енергії (single-sidedvibro-impactnonlinearenergysink – SSVI NES). Показано, що навіть легкий демпфер може зменшити амплітуду та швидкість первинної структури в її коливальному русі. Подальша оптимізація параметрів демпфера має посилити цей ефект. Моделювання удару нелінійною контактною силою Герца дає можливість докладніше врахувати механічні характеристики поверхонь, що співударяються. Введення у розрахункову схему початкової відстані між первинною структурою та демпфером дозволяє врахувати удар між ними та побачити, коли цей удар відсутній.

Ключові слова: віброударний, первинна структура, демпфер, нелінійний поглинач енергії.

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In this paper, we consider a two-mass 2-DOF vibro-impact system, consisting of a linear oscillator, called the primary structure, and an impact damper attached to it. A damper with a small mass hits a wall rigidly connected to the primary structure. This scheme corresponds to the scheme of single-sided vibro-impact nonlinear energy sink – SSVI NES. It is shown that even a light damper can reduce the amplitude and velocity of the primary structure oscillatory movement, that is, decrease its energy. Further optimization of damper parameters should improve this effect. The impact simulation using Hertz's nonlinear contact force makes it possible to take into account the mechanical characteristics of all colliding surfaces in more detail. The introduction of the

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Tabl. 2. Fig. 5. Ref. 15.

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Лізунов П.П., Погорелова О.С., Постнікова Т.Г. **Динамика первинної структури з'єднаної з однобічним віброударним нелінійним поглиначем енергії** // Опір матеріалів і теорія споруд: наук.-тех. збірн. – К.: КНУБА. 2022. – Вип. 109. – С. 20-29. – Англ.
Розглядається двох масова віброударна система з 2 ступнями вільності, яка складається з лінійного осцилятора, що названий первинною структурою, та з'єднаного з нею демпфера. Демпфер малої маси б'ється об стінку, яка жорстко скріплена з первинною структурою. Ця схема відповідає схемі однобічного віброударного нелінійного поглинача енергії (single-sidedvibro-impactnonlinearenergysink – SSVI NES). Показано, що навіть легкий демпфер може зменшити амплітуду та швидкість первинної структури в її коливальному русі. Подальша оптимізація параметрів демпфера має посилити цей ефект. Моделювання удару нелінійною контактною силою Герца дає можливість докладніше врахувати механічні характеристики поверхонь, що співударяються. Введення у розрахункову схему початкової відстані між первинною структурою та демпфером дозволяє врахувати удар між ними та побачити, коли цей удар відсутній.
Табл. 2. Рис. 5. Бібліогр.15.

Автор (вчена ступень. вчене звання. посада): *доктор технічних наук. професор. завідувач кафедри будівельної механікиКНУБА. директор НДІ будівельної механіки*
ЛІЗУНОВ Петро Петрович
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)921-70-05*
E-mail: lizunov@knuba.edu.ua
ORCID ID: http://orcid.org/0000-0003-2924-3025

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