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CHOICE OF THE MODEL FOR VIBRO-IMPACT NONLINEAR SINK

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The nonlinear energy sink (NES) is defined as a single-degree-of-freedom structural element with relatively small mass and weak dissipation, attached to a primary structure via essentially nonlinear coupling. It is a passive energy dissipation device designed to rapidly absorb vibration energy (due to shock, blast, earthquakes, etc.) from a primary structure and locally dissipate it. The article contains a mini-review of the works on NESs. Design schemes for single-sided and double-sided vibro-impact NESs (SSVI and DSVI NESs) are proposed on the basis of conceptual and design NES schemes that exist in the world scientific literature. The motion equations and the impact rule are given. The quasistatic Hertz contact law is adopted as the impact rule. Various representations of the impulsive loading on the primary structure are discussed. These are excitations by initial velocities only, periodic excitation, a shock in the half-sine form, single-sided periodic impulses of a rectangular shape,wind, seismic and broadband excitation. The Tables of some numerical parameters that can be accepted for VI NES are given. Using the presented data, the authors intend to investigate both the efficiency of SSVI and DSVI NESs under different types of impulsive load, and their dynamical behavior with the changing in their parameters.

Keywords: nonlinear energy sink,impulsive loading, vibro-impact, primary structure, optimized, single-sided, double-sided.

1. Introduction

Vibration control in engineering has attracted the attention of a lot of scientists and engineers for many years. Vibration mitigation is essential to many dynamical and engineering structures that are subjected to destructive vibration amplitudes induced by impulsive loading, seismic excitation, blasts, flutter, collisions, fluid–structure interaction and so on. Unprotected structures by vibration absorbers could be exposed to failure, which lead to enormous losses in human lives, major equipment and economy [1]. In the past two decades, a nonlinear oscillator without linear stiffness, termed as a nonlinear energy sink, has received much attention due to its passive vibration reduction characteristics. The nonlinear oscillator is defined as a nonlinear energy sink, serving as a passive device to reduce vibrations [2].

The nonlinear energy sink (NES) has been defined as a single-degree-of-freedom (SDOF) structural element with relatively small mass and weak dissipation, attached to a primary structure via essentially nonlinear coupling [3]. This a light-weighted nonlinear dynamical attachment performs passive targeted energy transfer (TET) by means of its nonlinear dynamical action in a broadband frequency- energy fashion. It is a passive energy dissipation device designed to rapidly absorb vibration energy (due to shock, blast, earthquakes, etc.) from a primary structure and locally dissipate it. The resulting TET, (which can occur in a broadband fashion) significantly reduces the level of vibration of the primary structure. This TET is usually achieved through single or cascade of resonance captures with the associated linear primary structure [1]. There are comprehensive reviews of state-of-the-art researches on NESs [4-7], monographs [8,9], and numerous articles on this problem [10-13]. Nonlinear energy sinks have attracted much attention because of their ability to achieve energy-targeted transfer under certain conditions. The introduction of essential nonlinearities may effectively and passively suppress vibrations of systems, but it may complicate dynamic responses of the systems.

Various types of NES are being investigated. Vibro-impact VI NES is one of them. The VI NESs consist of linear stiffness and viscous damping elements analogous to the tuned mass damper. In addition to that, they incorporate rigid barriers fixed to the top floor of the primary structure to cause consecutive vibro-impacts generating strongly non-smooth nonlinear coupling between the NES motion and the structural modes of the primary structure. The single-sided vibroimpact (SSVI) nonlinear energy sink (NES) is considered the most effective and efficient. The efficiency and dynamical behavior of single-sided vibro-impact NESs (SSVI NES) and double-sided vibro-impact NESs (DSVI NES) are studied in numerous scientific articles [14-16]. Their conceptual schemes are shown in Fig. 1, 2. These papers present experimental and numerical studies. In [13, 17], the nine-story base structure was designed and built specifically for this project; it is 5.13 m tall and has a mass approximately equal to 11 000 kg. Six NESs are installed in the base structure; they are built into the floor plates of the eighth and ninth floors. One of the NESs on each floor is SSVI NES.

The research of impact damper has been around two main themes [18]. The first one is about the dynamics: response regimes and stability, bifurcation and chaos by numerical study with the combination use of time series, phase trajectories, bifurcation diagrams, Poincaré maps, Lyapunov exponents, and wavelet transform. Hilbert transform is also used in order to compute approximate transient amplitudes and phases. Another topic of research is concentrated on the efficiency of energy dissipation for free or forced vibration. The influence of system parameters (e.g. mass ratio, clearance and coefficient of restitution) and initial conditions on the dynamics and efficiency of energy reduction is considerably investigated and has to be demonstrated with analytical and numerical results.

In practical applications, the mass and the stiffness of the primary structure are given andgenerally cannot be changed. But the parameters of the SSVI NES attached to the structure have to be optimized [19]. The optimization of system parameters is an important part of the study of NESs. The selection of the parameters such as mass, stiffness, and damping of the NES will greatly influence the control performance. If the parameters are not optimized, the effectiveness of the vibration control may be reduced or negated. Various methods have been proposed for selecting a NES's optimum configuration.

The SSVI NES is a device that can rapidly reduce the vibration response of structures. With the addition of an impact surface, a discontinuous restoring force is realized via impact when the motion of the SSVI NES mass reaches the position of the impact surface. The discontinuous restoring force is an essential nonlinearity that provides a sharp change in the velocity of the SSVI NES and the structure to which the SSVI NES is attached.

Investigations on NES have attracted a lot of attention since a NES was proposed. Designs, analysis, and applications of NESs are still active since different configurations are needed in various practical circumstances.

This paper is mini-review and analysis of the literature about vibro-impact NES and a "statement of intent" that we have made based on this analysis. In accordance with these intents, we formulate the tasks that we will solve for our models of vibro-impact NESs:

- The optimization of the parameters of the VI NESs attached to the primary structure.
- Analysis of the efficiency of SSVI NES and DSVI NES forvibration mitigation of impulsively loaded primary structure with different descriptions of the external impulsive force.
- Analysis of the dynamical behavior of VI NESs in dependence on changing in its parameters and types of external loading.

2. Conceptual and design schemes of single-sided and double-sided vibro-impact nonlinear energy sinks

Conceptual schemes (Fig. 1, 2) of single-sided and double-sided vibro-impact nonlinear energy sinks (SSVI NES and DSVI NES) are given in fundamental works [8, 17].

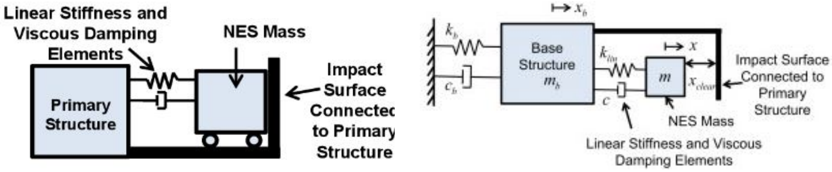


Fig. 1. Conceptual models of Single-Sided Vibro-Impact NES (SSVI NES): (a) in [8], (b) in [17]

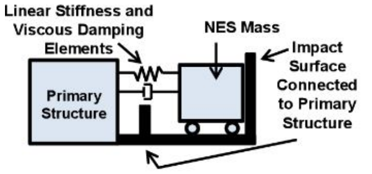


Fig. 2. Conceptual model of Double-Sided Vibro-Impact NES (DSVI NES) [8]

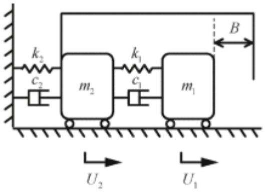
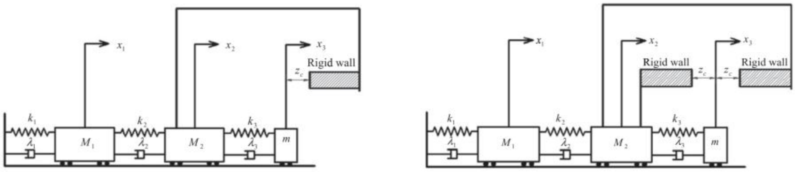


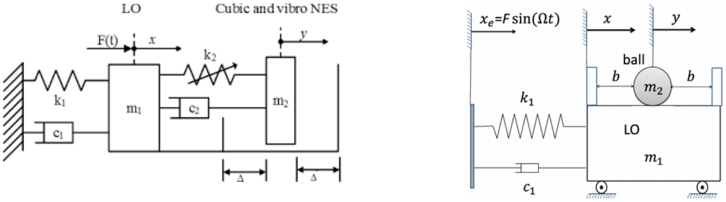
Fig. 3. Single-degree-of-freedom oscillator with a single-sided vibro-impact NES [19]

Design schemes (Fig. 3, 4, 5) of SSVI NES and DSVI NESs are given, for example, in papers [18, 19, 20, 21].



(a) (b)

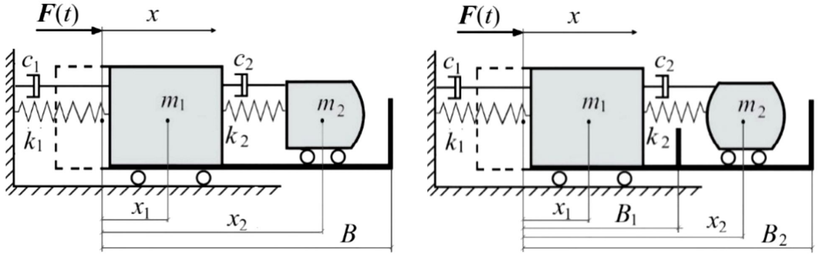
Fig. 4. Single-sided (a) and double-sided (b) VI NES on the top floor of the two- degree-of-freedom linear primary structure [20]



(a) (b)

Fig. 5. Double-sided VI NES: (a) sketch of the vibro-impact cubic NES and LO [21];
(b) scheme of a vibro-impact NES (impact damper) [18]

After analysis of the models of VI NES that discuss in the world scientific literature, we choose the following models (Fig. 6).



(a) (b)

Fig. 6. Design schemes of VI NES: (a) single-sided; (b) double-sided

The vibro-impact movement of single-sided VI damper is desribed by the following equations.

The masses are concentrated in the mass centers of both bodies. The origin of the $x$coordinate is chosen at themass center of the primary structure m_1 at the moment when the spring is not deformed

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

The initial conditions are

$$x_1(0) = 0,\ \ x_2(0) = D,\ \ \dot{x}_1 = V_1,\ \dot{x}_2 = V_2, \tag{2}$$

where D is the initial distance between bodies.

An impact occurs when $x_2 = B$. When $x_2 < B$, no impacts occur. There must be no impact between the primary structure m_1 and the attached mass m_2: $x_2 > x_1$, $x_2 \neq x_1$.

Here (z) is Heaviside step function relatively deformation $z = x_2 - B$

$$H(z) = \begin{Bmatrix} 1, z \geq 0 \\ 0, z < 0 \end{Bmatrix}.$$

$F_{con}(z)$ is contact interactive force that simulates an impact and acts only during an impact. It also depends on deformation$z$.

In most works, the impact is considered instantaneousю. At that time instant, continuity of displacements and discontinuity (jump) of velocities are imposed with using the coefficient of restitution r_c that depends on the material of the rigid stops. The question of the value of the restitution coefficient is studied. Most of investigations has implemented a coefficient of restitution of 0.7, which closely corresponds to a steel-to-steel impact. However, significant improvement in the SSVI NES performance is obtained when the coefficient of restitution is found to be near 0.45. In [1], the authors claim that the performance of the enhanced SSVIe NES of nearly 0.45 coefficient of restitution is found to be more robust to the initial impulsive energy levels and to its physical parameters variation. However, in [22], the authors study the VI NES with a finite contact duration model. They use Hertz model of finite duration collision and compare it with two other models.

We have studied this problem in our previous papers [23, 24, 25]. Now we simulate an impact with nonlinear interactive force according to contact quasistatic Hertz law [26].

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

Here ν_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. We'll consider that the impact surface connected to Primary Structure is flat and the colliding damper surface is a sphere of the large radius R. Then in the collision of a plane and a sphere $A = B = 1/2R$, q=0.318.

The vibro-impact movement of double-sided VI damper is desribed by the following equations.

$$\begin{gathered} m_1\ddot{x}_1 = -c_1\dot{x}_1 - k_1x_1 - c_2(\dot{x}_1 - \dot{x}_2) - k_2(x_1 - x_2 + D) + F(t) - \\ -H(z_1)F_{con}(z_1) + H(z_2)F_{con}(z_2), \\ m_2\ddot{x}_2 = -c_2(\dot{x}_2 - \dot{x}_1) - k_2(x_2 - x_1 - D) + H(z_1)F_{con}(z_1) - H(z_2)F_{con}(z_2), \\ z_2 = x_2 - B_2, \; z_1 = B_1 - x_2. \qquad (4) \end{gathered}$$

Right impact occurs when $x_2 = B_2$. When $x_2 < B_2$ right impact does not occur.

Left impact occurs when $x_2 = B_1$. When $x_2 > B_1$ left impact does not occur.

3. External loading

In the world scientific literature, various methods for setting an impulsive load are proposed.

3.1. Initial velocities only. In [19], the excitation is given by initial conditions only:

$$F(t)=0;\ \dot{x}_1(0)=V_1,\ \dot{x}_2(0)=V_2,\ V_1=V_2.$$

Displacements and velocities of primary structure fade out (Fig. 7):

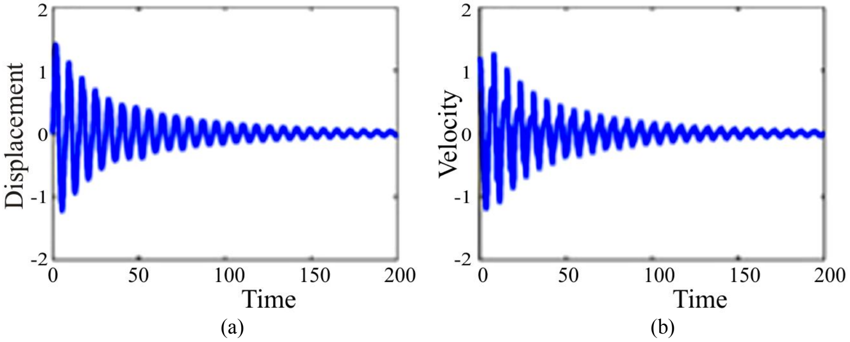
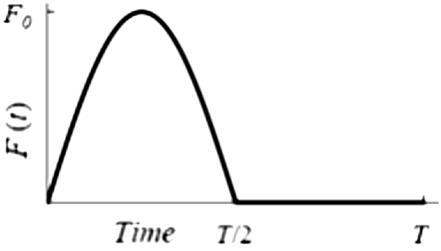


Fig. 7. Response due to initial velocities $\dot{x}_1 = \dot{x}_2$:
(a) primary system displacement; (b) primary system velocity

3.2. A periodically forced linear oscillator with impact attachment has been studied in [18, 27, 28].

3.3. A shock in the half-sine form. In [29], it is assumed that the linear oscillator is forced by ahalf-sine shock $F(t)$ of strength F_0 and duration T (Fig. 8) and that the integrated two-DOF system possesses zero initial conditions.



$$F(t)=\begin{cases} F_0\sin\dfrac{2\pi t}{T}, & 0\le t\le\dfrac{T}{2}\\ 0, & t\ge\dfrac{T}{2}\end{cases}$$

Fig. 8. A shock in the half-sine form

3.4. Single-sided periodic impulses of a rectangular shape. In [30], external loading $F(t)$ for time interval $[0, T]$ is represented by the analytical expression

$$F(t)=F_0 \text{ at } 0^+\le t\le t_0^-;\ F(t)=0 \text{ at } t_0^+\le t\le T,$$

where F_0 – value and t_0 – duration of impulsive load. Signs "-" and "+" denote the time moments immediately before and after the momentum jump at $t = 0$ and $t = t_0$ (Fig. 9). It is assumed that the number of impulse repetitions is so large that the structure oscillations are steady state.

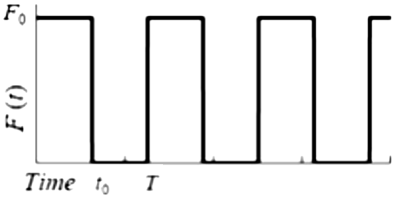


Fig. 9. Single-sided periodic impulses

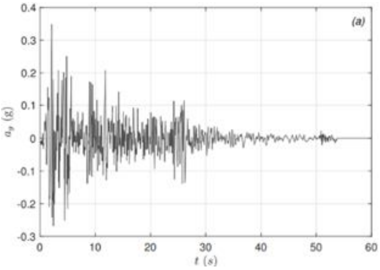


Fig. 10. Time history of the ElCentro NS(1940) earthquake

3.5. Seismic excitation. Dynamic response of structures due to wind load and seismic excitation still remain a major concern in the field of civil engineering.

In [22], the authors choose the well-known El Centro NS signal (1940) as the primary seismic excitation (Fig. 10).

3.6. Broadband excitations. In [21], the authors considered the VIC (vibro-impact cubic) NES and proposed for its broadband excitations such as impulses simulated before. They write: "There are many kinds of broadband excitations on which the responses are not easily to be obtained or analyzed by analytical methods". The authors succeeded to give an insight into the effectiveness of the VIC NES on excitations such as input with sufficient bandwidth, chirp signal and random signal. They noted that design criteria for these circumstances are not studied thoroughly and comparison is set as an LO without NES. Examples are given in Fig. 11, 12, 13, 14.

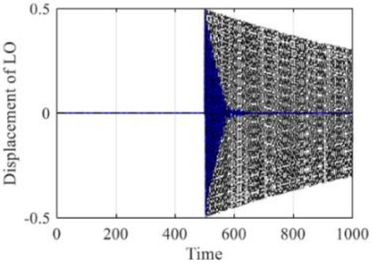


Fig. 11. Input with sufficient bandwidth: blue line with and dark dashed line without VIC NES

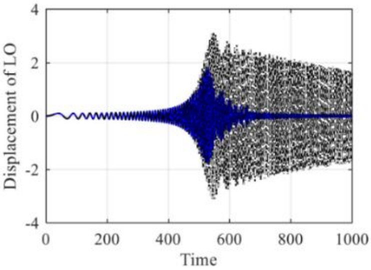


Fig. 12. Chirp signal: blue line with VIC NES and dark dashed line without VIC NES

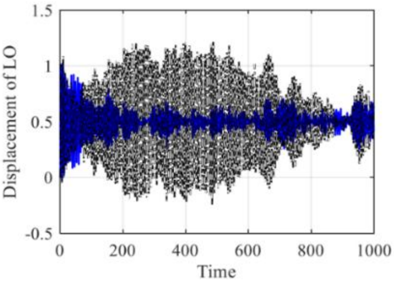


Fig. 13. Random excitations: blue line with VIC NES and dark dashed line without VIC NES

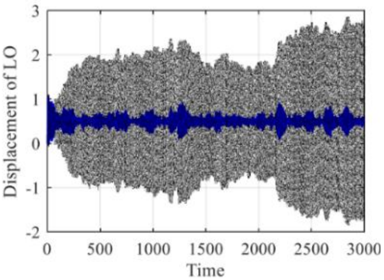


Fig. 14. Random signal with a harmonic signal on the natural frequency of the LO: blue line with VIC NES and dark dashed line without VIC NES

3.7. Wind loading. In [31], the mitigation of cable vibrations caused by wind loading is studied. NES is used for this purpose. Wind loading is given as a cubic nonlinear aerodynamic force and is described by a complex formula.

Naturally, many works study the wind loading influence on the building generally and on the tower structure in particular. For example, we present the idealization of the process of wind action on constructions from [32].

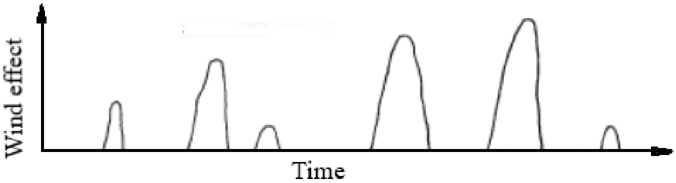


Fig. 15. Idealization of the time process of wind effect

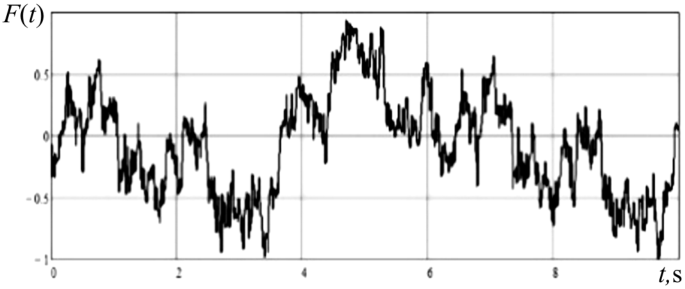


Fig. 16

In [33], the pulse component of wind load on the tower structure $P(z,t)$ with some assumptions is presented in the form $P(z,t) = P_{pc}(z)F(t)$, where $F(t)$ is a random process. Under certain conditions, its graph has the form shown in Fig. 16.

4. Numerical parameters

In practical applications, the mass and the stiffness of the primary structure are given and generally cannot be changed. The parameters of the VI NESs attached to the structure have to be optimized.

It is recommended to take the mass of the attached NES as 0.01 of the primary structure mass.

In the scientific literature, one can find some parameters that have been used in experimental and numerical studies. These data can help in choosing the initial parameters of VI NES, which then need to be optimized.

4.1. In [13,17], the authors describe a structural system, which was designed and built specifically for this project. It consists of a large-scale nine-story steel frame (base structure) and a system of six NESs.

The base structure is 5.13 m tall and has a mass approximately equal to 11,000 kg. The NESs are builtinto the two highest floors of the base structure. SSVI NES that have been used are shown in Fig. 1 (b).

Table 1 shows their optimized and estimated parameters of the physically realized system of NESs.

Table 1

Optimized and estimated physical parameters
Of SSVI NES devices: damping coefficient *c*, stiffness coefficient *k*

Optimized parameters				Estimated physical parameters		
Floor	Stiffness (N/m)	Damping (Ns/m)	Clearance (mm)	Mass (kg)	Stiffness (N/m)	Damping (Ns/m)
8	14546	503	-1.5	340	15,000	50
9	12219	573	-1.5	340	12,000	50

The authors note that the mass ratios of the NESs are 3.5% of total structure mass that is relatively high compared withcommonly utilized values in linear absorbers. They explain this fact.

4.2. In [18], the authors consider the system of harmonically forced Linear Oscillator (LO) attachedwith VI NES (Fig. 5 (b)).The parameters of this experimental system have been identified by performing modal analysis and are summarized in Table 2. The excitation frequency is fixed to 8 Hz.

Table 2

Parameters of the experimental system

Physical parameters				
m_1, kg	m_2, kg	k_1, N/m	c_1, Ns/m	b, mm
4.168	32	11470	3.02	11.5

4.3. In [34], the authors describe the experimental a three-story steel frame structure and give someof its parameters.

Table 3

Identified properties of the primary structure

Story	Mass (kg)	Stiffness coefficient (N/m)	
		Six-column	Four-column
Top	32.40	2.55×10^4	1.62×10^4
Middle	29.61	2.40×10^4	1.47×10^4
Bottom	29.61	2.62×10^4	1.55×10^4

Table 4

Design parameters of optimal control devices

Parameter	DM		TMD
	Linear	Nonlinear	
Mass (kg)	2.29	2.29	4.58
Damping coefficient (N·s/m)	1.61	1.61	3.23
Stiffness coefficient (N/m or N/m3)	337	2.06×10^5	700

Table 5

Design parameters of physical control devices

Structure	Parameter	DM/VIDM		TMD VITMD
		Linear	Nonlinear	
Mass (kg)		2.282	2.294	4.58
Six-column	Damping coefficient (N·s/m)	2.42	1.58	2.45
	Stiffness coefficient (N/m or N/m^3)	400	1.2×10^5	820
	Clearance (mm)	2		1.5
Four-column	Damping coefficient (N·s/m)	2.42	2.38	3.51
	Stiffness coefficient (N/m or N/m^3)	400	1.2×10^5	750
	Clearance (mm)	4		0

One may see that some physical parameters differ from the optimal ones.

These data from the scientific literature can serve as a guideline for selecting the NES input parameters to be optimized.

4. Conclusions

Based on the world scientific literature, models of single-sided and double-sided vibro-impact nonlinear energy sinks (SSVI and DSVI NESs) are proposed.

They are the passive energy dissipation devices designed to rapidly absorb vibration energy (due to shock, blast, earthquakes, etc.) from a primary structure, to which they are attached, and locally dissipate it. The motion equations and the impact rule are given. Methods of specifying an impulsive loading on the primary structure are discussed. Some numerical parameters that can be used as initial ones for NES and then have to be optimized are given. All these data enable:

- to create a complete mathematical model of VI NES;
- to studyits efficiencyforvibration mitigation of impulsively loaded primary structure with different descriptions of the external impulsive force;
- to analyze its dynamical behavior in dependence on changing in its parameters and types of external loading.

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ВИБІР МОДЕЛІ ВІБРОУДАРНОГО НЕЛІНІЙНОГО ПОГЛИНАЧА ЕНЕРГІЇ

Нелінійний поглинач енергії (*NES*) визначається як структурний елемент з одним ступенем вільності з відносно невеликою масою та слабким розсіюванням, приєднаний до первинної структури за допомогою суттєво нелінійного зв’язку. Це пристрій пасивного розсіювання енергії, призначений для швидкого поглинання енергії вібрації (внаслідок ударів, вибуху, землетрусу тощо) від первинної конструкції та локального її розсіювання. У статті міститься міні-огляд робіт з *NES*. На основі концептуальних та розрахункових схем *NES*, які існують у світовій науковій літературі, запропоновано розрахункові схеми однобічних та двобічних віброударних *NES* (*SSVI* та *DSVINES*). Дано рівняння руху та ударне правило. Як ударне правило прийнято квазістатичний контактний закон Герца. Обговорюються різні уявлення імпульсного навантаження на первинну структуру. Це збудження лише початковими швидкостями, періодичне збудження, удар напів-синусоїдної форми, односторонні періодичні прямокутні імпульси, вітрове, сейсмічне та широкосмугове збудження. Наведено таблиці деяких числових параметрів, які можуть бути прийняті для віброударних *NES*. Використовуючи наведені дані, автори мають намір дослідити як ефективність роботи однобічних та двобічних віброударних *NESs* при різних видах імпульсного навантаження, так і їхню динамічну поведінку при зміні їхніх параметрів.

Ключові слова:нелінійний поглинач енергії, імпульсне навантаження, віброударний, первинна структура, оптимізований, однобічний, двобічний.

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Базуючись на джерелах світової наукової літератури, автори пропонують моделі однобічного та двобічного віброударних нелінійних поглиначів енергії, які призначаються для пом'якшення коливань первинної структури, з якою ці пристрої жорстко пов'язані. Дано рівняння руху та ударне правило. Обговорюються різні варіанти завдання зовнішнього імпульсного навантаження на первинну структуру та деякі числові параметри, які в подальшому дослідженні потребують оптимізації.

Табл. 5. Рис. 16. Бібліогр. 34 назв.

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Being based on the sources of world scientific literature, authors offer models one-sided and bilateral vibroshock nonlinear absorbers energies, which target at softening of vibrations of primary structure which these devices are hardly CPLD with. Equalization of motion and shock rule is given. The different variants of task of the external impulsive loading come into a question on a primary structure and some numerical parameters which in subsequent research need optimization.

Tabl. 5. Fig. 16. Ref. 34.

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