Table 3
Tendency of increasing the clearance C and decreasing the damping coefficient c_2 with decreasing the damper masa

Parame-ters	Variant							
	SS-1(40)	SS-2(40)	SS-3(40)	SS-4(40)	DS-1(40)	DS-2(40)	DS-3(40)	DS-4(40)
c_2, N·s/m	232	76.7	64.1	42.6	232	64.8	97.6	74.5
C, m	0.300	0.518	0.644	0.771	0.158	0.238	0.260	0.276

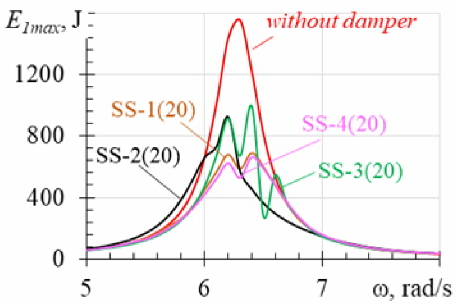
6. Dynamic behavior of the system with attached dampers of mass m_2 =20 kg

Optimization procedures allowed us to find several damper parameter sets that provide a reasonably good mitigation of the PS vibrations even at a lower damper mass m_2. However, as numerous tests have shown, the tendency for the clearance C to increase and the damping coefficient c_2 to decrease was increasingly strong. In addition, the dynamics of even DSVI NES is no longer calm; it becomes complex and exhibits irregular regimes. Let's look at these phenomena in more detail. Table 4 presents the characteristics of the four variants for SSVI NES and DSVI NES with optimized design. Table 4 demonstrates very large values of the clearance C and small values of the damping coefficient c_2 .

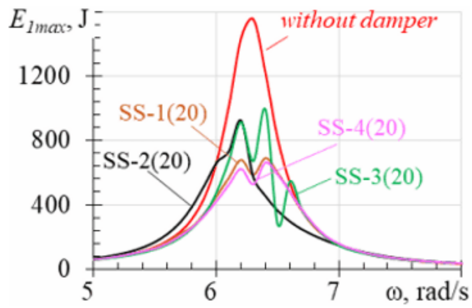
Table 4
Information about 4 variants of SSVI NES and DSVI NES of mass m_2=20 kg with optimized design

Parame-ters	Variant							
	SS-1(20)	SS-2(20)	SS-3(20)	SS-4(20)	DS-1(20)	DS-2(20)	DS-3(20)	DS-4(20)
k_2, N/m	205	225	125	198	697	699	678	679
c_2, N·s/m	42.1	35.3	28.9	36.0	19.2	19.6	13.9	10.3
D (V), m	0.135	0.0154	0.0440	0.759	0.365	0.0227	0.0127	0.00544
C, m	0.758	0.908	0.839	0.871	0.653	0.650	0.728	0.774
$E_{1\max}$, J at ω=6.3 rad/s	586	573	672	526	200	204	134	101
Regimes	T,0,0 T,1,0 2T,2,2	T,1,0 3T,3,1	T,1,0 T,1,1	T,0,0 T,1,0 2T,2,2 2T,1,0	T,0,0 T,1,1 AM	T,0,0 T,1,1 AM	T,0,0 T,1,1 3T,2,2 T,1,1 with rare bursts AM	T,0,0 Chaotic T,1,1 3T,2,2 AM

Fig. 7 presents the dependence of the maximum total energy $E_{1\max}$ of the PS on the exciting force frequency for these four variants.



(a)



(b)

Fig. 7. Maximum total energy of the PS with different attached dampers of mass m_2 =20 kg depending on the exciting force frequency; (a) for SSVI NES; (b) for DSVI NES

The areas of bilateral impacts remain narrow.

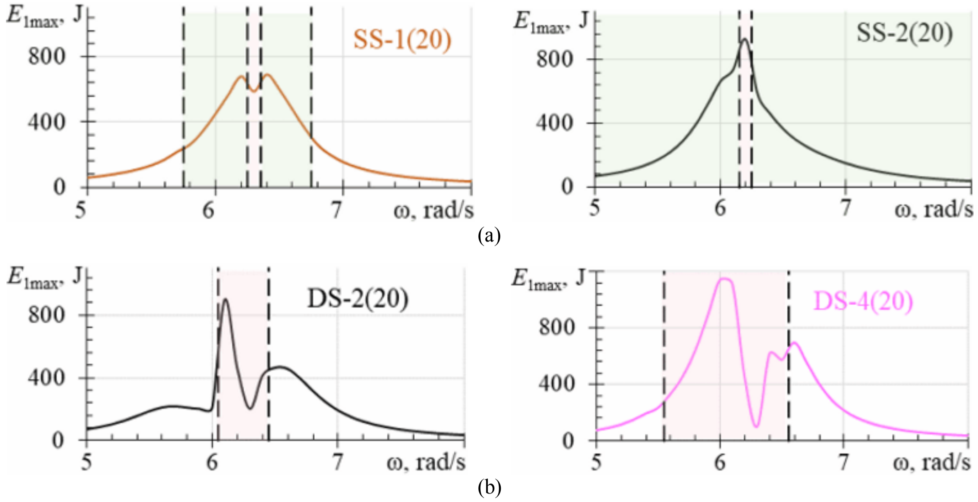


Fig. 8. The areas of bilateral and unilateral impacts for different vibro-impact nonlinear energy sinks with mass m_2=20 kg depending on the exciting force frequency: (a) for SSVI NES; (b) for DSVI NES

Let's show the chaotic motion that occurs in the system with attached DSVI NES of DS-4(20) variant at low exciting force frequency ω =5.7 rad/s. Fig. 9 presents its characteristics.

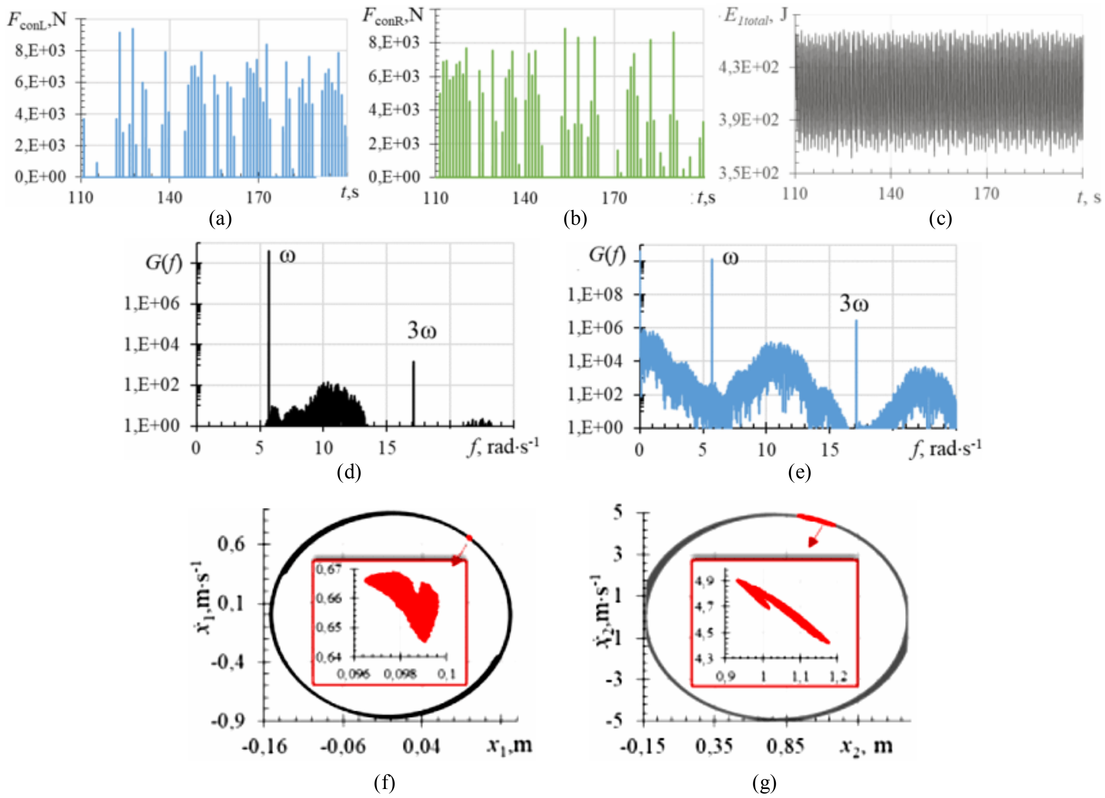


Fig. 9. Characteristics of chaotic motion of the system with variant DS-4(20) attached to PS at exciting force frequency ω =5.7 rad/s. (a) Contact impact forces at impacts on the left obstacle. (b) Contact impact forces at impacts on the right obstacle.(c) Total PS energy depending on time. (d) Fourier spectrum for PS in logarithmic scale. (e) Fourier spectrum for the damper in logarithmic scale. (f) Phase trajectories with Poincaré map in red for PS. (g) Phase trajectories with Poincaré map in red for the damper

This motion exhibits broad continuous Fourier spectra for both PS and the damper. The Poincaré maps have the shape of smears. This is typical for chaotic movement.

7. Dynamic behavior of the system with attached dampers of mass m_2 =10 kg

In world scientific literature it is often recommended to use NES with a small mass m_2, which is 1% of the PS mass m_1. Therefore, it is worthwhile to see how such a NES reduces the PS vibrations and what is its optimized design.

Numerous numerical experiments have shown that the trend noted above is developing. The clearance C increases to huge values; the damping coefficient c_2 is greatly reduced. The dynamics becomes complex for both SSVI NES and DSVI NES; the symmetry of the impacts for DSVI NES is broken. However, despite these phenomena, VI NESs with these parameters provide good mitigation of the PS vibrations. Let's show in detail the dynamic behavior of the system with dampers of mass m_2 =10 kg attached to PS. Table 5 presents the characteristics of the four variants for SSVI NES and DSVI NES with optimized design.

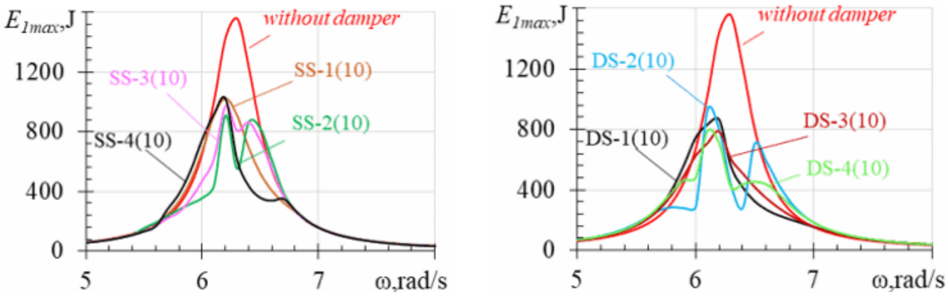


Fig. 10. Maximum total energy of the PS with different attached dampers of mass m_2 =10 kg depending on the exciting force frequency; (a) for SSVI NES; (b) for DSVI NES

Table 5 shows huge values of the clearance C and very small values of the damping coefficient c_2. The rows with the title "Regimes" demonstrate the presence of different irregular motions in the system with these VI NESs attached to the PS. Fig. 10 presents the dependence of the maximum total energy $E_{1\max}$ of the PS on the exciting force frequency for these four variants.

Table 5

Information about 4 variants of SSVI NES and DSVI NES of mass m_2=10 kg with optimized design

Parameters	Variant							
	SS-1(10)	SS-2(10)	SS-3(10)	SS-4(10)	DS-1(10)	DS-2(10)	DS-3(10)	DS-4(10)
k_2, N/m	133	98.8	103	127	354	414	387	428
c_2, N·s/m	18.3	6.88	13.4	7.78	7.14	14.8	8.57	12.6
D (V), m	0.135	0.152	0.171	0.207	0.0194	0.185	0.149	0.0276
C, m	0.975	2.01	1.30	1.67	1.037	0.735	0.985	0.799
$E_{1\max}$, J at ω=6.3 rad/s	428	603	411	560	428	603	411	560
Regimes	T,0,0 T,1,0 Chaotic	T,0,0 T,1,0 Chaotic	T,0,0 T,1,0 Chaotic	T,0,0 T,1,0 Chaotic	T,0,0 Chaotic	T,0,0 T,1,1	T,0,0 Chaotic	T,0,0 Chaotic T,1,1 with rare bursts T,1,1 AM

The areas of bilateral impacts are extremely narrow (Fig. 11).

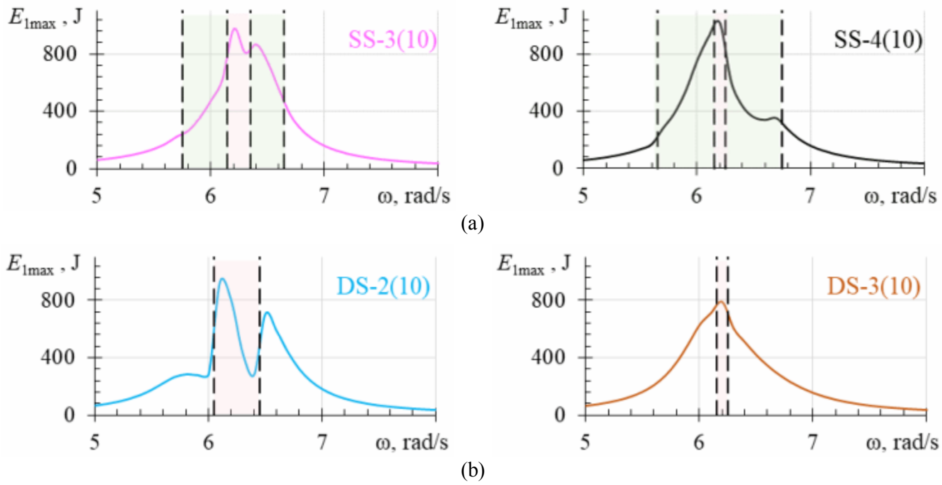


Fig. 11. The areas of bilateral and unilateral impacts for different variants of VI NESs with mass m_2=10 kg depending on the exciting force frequency: (a) for SSVI NES; (b) for DSVI NES

As can be seen from Fig. 11 (a) for the SSVI NES, there are some regions with unilateral damper impacts on the PS directly. Fig. 11 (b) shows that the DSVI NES operates as a nonlinear vibro-impact device in an extremely narrow region of the exciting force frequency. The system performs shockless T,0,0 movement throughout the rest of the exciting force frequency range. The DSVI NES operates as a linear damper without the nonlinearity that occurs when hitting the obstacles. The SSVI NES operates as a nonlinear vibro-impact device over a wider range of exciting force frequencies, but it makes unilateral impacts on the PS directly and does not impact the obstacle. Generally speaking, the SSVI NES can be thought of as a double-sided device, only asymmetrical, since it strikes the barriers from two sides – the obstacle on the right and the PS directly on the left.

Let's show the characteristics of chaotic movement for DS-4(10) at exciting force frequency ω=6.1 rad/s (Fig. 12). The picture of this chaotic movement is similar to the picture of chaotic movement in Fig. 9 for damper with mass m_2=20 kg, but the asymmetry of the left and right contact forces has increased. Figs. 12 (a), (b) clearly show asymmetry of the impacts on the left (Fig. 12, (a)) and on the right (Fig.12, (b)) obstacles. The wide continuous Fourier spectra (Figs. 12, (d), (e)) are typical for chaotic motion. The shape of Poincaré maps in the form of smears are also typical for the chaotic motion.

It is worth emphasizing that low-mass dampers are good in mitigating the PS vibrations when their optimal parameters have unusual non-standard values, namely large clearance C and small damping coefficient c_2. When they have "normal" usual values, the mitigation is very weak, it is almost non-existent. Let's show the performance of the SSVI NES and DSVI NES with such design as an example. The damper parameters are presented in Table 6. Fig. 13 shows the behavior of the PS energy with attached dampers with usual "normal" parameters versus the PS energy with attached dampers with unusual "strange" parameters. The areas of bilateral impacts for these dampers are also narrow and located near the resonant frequency. The impacts are symmetrical for DSVI NES and asymmetrical for SSVI NES. The unilateral direct impacts of the SSVI NES on the PS occur throughout the rest of the exciting force frequency range. A system with the attached DSVI NES performs shockless motion over the entire exciting force frequency range, except for a narrow band of bilateral impacts. The DSVI NES operates in the shockless zone as a linear damper.

Table 6
The "normal" parameters of SSVI NES and DSVI NES with mass m_2=10 kg.

Paramters	**Variant**	
	SS-5(10)	DS-5(10)
k_2, N/m	215	215
c_2, N·s/m	250	132
D (V), m	0.01	0.1
C, m	0.1	0.1

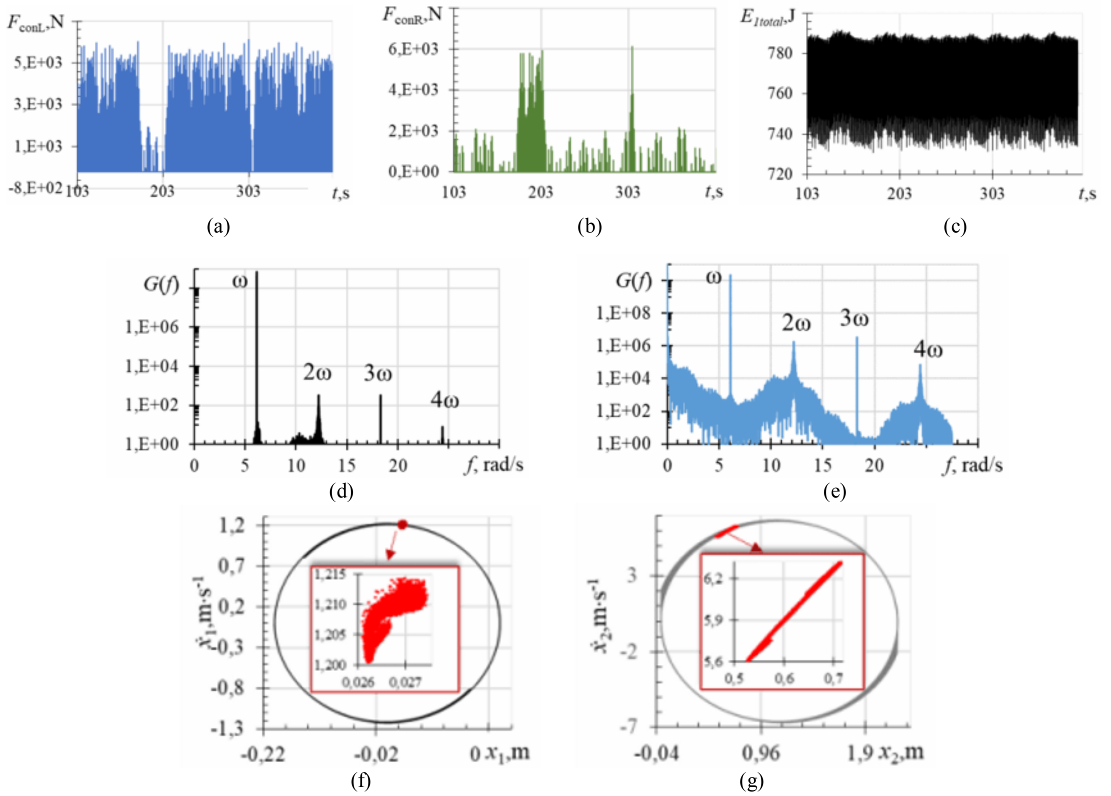


Fig. 12. Characteristics of chaotic motion of the system with variant DS-4(10) attached to PS at exciting force frequency ω =6.1 rad/s. (a) Contact impact forces at impacts on the left obstacle.(b) Contact impact forces at impacts on the right obstacle.(c) Total energy of PS. (d) Fourier spectrum for PS in logarithmic scale. (e) Fourier spectrum for the damper in logarithmic scale. (f) Phase trajectories with Poincaré map in red for PS. (g) Phase trajectories with Poincaré map in red for damper

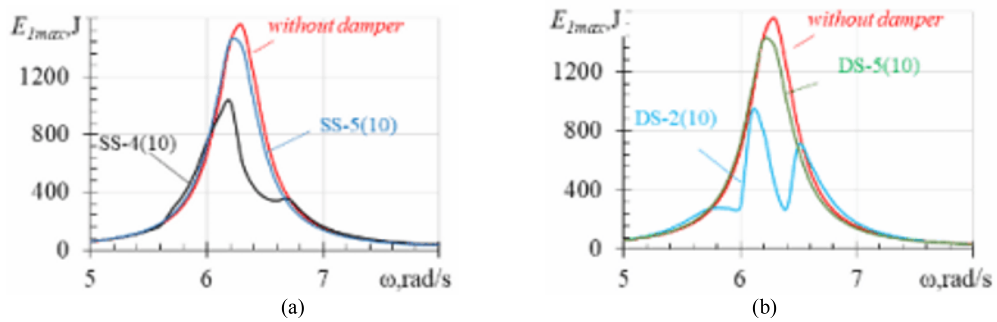


Fig. 13. Maximum total energy of the PS when dampers of mass m_2=10 kg with usual “normal” parameters are attached to it: (a) for SSVI NES; (b) for DSVI NES

8. Conclusions

Numerous numerical experiments, the results of which are presented above in Figures and Tables, allow us drawing the following conclusions.

- There are many sets of damper parameters that provide similar high efficiency in reducing the PS vibrations.
- Optimization procedures produce ambiguous results and allow for a great deal of arbitrariness.
- Symmetrical double-sided and asymmetrical single-sided vibro-impact nonlinear sinks with optimized design provide the similar efficiency in mitigating the PS vibrations. From this point of view, none of these damper types offers any advantages.

- The NESs with larger mass provide good mitigation of the PS vibrations when they have "normal" usable design. When the damper mass is reduced, its efficiency is preserved, but the optimal parameters providing such efficiency become very "strange", namely: the clearance becomes huge and the damping coefficient becomes very small.
- The system dynamics changes when the damper mass is reduced. When the damper has a larger mass, a system with a DSVI NES attached to the PS exhibits quiet periodic dynamics with symmetrical impacts on the left and right obstacles. A system with a lighter DSVI NES exhibits irregular motions with asymmetrical impacts on the left and right obstacles.
- The SSVI NES hits both right obstacle and the PS directly. From this point of view, it can be considered as double-sided device, since it hits the barriers on two sides. However, these impacts are asymmetrical. Dynamics of SSVI NES is complex with different both periodic and irregular movements.
- Bilateral impacts occur in a very narrow range of the exciting force frequency. The narrow areas of bilateral impacts are located near resonance. In the rest frequency range, the system with DSVI NES performs a shockless motion without any impacts. The DSVI NES acts as a linear damper because there is no nonlinearity created by impacts. The SSVI NES also exhibits a narrow region of bilateral impacts, but over a wider frequency range makes unilateral direct impacts on the PS.

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ВПЛИВ МАСИ НА ЕФЕКТИВНІСТЬ ТА ДИНАМІКУ ОДНОБІЧНИХ ТА ДВОБІЧНИХ ВІБРОУДАРНИХ НЕЛІНІЙНИХ ПОГЛИНАЧІВ ЕНЕРГІЇ

У цій статті досліджується ефективність асиметричних односторонніх і симетричних двосторонніх віброударних нелінійних поглиначів енергії (SSVI NES і DSVI NES), тобто віброударних демпферів, у зменшенні небажаних коливань важкої основної конструкції (PS), до якої ці демпфери прикріплені. Також досліджено динамічну поведінку цієї віброударної системи. Ефективність демпфера і поведінка системи досліджуються для демпферів з чотирма різними масами, оскільки оптимізація інших параметрів демпфера проводиться для заздалегідь визначеній масі. Показано вплив зміни маси демпфера на його ефективність і динамічну поведінку системи. Демпфери з різною масою і оптимальною конструкцією демонструють подібну високу ефективність у зменшенні коливань PS, але оптимальна конструкція демпфера з меншою масою має незвичні параметри, а саме: великий зазор і малий коефіцієнт демпфування. SSVI NES ударяє не тільки перешкоду, жорстко зв'язану з PS, але й безпосередньо PS. З цієї точки зору його можна вважати двостороннім DSVI NES, тільки асиметричним. DSVI NES ударяє ліву і праву перешкоди, жорстко зв'язані з PS. Області двосторонніх ударів вузькі і розташовані поблизу резонансної частоти збуджуючої сили. У решті частотного діапазону SSVI NES здійснює односторонні прямі удари по PS; DSVI NES здійснює безударний рух без будь-яких ударів і працює в цьому діапазоні частот як лінійний демпфер без будь-якої нелінійності.

Численні чисельні тести забезпечили можливість показати динаміку системи з 36 різними демпферами, а саме для чотирьох мас, для двох типів демпферів для кожної маси і для декількох варіантів оптимальної конструкції демпфера. Оптимальна конструкція не єдина, вона може мати багато варіантів, оскільки існує безліч наборів параметрів демпферів, які забезпечують подібне зменшення коливань основної конструкції. Тому сама процедура оптимізації не дає і не може дати однозначного результату, допускає велику довільність у її виконанні і вимагає від виконавця великого досвіду і майстерності.

Ключові слова: нелінійний поглинач енергії, демпфер, віброударний, однобічний, двобічний, оптимізація, двосторонні удари.

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INFLUENCE OF MASS ON THE EFFICIENCY AND DYNAMICS OF SINGLE-SIDED AND DOUBLE-SIDED VIBRO-IMPACT NONLINEAR ENERGY SINKS

This paper studies the efficiency of the asymmetric single-side and symmetric double-sided vibro-impact nonlinear energy sinks (SSVI NES and DSVI NES), that is, vibro-impact dampers, in mitigating unwanted vibrations of the heavy primary structure (PS) to which these dampers are attached. The dynamic behavior of this vibro-impact system is also investigated. The damper efficiency and system behavior are studied for dampers with four different masses, as optimization is carried out for other damper parameters at a predetermined mass. The effect of the damper mass changing on its efficiency and system dynamic behavior is shown. The dampers with different masses and optimal design exhibit similar high efficiency in mitigating the PS vibrations, but the optimal design of the dampers with lower mass has unusual parameters, namely the huge clearance and small damping coefficient. The SSVI NES hits not only the obstacle hardwired to the PS but also the PS directly. From this point of view, it can be considered as double-sided DSVI NES only asymmetric. The DSVI NES hits the left and right obstacles rigidly connected with PS. The regions of bilateral impacts are narrow and located near the resonant frequency of the exciting force. In the rest of the frequency range, the SSVI NES makes unilateral direct impacts on the PS; the DSVI NES performs shockless motion without any impacts and operates in this frequency range as a linear damper without any nonlinearity.

The numerous numerical tests were able to show the system dynamics with 36 different dampers, namely for four masses, for two damper types for each mass, and for several variants of the optimal damper design. The optimal design is not unique; it can have many variants, since there is a lot of damper parameter sets that provide similar mitigation of the main structure vibrations. Therefore, optimization procedure itself does not and cannot give an unambiguous result, allows for great arbitrariness in its execution and requires great experience and skill from the performer.

Keywords: nonlinear energy sink, damper, vibro-impact, single-sided, double-sided, optimization, bilateral impacts.

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Лізунов П.П., Погорелова О.С., Постнікова Т.Г., Геращенко О.В. **Вплив маси на ефективність та динаміку однобічних та двобічних віброударних нелінійних поглиначів енергії** // Опір матеріалів і теорія споруд: наук.-тех. збірн. – К.: КНУБА. 2024. – Вип. 113. – С. 3-17. – Англ.
Ефективність асиметричних односторонніх і симетричних двосторонніх віброударних нелінійних поглиначів енергії тобто віброударних демпферів, для зменшення небажаних коливань основної конструкції є досить високою і подібною для демпферів з різною масою і конструкцією. Однак їхня динамічна поведінка відрізняється. Оптимальна конструкція демпферів з меншою масою має незвичний, «дивний» набір параметрів. Області двостороннього впливу демпфера на обидва бар'єри вузькі і розташовані поблизу резонансної частоти збуджуючої сили.

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Lizunov P.P., Pogorelova O.S., Postnikova T.G., Gerashchenko O.V. **Influence of mass on the efficiency and dynamics of single-sided and double-sided vibro-impact nonlinear energy sinks** // Strength of Materials and Theory of Structures: Scientific-and-technical collected articles. – K.: KNUBA. 2024. – Issue113. – P. 3-17.
The efficiency of the asymmetric single-sided and symmetric double-sided vibro-impact nonlinear energy sinks, that is, or vibro-impact dampers, for mitigating unwanted vibrations of the main structure are quite high and similar for dampers with different masses and designs. However, its dynamic behavior is different. The optimal design of the dampers with lower mass has unusual, "strange" parameter set. The regions of bilateral damper impacts on the both barriers are narrow and located near the resonant frequency of the exciting force.
Tabl. 6. Figs. 13. Refs. 24.

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