Вісник Тернопільського національного технічного університету
Scientific Journal of the Ternopil National Technical University
2017, № 4 (88)
ISSN 2522-4433. Web: ***visnyk.tntu.edu.ua***

MECHANICS AND MATERIALS SCIENCE

МЕХАНІКА ТА МАТЕРІАЛОЗНАВСТВО

UDC 539.3

CALCULATION OF CONSTRUCTIVE PARAMETERS OF SMA DAMPER

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Summary*. Shape memory alloy (SMA) based damper device is presented in this paper. The device is composed of pre-tensioned SMA wires and two pre-compressed springs which supply tension of the wires. Pre-tensioned SMA wires provide the system reliability and good damping properties. After removing the external load pre-compressed springs provide recovery of the device to its original shape. The calculation method of strength and constructive parameters of the damping device is offered. The internal force, the maximal displacement value and the pre-tension magnitude of SMA wires are defined. The maximum allowable internal force of the wires is determined.*

Key words*: damper device, constructive parameters, shape memory alloy, pseudoelasticity.*

Received 03.01.2018

Statement of the problem. At present the shape memory alloys (SMA) are increasingly used in many industries due to their properties [1–6], depending on the temperature of martensitic transformation and mechanical properties [7]. Because of its biocompatibility, high mechanical characteristics and corrosion resistance [8–10] NiTi alloys are intensively used in biomedical engineering. Due to the effect of pseudoelasticity [11] and high capacity of energy dissipation [12], SMA are used in civil engineering [13–16]. Thus, it is efficient to use SMA as a damper in structural elements subjected to vibration, resonance, oscillation and other cyclic loads.

However, the use of SMA in vibration damper devices for transporting long-length structures, taking into account the reliability of the device during continuous operation is not sufficiently investigated.

Analysis of the available research results. At present, devices with shape memory alloys are used in civil engineering to reduce damage during seismic loading [13–15] or to reduce the amplitude of oscillations and increase the durability of structural elements [16]. Such devices are designed for high amplitude and high frequency loading, but with a low loading period.

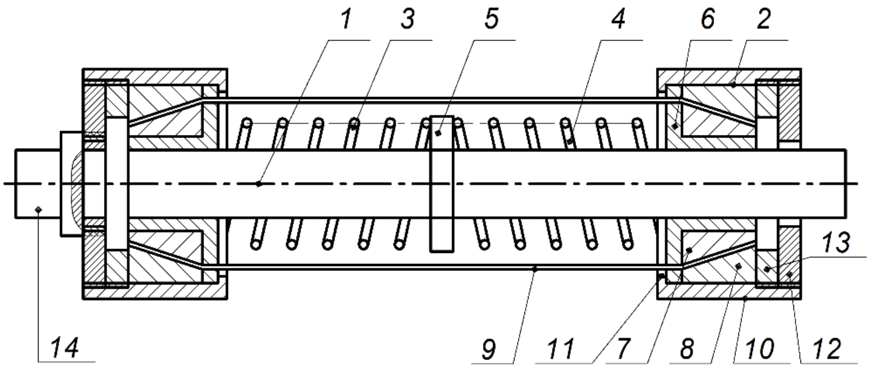
The disadvantage of their use as a damper for the transportation of long-length structures is the low reliability of the device during continuous operation.

The objective of the work. In order to ensure the structural strength of the damper device, with the elements made from shape memory alloy, it is necessary to calculate its design parameters, as well as to select load conditions, permissible load and force of the pre-tension of the SMA wires.

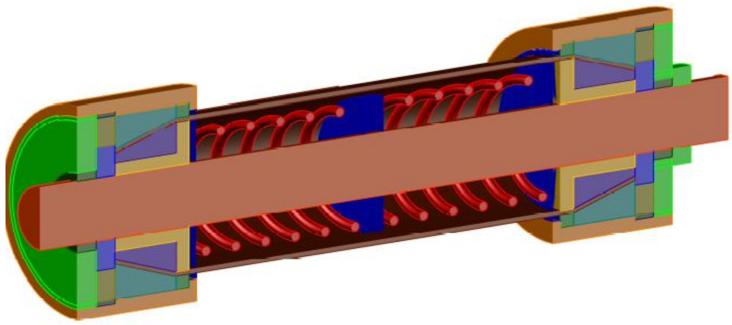
Statement of the problem. Investigations of the damper device based on the shape memory alloy are presented in this paper. The device [17] consists of pre-tensioned wires made of shape memory alloy and two compressed springs providing the wires tension. The pre-tensioned wires made of shape memory alloy ensure the system reliability and good damping properties. Pre-compressed springs provide the required restoring force after removing the external load on the device to bring the device to its original shape. The method of calculation of a damper device particularly the calculation of forces and displacements of damping and restoring elements of the device in the initial state and at maximum loads is presented in this paper. The stress value in the wires with SMA under the pre-tension is interpreted.

The results of the investigations

The design of the device. The offered damping device (Fig. 1) contains an axis 1 with two side fixing systems 2 on it. Springs 3 and 4 are placed between these systems. The springs are separated by a central locking device 5, the side mounting systems are equipped with fastening sleeves 6 with apertures on which the cone 7 is placed with a conical sleeve 8, between which the 9 SMA wires are locked. Each side fixing system is equipped with a cylindrical cage 10 with an inner ring stop 11 on one side and an inner thread 12 on the opposite side, in which the ring 13 is threaded pressing the conical sleeve through the intermediate washer 14. The threaded ring 13 of the left side fixing system is connected to the rod 15.



a



b

Figure 1. Schematic diagram of the damper for transportation of long elements: 2D cross section view – a); 3D cross section view – b)

The principle of the device operation. Under the action of the initial conditions, the central locking device 5 is in equilibrium condition, since the resultant force acting on the lock of two compressed on both sides springs 3, 4 equals zero. In case of tensile loading of the damper device through the rod 15 and the axis 1, the latter moves to the right and the locking device 5, which is rigidly fixed on the axis, compresses the spring 4 and weakens the spring tension 3. When removing the external force under the action of springs 3 and 4, the axle with the central locking device 5 moves to the starting position reducing the tension forces of the wires with the SMA. When reloading, the part of the energy of elastic deformation is scattered in the SMA material due to the properties of pseudoelasticity.

The scheme of the damper device in the initial state and under applied load P determining the dimensions and displacements; Δl_s is the displacement of the spring caused by an external load; Δl_w is elongation of SMA wires is shown in Fig. 2.

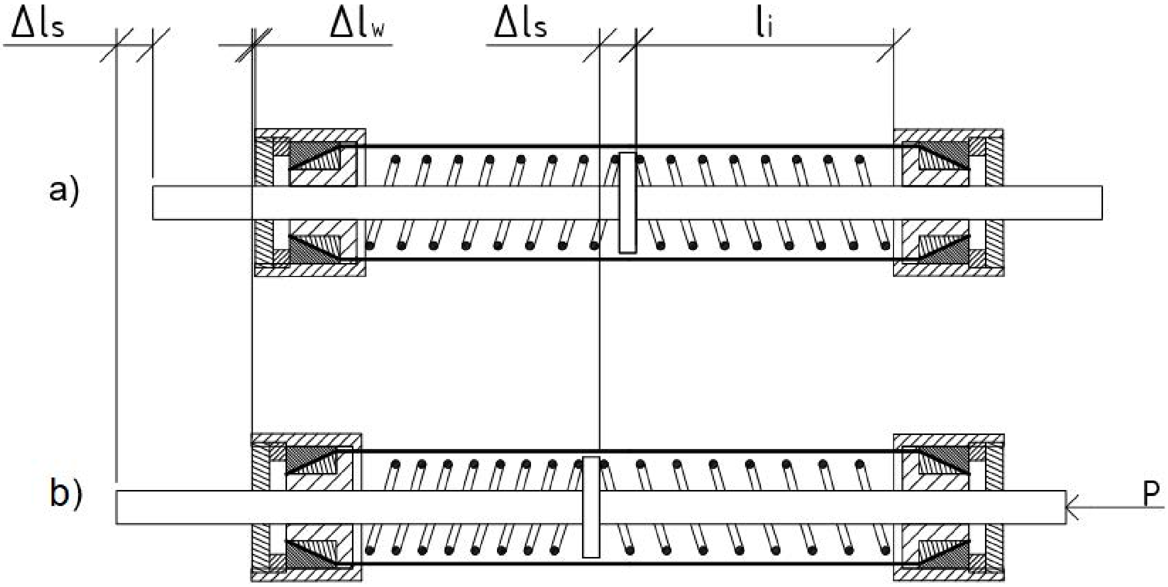


Figure 2. Device in initial state – a); under applied load P – b)

Each of the compressed springs installed in the device has a length l_i, in the free state it has a length of $l_i + \Delta l_1$

$$\Delta l_1 = \frac{N_{1,2}}{k} , \tag{1}$$

where $N_{1,2}$ is the internal force of the springs after their initial compression when installed in the device; k is the stiffness of the spring. SMA wires will be elongate with the same force.

Let us consider the simplified model of the damper device (Fig. 3). Here F_1 is the response to the spring compression 1; F_2 is the response to the spring compression 2; F_w is the force of wires tension.

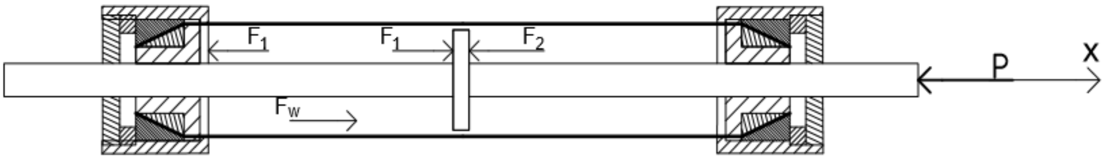


Figure 3. Schematic diagram of the device

$F_1 = F_2$ is in the initial state when there is no external loading (at $P = 0$).

Let us consider a certain deviation from equilibrium under the action of force P, applied to the axis (Fig. 3). The response of the spring 1 when it is displaced by the value Δl_s (Fig. 2) is equal to the initial compression when installed plus the force caused by its subsequent compression.

$$F_1 = N_{1,2} + k\Delta l_s \ . \tag{2}$$

Spring response 2

$$F_2 = N_{1,2} - k\Delta l_s \ . \tag{3}$$

That is, the spring compression force is equal to the initial pre-compression when installed minus the force caused by its elongation under the force P. In this case the condition $F_2 \geq 0$ must be satisfied.

Let's make the projections of forces on the x-axis:

$$F_1 - F_1 - F_2 + F_w - P = 0,$$

where F_w will be equal to

$$F_w = P + F_2. \tag{4}$$

Let us consider the boundary states. It should be noted that the springs should be compressed while the damper is working:

$$F_1 \geq 0; \quad F_2 \geq 0.$$

Case 1

Let us consider the case (fig. 4) where the spring 1 reaches the maximum compression under the action of the external force P_{1max}, while in the spring 2 the stresses are zero ($F_2 = 0$). Having done the projection of all forces on the x-axis, we have that the wires take up the internal force equal to the external load.

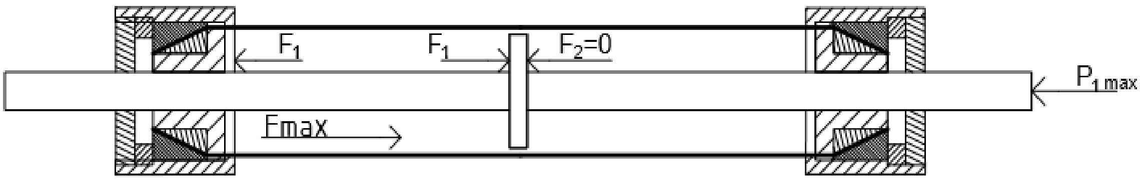


Figure 4. Schematic diagram of the device for $P = P_{1max}$; $F_2 = 0$

$$F_{max} = P_{1max} , \tag{5}$$

where F_{max} is the maximum force in the wires at which their elongation equals Δl_{max} .

Case 2.

When the spring under the action of the load external weight returns to its original shape (the stock moves to the right), the compression strength is reduced in the spring 1, and the compressive strength increases in the spring 2 (fig. 5).

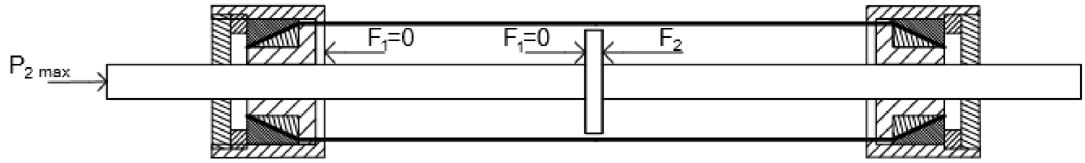


Figure 5. Schematic diagram of the device for $P = P_{2max}$; $F_1 = 0$

$$P_{2max} = F_{2l}\,, \tag{6}$$

where F_{2l} is the limiting force of spring compression 2.

Let's write down the condition when the given case 2 is true

$$\begin{cases} P_{2\max} = F_{2l} \\ F_1 = 0 \end{cases};$$

$$F_1 = N_{1,2} - k\Delta l_{sl} = 0\,.$$

Δl_{sl} is limit compression of the spring 2 when the displacement of the spring 1 is equal to zero

$$N_{1,2} = k\Delta l_{sl}\,;$$

$$\Delta l_{sl} = \frac{N_{1,2}}{k} = \Delta l_1\,. \tag{7}$$

So the stresses in the first spring will equal zero, if it is stretched to value Δl_1 from the initial state when installed, and in its in turn, the second spring is compressed to the same value Δl_1, from which we can write:

$$F_{2l} = N_{1,2} + \Delta l_1 k\,,$$

defining $N_{1,2}$ from equation (1), we get:

$$F_{2l} = 2\Delta l_1 k = 2N_{1,2}\,, \tag{8}$$

If the springs 1 and 2 are the same then you can write:

$$F_{1l} = F_{2l}\,, \tag{9}$$

where F_{1l} is the limiting force of spring compression 1.

Fig. 6 shows a force-displacement diagram presenting the pseudoelastic properties of the SMA. The diagram consists of two areas: the area on which the material is in austenitic state with the modulus of elasticity E_1; the area where the austenitic-martensitic transformation takes place with the modulus of elasticity E_2. The SMA wires during the operation process will be elongate by the value Δl_w:

$$\Delta l_w = \Delta l_I + \Delta l_{II} = \frac{F_w^A l_w}{E_A A_w n_w} + \frac{\left(F_w - F_w^A\right) l_w}{E_2 A_w n_w}, \tag{10}$$

where Δl_I and Δl_{II} are elongation of wires in the areas where the modulus of elasticity equals E_1 and E_2, respectively; l_w is the initial length of the wires; A_w is the wire cross section area; n_w is the number of wires; E_1 is the austenite modulus; E_2 is the martensite modulus; F_w^A is the limiting internal force in the wires when the elastic modulus is equal to E_1; F_w is the internal force in the wires under the action of force P.

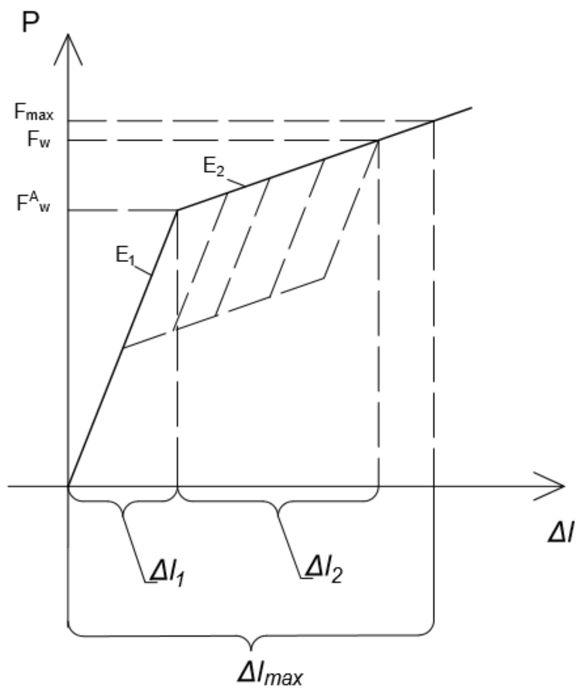


Figure 6. The force-displacement curve P-Δl of SMA

A maximum elongation of NiTi shape memory alloy under which the pseudoelasticity effect still remains is approximately 6% [11].

That is

$$\Delta l_{w.\max} = 0.06 \Delta l_{wi}, \tag{11}$$

where Δl_{wi} is the length of the wires in stress-free state; $\Delta l_{w.\max}$ is the maximum elongation of wires; Δl_{wl} is the length of the wires at their maximum elongation.

Taking into account the fact that the device is designed for damping the oscillations under the symmetric cycle as well as taking into account the deformation diagram of the SMA (Fig. 6), we assume that when there is no external load, the initial relative elongation of the wires is $\Delta l_{w0} = 0.5 \Delta l_{w.\max} = 0.03\ \Delta l_{wi}$.

Formula (10), for the limiting elongation of the wires Δl_{wl} can be represented as follows

$$\Delta l_{wl} = \frac{\sigma_w^A \, l_w}{E_1} + \frac{\sigma_{\max} \, l_w}{E_2} - \frac{\sigma_w^A \, l_w}{E_2}, \tag{12}$$

where σ_{max} is the maximum stress in the wires $\sigma_{max} \leq [\sigma]$.

Now you need to relate the elongation of the Δl_w wires to the spring compression of the Δl

$$\Delta l_w = \frac{F_w^A \, l_w}{E_1 \, A_w \, n_w} + \frac{\left(F_w - F_w^A\right) l_w}{E_2 \, A_w \, n_w}, \tag{13}$$

We substitute the equation (3) in expression (4).

$$F_w = P + F_2 = P + N_{1,2} - k\,\Delta l_{\text{w}}. \tag{14}$$

Now let us substitute the last expression in equation (13):

$$\Delta l_w = \frac{F_w^A \, l_w}{E_1 \, A_w \, n_w} + \frac{\left(\left(P + N_{1,2} - k\,\Delta l_s\right) - F_w^A\right) l_w}{E_2 \, A_w \, n_w}. \tag{15}$$

Expression (14) shows the dependence of the elongation of the wires on the compression of the spring.

Assuming that the initial tension of the wires is equal to 3% from the initial length of the wire, we can write down the initial force of the spring compression:

$$\Delta l_{wi} = 0.03 \, l_w = \frac{N_{1,2} \, l_w}{E_1 \, A_w \, n_w}, \tag{16}$$

$$N_{1,2} = \frac{E_1 \, A_w \, n_w \, 0.03 \, l_w}{l_w} = 0.03 E_1 \, A_w \, n_w. \tag{17}$$

The expressions (16) and (17) are given for the case when $N_{1,2} \leq F_w^A$.

Having formula (17), we can substitute it in expression (8) to determine the boundary force:

$$F_{2l} = 2N_{1,2} = 2 \cdot 0.03 \, E_1 \, A_w \, n_w = 0.06 \, E_1 \, A_w \, n_w. \tag{18}$$

Conclusions. The damper device based on the use of the pseudoelasticity effect of the shape memory alloys, which can be used for transporting long-length structures is offered. The device consists of pre-tensioned wires made of alloy shape memory alloys and two compressed springs, providing the wire elongation. The pre-tensioned SMA wires provides the system reliability and good damping properties, and pre-compressed springs - restoring the device to its original shape after removing the external load.

The techniques of calculating the strength and design parameters of the damper device are offered. The internal forces and magnitude of the preliminary tension of the SMA wires and the maximum of device displacement under the applied force are determined. The maximum permissible internal forces in the SMA wires is also determined.

These calculations of the structural parameters allow to provide the structural strength of the SMA damper.

Acknowledgements.

This study is part of the research project No. 0117U002244 financed by the Ministry of Education and Science of Ukraine. The authors kindly acknowledge the support in accomplishment of the research program.

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УДК 539.3

РОЗРАХУНОК КОНСТРУКТИВНИХ ПАРАМЕТРІВ ДЕМПФУЮЧОГО ПРИСТРОЮ ІЗ СПФ

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Резюме. *Запропоновано демпфуючий пристрій, заснований на використанні ефекту псевдопружності сплавів із пам’яттю форми (СПФ). Пристрій складається із попередньо розтягнених дротів із сплаву з пам’яттю форми та двох стиснених пружин, які забезпечують розтяг дротів. Попередньо розтягнені дроти зі сплаву з СПФ забезпечують надійність системи й добрі демпфуючі властивості, а попередньо стиснені пружини – відновлення пристрою до початкового положення після зняття зовнішнього навантаження. Запропоновано методику розрахунку міцнісних і конструктивних параметрів демпфуючого пристрою. Визначено зусилля та величину попереднього натягу дротів СПФ та максимальне граничне значення переміщення його пристрою під дією зовнішнього зусилля. Також визначено гранично допустиме зусилля у дротах.*

Ключові слова: *демпфуючий пристрій, конструктивні параметри, сплав з пам’яттю форми, псевдопружність.*

Отримано 03.01.2018