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DESIGN OF ASSOCIATED MECHANICAL STRUCTURE OF SHAPE MEMORY ALLOY ACTUATORS

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Abstract: *The paper is focused on highlighting the influence of the associated mechanical structure (AMS) of shape memory alloy actuators (SMAA,) on their performance in terms of generated stroke and force. In this sense, we've designed and developed a linear SMAA using shape memory alloy wire as an active element, and outlined the analytic results.*
Key words: *shape memory alloy, linear actuator, mechanical structure, prototype.*

1. INTRODUCTION

1.1 Shape memory alloys (SMA)

The *thermal shape memory effect* describes the effect of restoring the original shape of a plastically deformed sample, by heating it, [1]. This phenomenon results from a crystalline phase change known as *thermo-elastic martensitic transformation*. At temperatures below the transformation temperature, shape memory alloys are martensitic [3]. In this condition, their microstructure is characterized by *self-accommodating twins*. The martensitic is soft and can be deformed quite by de-twinning. Heating above the transformation temperature, recovers the original shape and converts the material to its high strength, austenitic, condition (Figure 1), [4], [5].

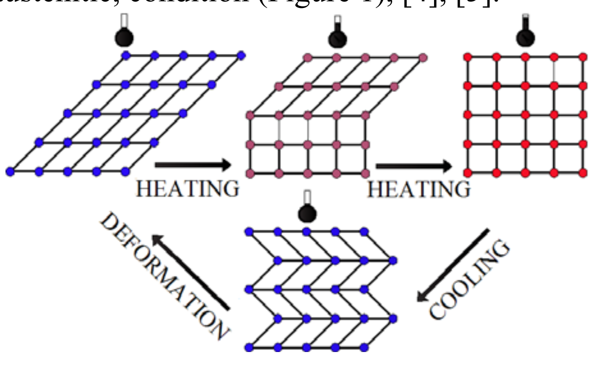


Fig. 1. The thermally induced shape-memory effect

The main groups of materials with shape memory properties are [2]:

- Alloys of Fe, Co, Ti, Zr, like: Fe-Pt, Fe-Ni, Fe-Cr, Fe-Ni-Cr, Fe-Ni-Co-Ti, Fe-Mn-Si;
- Alloys with tetra-cubical transformation phase: In-Ti, In-Cd, Mn-Cu, Mn-Si;
- Pure metals: Co, Ti, Zr;
- Alloys of Ni-Ti and Cu-based.

1.2 Shape memory alloy actuators (SMAA)

One of the basic applications for SMA is unconventional actuating systems. The actuator includes two basic components, one of which provides the energy required (based on the signals received from the control system), and the second that converts the received energy in to mechanical energy, used to produce forces or torques and linear or angular strokes, [6].

The main components of a SMAA are schematically represented in Figure 2:

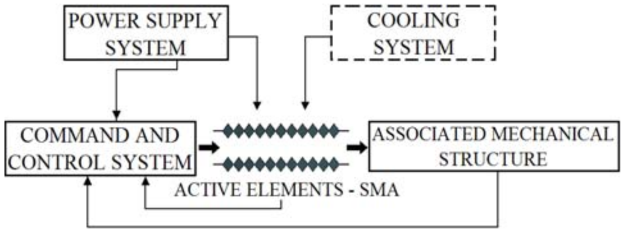


Fig. 2. The structure of a shape memory alloy actuator

- **Command and control system** – directs the energy from the power supply system to the SMA active elements, by controlling the timing and intensity of the generated mechanic energy (manual control circuits, automatic open/closed-loop control circuits). Also, limits the power supplied to SMA's protecting them from overheating (active/passive control systems for amperage, pulse-width modulation circuits PWM).
- **Associated mechanical structure (AMS)** – converts the SME in mechanic energy by supporting SMA elements in order to obtain the required force and stroke, and protecting against overloads and excessive deformation. One-way SMA elements require an antagonistic force in the cooling phase in order to return to its original shape.
- **Active elements SMA** – Their geometrical characteristics are determined based on: required stroke and associated mechanical structure (**length**); force or torque (**cross section**); environment temperature / transformation temperature (**speed of response**); actuating methods (heating) and recovery (cooling) (**geometry**).

Figure 3 presents the most common used geometries for SMA elements like: wire with circular cross section, helicoidally traction/compression springs, strips, tubs, flexional springs, membrane, preformed springs, torsion bar springs [4].

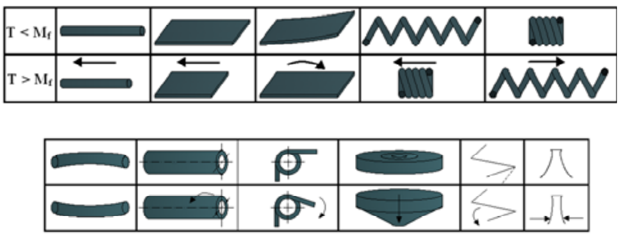


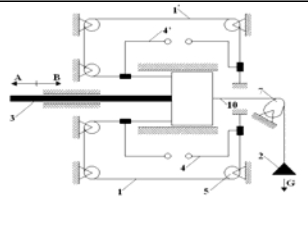
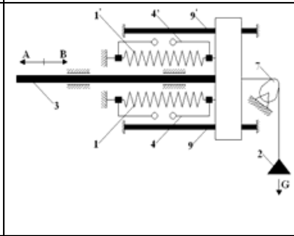
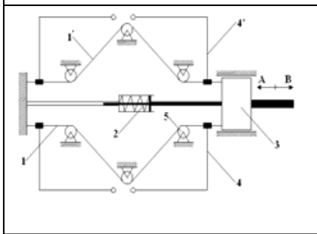
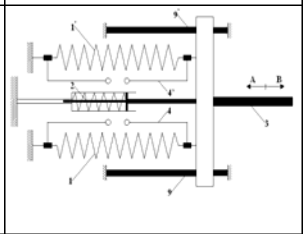
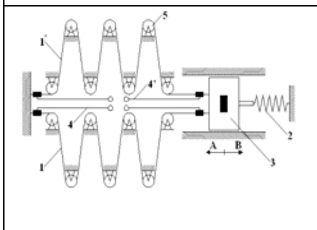
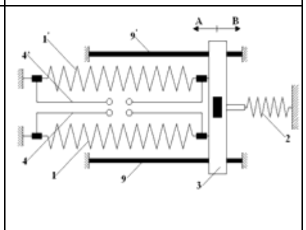
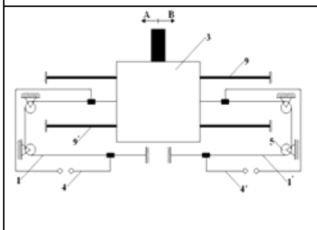
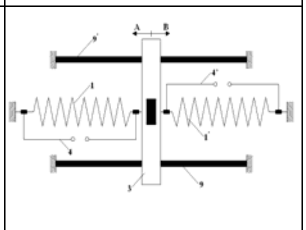
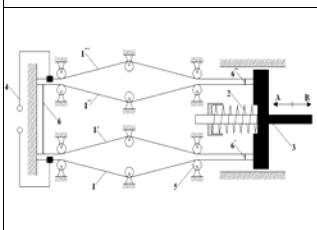
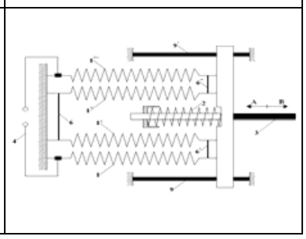
Fig. 3. SMA active elements

2. SYNTHESIS OF ASSOCIATED MECHANICAL STRUCTURES FOR LINEAR SMMA

In the following, we propose the synthesis of structural designs for linear SMAA, exposing the main components of the AMS and explaining the operating principle. The main criteria in differentiating the models are the type of active elements: (A) actuators with SMA wire(s) as active element(s); (B) actuators with spring(s) as active element(s).

Table 1

Structural designs of linear SMAA

A		B
	**1**	
	**2**	
	**3**	
	**4**	
	**5**	

Common notations used:

- 1, 1', 1'', 1'''' – SMA, wires or springs;
- 2 – helicoidally spring or weights
- 3 – moving rods
- 4, 4' – conductor wires;
- 5 – roller;
- 6, 6', 6'' – conductor wire -serial connection
- 7 – cam;
- 9, 9' – guide rail;
- 10 – cable

Model A1: after being heated by an electrical current through the conductor wires

(4), the active elements (1) contract to their memorized dimension, causing the translation of the rod (3) in direction “A”. Being a one-way SMA, in the cooling phase, the antagonistic force generated by the weight (2) in needed to return the SMA to its original dimension.

Model A2: the main differentiator from the previous model is the helicoidally compression spring (2) used in the cooling phase, for the recovery at the initial dimension. The disadvantage in this case is given by the increasing elastic force generated by the spring (2) in the moment of compression.

Model A3: the positioning of the rollers (5) describes a sinusoidal path of the SMA wire, thus obtaining a higher length for the active elements (1) and resulting in an increase of stroke for the rod (3) in direction A.

Model A4: this differential (bidirectional) actuator uses two active elements (1) mounted antagonistic. The relaxation phase (elongation) of one SMA wire is caused by the contracting phase of the second wire, activating the wires sequentially.

Model A5: by using SMA wires connected in parallel, the generated pulling force is higher.

Models B1…B5 have almost identical AMS’s, except the rollers used to guide the SMA wires. The use of springs as active elements facilitates the serial interconnecting, thus obtaining double stroke for the actuators.

3. PROPOSED SOLUTIONS OF AMS’s FOR LINEAR SMAA

The below models are “electric piston (EP)” and “translation-stage (TS)” linear actuators that use SMA wires, activated by Joule effect as a result of carrying by an electric current.

3.1. EP 1 model (pulling)

The working principle is following: the SMA wires (1, 1’) are guided by twelve rollers (4, 4’) that are interlocked to the mobile (6) and static (7) subassembly. The linear movement of the rod (3) is assured by the guide rails (5, 5’). The recovery phase is assisted by compression spring (2). As a result of heating above transformation temperature ($T>A_f$), the SMA wires shortens, generating a stroke in Y direction. By using two or more wires connected in parallel, the pulling force at the level of the rod is amplified. The compact design (32x22x12.5 mm) makes the actuator ideal for applications in confined workspaces.

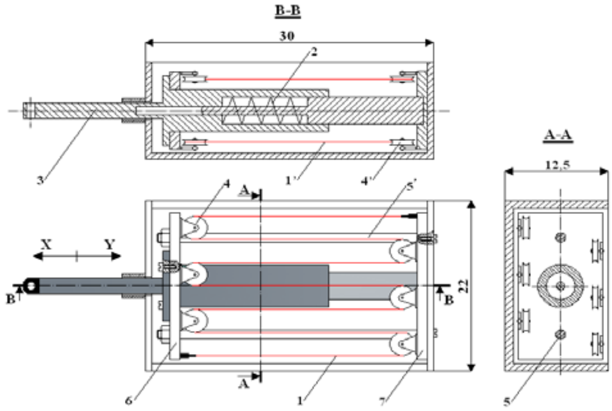


Fig. 4. Linear SMAA EP1

3.2. EP 2 model (pushing)

Figure 5 present a concept of EP actuator active in the pushing phase. It uses also two SMA one-way “educated” wires, fixed on the actuator housing through clips (5, 5’). The AMS includes also two articulated rigid elements (8, 8’), on which are mounted two rollers (6, 6’) for sustaining and guidance of the SMA elements. Two smaller articulated rigid elements (7, 7’) coupled between element (8, 8’) and the rod (3) through rotary unions convert the SME effect in linear stroke and thus obtaining a pushing force.

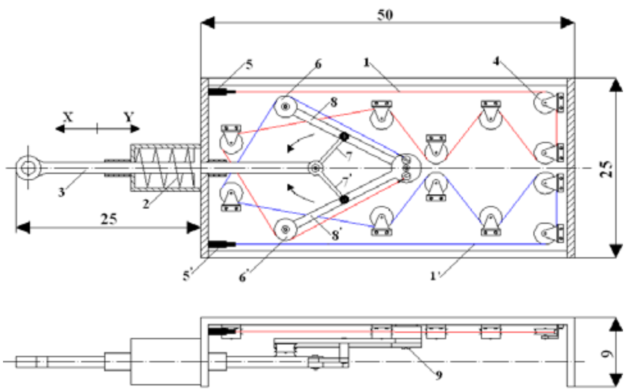


Fig. 5. Linear SMAA EP2

3.3. EP 3 model (pulling)

The main differentiator from the other models is the cylindrical case of the actuator. The rollers (4) are positioned to radiate, around the fixed shaft (8) and the mobile rod (3), offset from each other with 60˚, while rollers from the mobile rod are offset with 30˚ from the ones fastened on the case. By contracting the single SMA wire, the rod (3) translates in direction Y generating a specific pooling force.

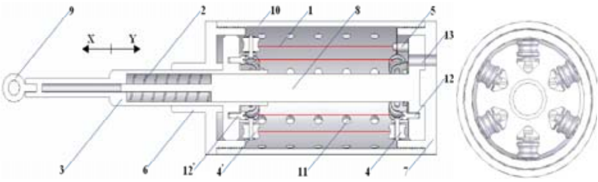


Fig. 6. Linear SMAA EP3

3.4. TS 1 model

A very simple design of translation-stage actuator (figure 7) uses one SMA wire (1) guided through six rollers (4), fastened at one end to actuator case and at the other end to guide-way (7) which, after the SMA wire contraction, will move the rod (3) in direction Y, guided by the slides (6, 6'). The return to initial position is assured by the elongation spring (3), used as antagonistic force. Disadvantage of this configuration is the relatively small force generated by using single SMA wire.

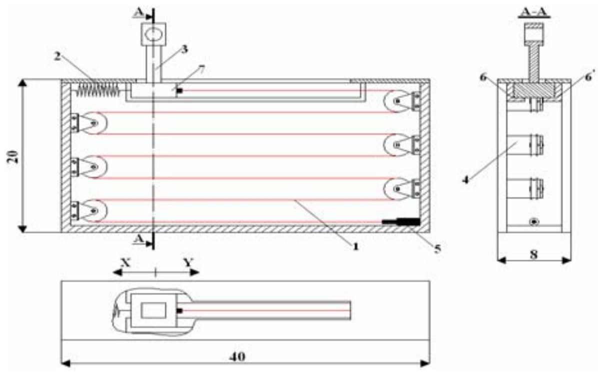


Fig. 7. Linear SMAA TS1

Based on these models we've designed a linear SMAA with SMA wires and developed the command and control system.

4. DEVELOPMENT OF A LINEAR SMAA

4.1. Analysis of proposed AMS

We've chosen a linear "electric-piston" design, active at pulling. What differentiates it from the other presented models is the configuration of the rollers. In order to reduce the cooling time, the case is provided with orifices that assure the air flow from the exterior, for forced cooling conditions.

The actuator is equipped with seven rollers from which six are fixed (4, 4') and one mobile (5). This configuration assures an amplified force through the pulley system with mobile axes and amplified stroke of the shaft (3).

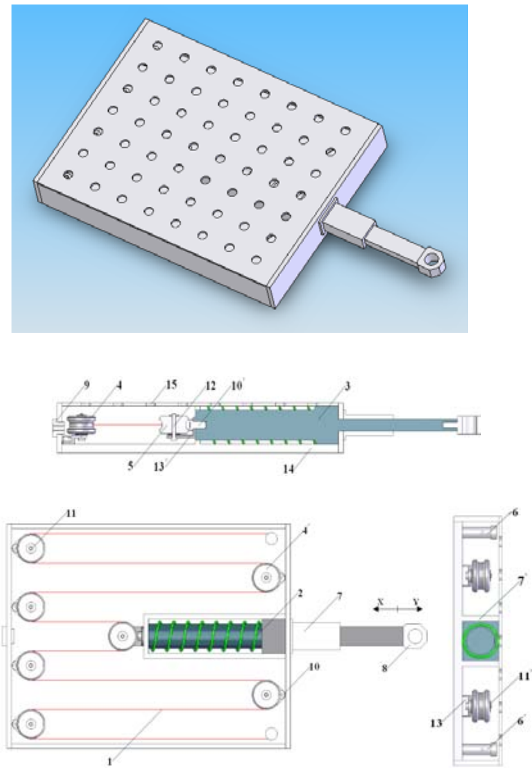


Fig. 8. The proposed linear SMAA

As active element (1) we've used SMA wire *Flexinol* of diameter Ø 150 μm and a calculated length of 425.94 mm. The wire is fixed on the case (14) through clips (6, 6'), that also have role of pretension. After being heated by an electric current the wire contracts and as a result, the shaft (3) moves in direction "X". The linearity of the stroke is assured by the slides (7, 7'). The recovery at the initial position (direction Y) is assured by the compression spring (2).

4.2. Evaluation of the stroke

As shown in [4] and [5], the stroke of any SMAA is determined by the length of the active element. For SMA wires, the contracting level is determined by the formula:

$$\Delta L = \varepsilon \cdot L \qquad (1)$$

L-wire length; ε-shape memory effect, usually 4%; ΔL-wire contraction

In our particular case, by using rollers as guidance for the SMA wire, we've obtained a stroke increase that is calculated based on the following sketch and formulas:

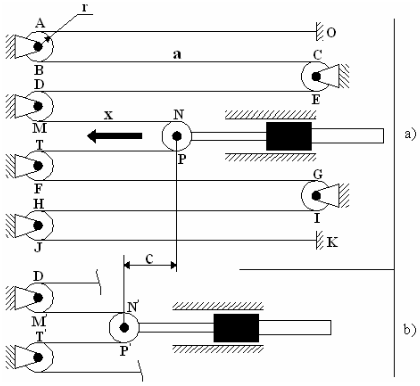


Fig. 9. Evaluation of the stroke

By using the following notations:

$$AO = BC = DE = FG = HI = JK = a$$
$$MN = PT = x$$
$$M'N' = P'T' = y$$

The total length of the wire is:

$$L = 6 \cdot a + 7 \cdot \pi \cdot r + 2 \cdot x \qquad (2)$$

It results:

$$x = \frac{L - 6 \cdot a - 7 \cdot \pi \cdot r}{2} \qquad (3)$$

After the recovery to its original shape, the length of the active element is:

$$L' = L - \Delta L = 6 \cdot a + 7 \cdot \pi \cdot r + 2 \cdot y$$

or (4)

$$y = \frac{L - \Delta L - 6 \cdot a - 7 \cdot \pi \cdot r}{2}$$

The stroke will be:

$$c = x - y = \frac{L - 6 \cdot a - 7 \cdot \pi \cdot r - L + \Delta L + 6 \cdot a + 7 \cdot \pi \cdot r}{2} = \frac{\Delta L}{2} \qquad (5)$$

Constructive, we chose:

a-distance between the roller $a = 50[mm]$

r-radius of rollers $r = 3[mm]$

ε-shape memory effect $\varepsilon = 4\%$

x-distance from the fix roller $x = 30[mm]$

The total length of the SMA wire will be:

$$L = 6 \cdot a + 7 \cdot \pi \cdot r + 2 \cdot x = 6 \cdot 50 + 7 \cdot \pi \cdot 3 + 2 \cdot 30$$
$$L = 425{,}94[mm]$$

The wire contraction is:

$$\Delta L = \varepsilon \cdot L = 0{,}04 \cdot 425{,}94 = 17{,}04[mm]$$

For this value, we obtain the stroke:

$$c = \frac{\Delta L}{2} = 8{,}52[mm]$$

4.3. Evaluation of the force

The force applied to the mobile element (roller) represents the summed forces from the two sectors of wire, according to pulley system with mobile axes principles.

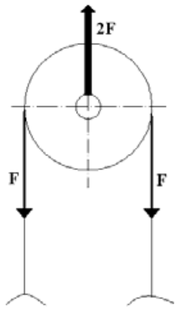


Fig. 10. Evaluation of the force

The developed force by the SMA wire is:

$$F_{M,R} = \sigma_{M,R} \cdot \frac{\pi \cdot d^2}{4} \qquad (6)$$

For the *Flexinol* wire used:

F_M – maximum force at recovery

F_R – recommended force at recovery

d – SMA wire diameter

$$d = 150[\mu m];$$

σ_M – maximum tensile stress at recovery

$$\sigma_M = 600[MPa]$$

σ_R – recommended tensile stress at recovery

$$\sigma_R = 35[MPa].$$

The calculated forces are:

$$F_M = \sigma_M \cdot \frac{\pi \cdot d^2}{4} = 600[N/mm^2] \cdot \frac{3{,}14 \cdot 0{,}0225[mm]}{4} = 10{,}59[N]$$
$$F_R = \sigma_R \cdot \frac{\pi \cdot d^2}{4} = 35[N/mm^2] \cdot \frac{3{,}14 \cdot 0{,}0225[mm]}{4} = 0{,}62[N]$$

We will consider $\sigma_R = 200[N/mm^2]$, thus:

$$F = 200[N/mm^2] \cdot \frac{3{,}14 \cdot 0{,}0225[mm]}{4} = 3{,}53[N]$$

The total force is:

$$F_T = 2 \cdot F = 7{,}06[N]$$

4.4. The developed prototype

The resistive heating of the active elements is assured by the electronic circuit presented in

Figure 11, by PWM (Pulse Wide Modulated) signals. This system was design and build in order to able to heat simultaneous four SMA wires.

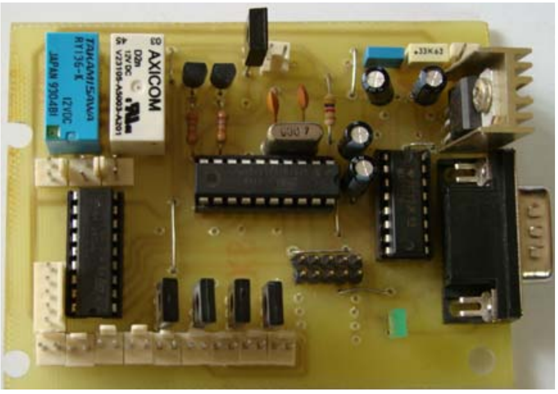


Fig. 11. The command and control system

The time frame between the contraction and relaxation of the SMA wire is controlled using *Bascom* software that offers the possibility to use a communication interface for controlling more than one actuator.

Figure 12 presents the prototype without the exterior casing in order to reveal the entire AMS.

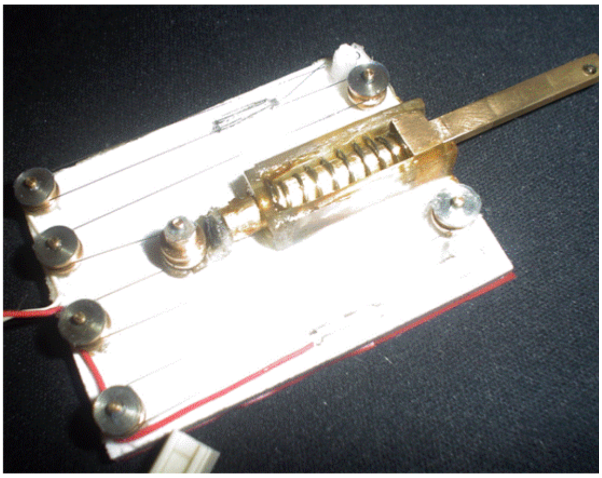


Fig. 12. The developed prototype – AMS view

5. CONCLUSIONS

In the domain of shape memory alloy actuators, the associated mechanical structures convert the SME in mechanic energy by supporting SMA elements in order to obtain the required force and stroke, and protecting against overloads and excessive deformation. One-way SMA elements require an antagonistic force in the cooling phase in order to return to its original shape. The stroke of any SMAA is determined by the length of the active element. In this case the mechanical structure design plays a critical role in obtaining the optimum path for the active element. The same for the generated force: it's important that the mechanical structure design allows the use of several active elements mounted in parallel.

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Proiectarea structurii mecanice asociate a actuatorilor pe bază de aliaje cu memoria formei

Rezumat: Lucrarea scoate în evidenţă influenţa structurii mecanice a actuatorilor pe bază de aliaje cu memoria formei, asupra performanţelor funcţionale ale acestora (cursă şi forţa/cuplu). S-au prezentat soluţii specifice actuatorilor liniari. S-a proiectat şi realizat un actuator liniar cu fire din aliaj cu memoria formei ca si elemente active.

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