Analyzing and Modeling Performance of a New SMA Actuator-Based Barrier Structure

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Abstract

This paper presents how a SMA spring-based barrier structure actually does work. An experimental model, consisting in a rather small SMA barrier, was built. The SMA spring is activated by applying different values of electric current and the barrier arm is charged with different concentrated weights. To collect data, a DAS acquisition system was used. Finally, some theoretical aspects regarding the dynamics of the structure motion were presented. The proposed dynamical study is made in dependent generalized coordinates. For obvious reasons, the mass of the spring was neglected, but all the rest of moving parts of the SMA actuator were taken into consideration. The paper ends with some authors' conclusions concerning the novelty and originality of their work.

1. Introduction

Shape memory alloys (SMAs) are such a class of smart materials that demonstrate the ability to return to some previously defined shape or size when subjected to the appropriate thermal procedure [1]. The cause is a martensitic phase transformation between a high temperature parent phase, austenite (A), and a low temperature phase, martensite (M). In the absence of stress, the start and finish transformation temperatures are denoted Ms, Mf (martensite start and martensite finish) and As, Af (austenite start and austenite finish) [1 - 3].

Starting with the 1970s, first with commercial products, the research concerning the application and control of SMA elements in engineering field has continued and expanded through the present, due to SMAS unique properties (pseudoelasticity, shape memory effects, hysteresis behavior, vibration damping capacity) [1, 3 - 5].

The authors have some experience in Smart Materials and Structures' field of more than 11 years. Their studies, carried out in the frame of some national or international specific projects, have been focused on the material characterization (tests on Shape Memory Alloys) as well as on design, computation and simulation of performances of such original structures applied especially in the robotic field [3, 6-10]. This work has been focused on finding some new applications of SMA spring actuators in barrier structures.

This study is motivated by the considerable interest, in recent years, in developing SMA actuators because of their advantages in producing large plastic deformations, force, work (force and displacement), low driving voltages, high power/weight and stroke length/weight ratios [1, 5, 11-13].

The first part of the paper describes an experimental model of a SMA spring-based barrier conceived by the authors.

In its second part, an experimental analysis of the SMA spring-based barrier structure behavior is made. This analysis takes into consideration different values of activating currents of SMA spring, as well as of weights of barrier arm.

The mathematical model of the analysis structure is developed in the last part of the paper.

The study of this experimental model is made in order to anticipate the behavior of a real structure.

2. Experimental arrangement description

The experimental model is designed to study the behavior of a small SMA-based barrier. There is no reason for a real barrier to work, in terms of quality, far different than a small barrier with motion provided by a SMA spring.

In this model, the SMA spring is used to move the barrier arm, when it's activated. There active shape-change control can effectively increase the efficiency of such a barrier for several different regimes.

The experimental arrangement of the analyzed SMA spring-based barrier is shown in Fig. 1. The main element of this arrangement is the SMA Electric Piston (position 7 in Fig. 1), a linear actuator mechanism that shortens in length with great strength and speed when it's activated by carrying an electric direct current. An inside placed SMA spring makes all these possible [8]. The SMA Electric Piston was purchased from the Mondo – tronics, Inc.

In the specific case of our model, Fig. 1, the electric current for powering the SMA Electric Piston can come from two sources:

a) internal power source (1), activated by the remote control (18), which ensures a constant direct current. In this case the switch (2) is on the right-hand position;

b) external power source, linked to the terminals (5, 6), which ensures a variable direct current. In this case the switch (2) is on the left-hand position.

In order to evaluate the functional characteristics of this barrier, a Data Acquisition System (DAS) was used to collect data.

The DAS was purchased from Gossen Metrawatt, and includes: race transducer-model 157 VISHAY (17), two multimeters METRAHit 29S (11, 12), software METRAwin 10, and an interface BD232 via PC.

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Fig. 1. Experimental arrangement of SMA-based barrier:
1 – internal power source box; 2 – switch; 3, 4 – connecting terminals for current measurement; 5, 6 – connecting terminals for external power source; 7 – seating base; 8 – fixed support linked to seating base; 9 – SMA Electric Piston; 10 – plug-in table; 11 – voltage channel of Data Acquisition System (DAS);
12 – current channel of DAS; 13 – metallic weights G2 (external loading); 14, 15 – connecting terminals for race transducer;
16 – barrier arm; 17 – race transducer; 18 – remote control

3. Operating mechanism

The SMA spring presents two really different forms or "phases" at the distinct temperatures Mf and Af. At the "low" temperature (Mf), the SMA spring is extended, and can be stretched easily or deformed by a small force. But when raised to the "high" temperature Af, by carrying an electric direct current, the SMA spring changes to a much harder form [14-16]. In this phase, it shortens in length, and exerts the necessary force to lift the barrier arm [8]. The SMA Electric Piston used in our model can lift up to 450g against gravity, yet the SMA Electric Piston itself weighs only 10g. The SMA Electric Piston was presented in detail in [8].

In order to achieve large motions in terms of angular displacements, the SMA actuator must be cleverly attached to the mechanism it operates. For our mechanism, consisting in a moving arm barrier that pivots over a fixed revolute joint, the small linear displacements of a SMA spring actuator is converted into large angular motions by fixing one end of the actuator and attaching the free end to the moving arm barrier close to the center of rotation of the revolute joint. This is very similar to how the biological muscles do move the links that make up the body. Of course, mechanical advantage is lost as the free end of the actuator approaches the center of rotation [1].

4. Experiments and results

The tests were made on the experimental arrangement presented in Fig.1, using an external 40V and 5A stabilized power source which ensures the possibility to get variable direct current. In order to analyze the operating mode and to have control on active shape-change of the SMA spring actuator, the following experiments were carried out: 1. determination of the SMA spring working time periods (time to start contracting t_{sc} , time to actuate t_a , time to relaxing t_{rel} , time to reset t_r) at three values of weights (position 13 in Fig. 1): G2₁=28.675g, G2₂=50.1g, G2₃=100.26g. In this case the SMA activating electric current and the stroke have constant values;

2. determination of the SMA spring working time periods at different values of the activating electric current, when the weight G2 and the stroke have constant values.

The race transducer converts the angular motion into electric voltage signal, as follows: 5V corresponds to 340°.

DAS made possible to put in evidence the displacement of the barrier arm as function of time for all activating currents and for all three weights.

As examples, in Figures 2, 3 and 4, the obtained results using a SMA activating direct current (I_a) of 3A, and for the weights $G2_1$, $G2_2$ and $G2_3$ respectively, are presented.



Fig. 2. Barrier arm displacement (stroke) and SMA active electric current time functions, for the weight G2₁



Fig. 3. Barrier arm displacement (stroke) and SMA active electric current time functions, for the weight G2₂



Fig. 4. Barrier arm displacement (stroke) and SMA active electric current time functions, for the weight G2₃

In our analysis, for all the tests, the value of the angular displacement (stroke) of barrier arm was 54.4° , which corresponds to 0.8V voltage signal.

All results are presented in the Table 1, where the parameters presented in this table have the following meaning:

- t_{sc} = time to start contracting, or the necessary time, from the start of current application, to reach the temperature As;

- t_a = time to actuate, or the contraction time, or the necessary time for the arm to reach the angular displacement of 54.4°;

- t_{rel} = time to relaxing, or the necessary time for the SMA spring to cool from a temperature greater or at least equal to Af to the temperature Ms. In all cases the cooling process ended at 23.1°C;

- t_r = time to reset, or the necessary time for the arm to come back at its initial position. In this status, the SMA temperature is under Mf.

Watching results, it becomes obvious that, because the SMA spring activates through electric heating, the contracting time varies in a quite significant range with the applied current; the higher the current, the faster the heating, and the faster the contraction and so, the stroke of barrier arm, considering the external weight as being constant. Of course, for a fixed value of the current, this period of time increases as the external weight gets higher.

The differences between whatever two values of relaxing time are small indeed and that because the differences between whatever two values of heating temperatures are small either.

The resetting time reduces as the external weight is getting higher at that because this adds to the minimal resetting force.

We find ourselves in a position to be able to choose a certain value for the current in order to obtain some desired work periods of time.

Table 1. Tim	es of work f	for the an	alyzed	barrier	correspondi	ng		
to a complete cycle up-down								

Weight	Ia	t _{sc}	ta	t _{rel}	t _r
[g]	[A]	[s]	[s]	[s]	[s]
G2 ₁ =28.675	1.76	24	51	16	63
G2 ₂ =50.1	1.76	32	105	14	61
G2 ₃ =100.26	1.76	53	116	14	54
G2 ₁ =28.675	1.92	20	25	14	60
G2 ₂ =50.1	1.92	24	43	13	54
G2 ₃ =100.26	1.92	30	62	14	47
G2 ₁ =28.675	2.22	14	14	13	57
G2 ₂ =50.1	2.22	16	18	12	42
G2 ₃ =100.26	2.22	19	34	13	38
G2 ₁ =28.675	2.7	10	8	12	51
G2 ₂ =50.1	2.7	8	10	13	40
G2 ₃ =100.26	2.7	9	16	12	37
G2 ₁ =28.675	3	6	6	11	38
G2 ₂ =50.1	3	7	7	12	35
G2 ₃ =100.26	3	8	11	13	34
G2 ₁ =28.675	3.8	3	4	11	40
G2 ₂ =50.1	3.8	4	5	11	37
G2 ₃ =100.26	3.8	5	7	10	32
G2 ₁ =28.675	4.2	3	3	11	37
G2 ₂ =50.1	4.2	4	4	10	31
G2 ₃ =100.26	4.2	4	5	9	26

5. The motion equations for the mechanical model

The mechanical model of the experimental arrangement simulating the barrier is shown in the Fig. 5. The force is ensured by the SMA spring. At least for the beginning of a certain motion of the barrier starting from an "at rest" position, the direction of this force can be considered as being vertical.

In the Fig. 5, the signification of each and every notation is obvious. We consider as known the ratio $k = \frac{AO_o}{AB}$. The length of the barrier arm *AB* is *L*. The mass center of this arm is noted *C*. Of course, we have *AC=CB*. The barrier arm is considered as being kind of homogenous and rigid. Its mass is noted m_1 . The external concentrated mass attached on the arm at its bound *B* is m_2 . We consider the case that k > 0 and k < 0.5. The mass of the actuator piston is m_3 and its length is $2L_2$ and its mass center C_1 is in its middle point. The mass of the actuator cylinder is m_4 and its length is $2L_2$ and its mass C_2 is in the middle of its symmetry axis.

We shall neglect the mass of the SMA spring.

The current position of the arm is described by the generalized coordinate q.

Due to the fact that DA_1 is kind of vertical it becomes obvious that q_1 can be expressed as function of q, applying, for example, the sinus theorem in the triangle A_1AD . So, the work will be done in *dependent coordinates*: q and q_1 .

The unit vector \vec{i}_i characterizes the $O_o x_i^o$ axis, j = 1, 2, 3.

We consider:

- the arm gravity force:

$$\vec{G}_1 = m_1 \vec{g} = -m_1 g \cdot \overset{\rightarrow 0}{i_2} \tag{1}$$

- the gravity force of the external weight:

0

$$\vec{F}_2 = m_2 \vec{g} = -m_2 g \cdot \vec{i}_2^{0}$$
 (2)



Fig. 5. Mechanical model of the experimental arrangement

- the gravity forces of actuator piston and cylinder:

$$\vec{G}_3 = m_3 \vec{g} = -m_3 g \cdot \vec{i}_2^{0}$$
(3)

$$G_4 = m_4 g = -m_4 g \cdot i_2^{(3)}$$
 (4)

- the SMA spring force, applied in A:

$$\vec{F} = -F \sin q_1 \vec{i}_1^{\to 0} - F \cos q_1 \vec{i}_2^{\to 0}, F > 0$$
(5)

The positioning vectors, with respect to R_0 , are:

$$r_{C}^{\rightarrow R_{0}} = L\left(\frac{1}{2} - k\right)\cos q \, \overrightarrow{i_{1}}^{\rightarrow 0} + L\left(\frac{1}{2} - k\right)\sin q \, \overrightarrow{i_{2}}^{\rightarrow 0} \tag{6}$$

$$\vec{r_{E}} = (-k L \cos q - 2L_{1} \sin q_{1}) \vec{i_{1}} + (-k L \sin q - 2L_{1} \cos q_{1}) \vec{i_{2}}$$
(8)

$$r_{C_1}^{\rightarrow R_0} = (-k L \cos q - L_1 \sin q_1) i_1^{\rightarrow 0} +$$
(9)

$$+(-k L \sin q - L_1 \cos q_1) i_2$$

$$\xrightarrow{\partial R_0}_{C_2} = (-k L - L_2 \sin q_1) \overrightarrow{i_1}^{0} + (10)$$

$$+(-H+L_2\cos q_1)\vec{i}_2^{\rightarrow 0}$$

We consider that, somehow, the motion has been initiated because we will not study, yet, any transitory regime.

The kinetic energy of the system, elementarily calculated, is:

$$T = \dot{q} \cdot \frac{m_{1}L^{2}}{2} \left[\frac{1}{3} + k(k-1) \right] + \dot{q} \cdot \frac{m_{2}L^{2}}{2} (1-k)^{2} + \frac{1}{2} m_{3} \left[\dot{q} \cdot \frac{k^{2}L^{2}}{k^{2}L^{2}} + \dot{q}_{1} \cdot \frac{k^{2}}{L_{1}^{2}} - 2\dot{q} \cdot \dot{q}_{1} kLL_{1} sin(q+q_{1}) \right] + \frac{m_{3}L_{1}^{2} q_{1}^{2}}{6} + \dot{q}_{1} \cdot \left(\frac{m_{4}r^{2}}{4} + \frac{4m_{4}L_{2}^{2}}{3} \right)$$

$$(11)$$

where r is the actuator cylinder radius and is known.

Obviously, we have:

$$\frac{\partial T}{\partial q} = 0; \qquad \frac{\partial T}{\partial q_1} = 0$$
 (12)

The generalized forces are:

$$Q = \overrightarrow{F} \cdot \frac{\partial \overrightarrow{r_E}}{\partial q} + \overrightarrow{G_1} \cdot \frac{\partial \overrightarrow{r_C}}{\partial q} + \overrightarrow{G_2} \cdot \frac{\partial \overrightarrow{r_B}}{\partial q} + \overrightarrow{G_2} \cdot \frac{\partial \overrightarrow{r_B}}{\partial q} + \overrightarrow{G_3} \cdot \frac{\partial \overrightarrow{r_C_1}}{\partial q} + \overrightarrow{G_4} \cdot \frac{\partial \overrightarrow{r_C_2}}{\partial q}$$
(13)
$$Q_1 = \overrightarrow{F} \cdot \frac{\partial \overrightarrow{r_E}}{\partial q_1} + \overrightarrow{G_1} \cdot \frac{\partial \overrightarrow{r_E}}{\partial q_1} + \overrightarrow{G_2} \cdot \frac{\partial \overrightarrow{r_B}}{\partial q_1} + \overrightarrow{G_3} \cdot \frac{\partial \overrightarrow{r_C_1}}{\partial q_1} + \overrightarrow{G_4} \cdot \frac{\partial \overrightarrow{r_C_2}}{\partial q_1}$$
(14)

The mathematical model of the motion will result from applying the well-known Lagrange equality [17, 18]:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial q}\right) - \frac{\partial T}{\partial q} = Q; \quad \frac{d}{dt}\left(\frac{\partial T}{\partial q_1}\right) - \frac{\partial T}{\partial q_1} = Q_1 \quad (15)$$

Relations (15) are, in fact, a two differential equations system with two unknowns: q and q_1 .

Using the relations (11), (7), (8), (9), (10), on one hand and (1), (2), (3), (4), (5), on the other hand, the system turns out to be kind of non-linear and having a complicate form, indeed. But, the fact of the matter is that those two unknowns are dependent. Indeed, taking into consideration that the trajectory of A is a circular one, it becomes obvious that:

$$A_{1}A = 2kL\sin\frac{q}{2} \tag{16}$$

The sine theorem leads to:

$$\frac{A_1 A}{\sin q_1} = \frac{AD}{\sin \frac{q}{2}}$$
(17)

The cosine theorem leads to:

$$AD^{2} = H^{2} + A_{1}A^{2} - 2H \cdot A_{1}A\cos\frac{q}{2}$$
(18)

Relations (16), (17) and (18) result into a direct and finite relation between q and q_1 . This relation and (15) leads the whole problem to a single differential equation having q as unknown. Solving this equation is quite a serious task and will be itself subject of a paper that proposes to combine the force-deformation characteristics of a SMA spring, as dependences of temperature, with the Lagrange model (15) and geometric restrictions (16), (17) and (18).

The value of the force F does come from the experimental results [16, 19]. In this paper we made no specific connections to the constitutive equation of the material the SMA spring is made of. At this point of our study, we have been focused only on the dynamics of the structure as a whole. Of course, we have to attach to the model its initial conditions. These conditions concerns mainly the initial position (that comes out from the beneficiary request) of the arm and that because, obviously, the initial arm velocity has zero value. This initial position has decisive impact on the initial deformation status of the SMA spring.

6. Conclusions

The proposed barrier structure is kind of lightweight and has a simple configuration because it contains no hydraulic fluids and compressor drive.

In normal functioning conditions the SMA spring can perform many thousands of cycles in great reliability and repeatability, resulting in a long-life and huge efficiency SMA based barrier structure.

The active shape-change control of the SMA spring can effectively increase the efficiency of a barrier at several different regimes. ELECO 2011 7th International Conference on Electrical and Electronics Engineering, 1-4 December, Bursa, TURKEY

Analyzing the experimental results, it turns out that our model behaves quite well in both cases of big and small activating currents, for all three external weights. For a given barrier structure, choosing some certain values for external weight and activating current will be made at specific beneficiary request.

As we mentioned earlier, the Lagrang-based model furnish some kind "external characteristic" of structure. This so-called external characteristic has to be putted together with the characteristic of the used SMA spring.

These new barrier structures may prove potential usefulness in: parking lots, toll gates, bridge barriers, apartment block access, toys etc.

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7. References

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