EXPERIMENTAL STUDY OF VIBRATION ATTENUATION IN A SMART COMPOSITE BEAM

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Abstract. *In this work, an epoxy beam reinforced by Ni-Ti shape memory alloy (SMA) wires was developed and experimentally studied. This active composite contains five pre-trained Ni-Ti SMA wire actuators, evenly distributed along the neutral plane of the epoxy beam, which can be activated by resistive heating. The results of different ways for electrical activation of the smart composite in a simply clamped mode are discussed. A thermal buckling effect was verified and the temperature – deflection behavior demonstrate how the shape recovery forces affect the active composite beam. It was also possible to demonstrate the viability of this concept for attenuation of mechanical vibrations by controlled electrical heating of the Ni-Ti wires actuators.*

Keywords: *Shape memory alloys, smart composites, smart structures, vibrations.*

1. INTRODUCTION

Shape memory alloys (SMA) are defined as a class of materials that have the ability to recover an imposed plastic deformation when heated above a critical temperature (Otsuka & Wayman,1998). SMA are thermo-responsive materials where deformation can be induced and recovered through temperature changes. There are two stable phases of the lattice structure for these special alloys that may exist, named martensite and austenite. Austenite phase represents the high temperature stable state with a high elastic modulus. Martensite represents the low temperature stable state with a lower elastic modulus. More recent applications for SMA have been focused in the medical field, and smart material research. “Smart Structures” have been defined by Michaud (2003), as material systems with intelligence and life features integrated in the microstructure of the material system to reduce mass and energy and produce adaptive functionality. Materials commonly classified as “smart materials” include piezoelectric materials, magnetostrictive materials, electrorheolgical fluids, magnetorheological fluids, and shape memory alloys. All of these materials possess the ability to change their inherent properties as a result of a sensing mechanism. SMA have the ability to change stiffness, shape, natural frequency, damping and other mechanical characteristics in response to a change in temperature. The recent interest in smart structures has shown that SMA have great potential for vibration, structural acoustic, and structural shape control (Turner, 2001). Lau *et al* (2002) have established that among these materials, SMA is most suitable for development and active control of smart composite structures. These authors studied the variation of natural frequencies of glass fiber epoxy composite beams with embedded SMA wires. It was verified that the natural frequencies initially decreased for the beam with low SMA wire fraction (between 0.5% and 3%) and increased with continuously increasing the SMA wire fraction (above to 3%). In the same way, other authors (Zhang *et al*, 2006) have reported similar results. Ju & Shimamoto (1999) studied damping property of epoxy matrix composite beams with embedded SMA fibers and also reported increase of natural frequencies with 4.9% of SMA wire fraction. Epoxy reinforced by trained Ni-Ti shape memory wires was experimentally investigated by static tests where the thermal buckling behavior was observed (Reis *et al*, 2007). The designed beam has five actuator wires evenly distributed along its neutral plane, called Shape Memory Alloy Hybrid Composites (SMAHC). Seven actuation modes were established and tested in a single cantilevered beam way. It was demonstrated that electrical activation of three actuator wires (central and extremity lateral) are sufficient to achieve a maximum tip deflection of approximately 1.1 mm by thermal buckling.

Other material used for control of vibration in flexible structures is piezoelectric ceramic. In this way, Trindade & Maio (2008) studied a multimodal passive vibration control of sandwich beams with shunted shear piezoelectric materials. These authors reports results on the use of thickness-shear piezoelectric patches connected to resistive shunt circuits for the passive vibration control of sandwich beams, where it was possible a reduction of approximately 20 dB in the vibration amplitude at resonance. Trindade, (2007) also worked a numerical investigation of active vibration control using simultaneous extension and shear piezoelectric actuation for a clamped–clamped sandwich beam.

In this work, an investigation of the dynamic response of the SMAHC beam specimen previously manufactured by Reis *et al* (2007) under mechanical excitation is realized. Results from measurements of the dynamic response of the

SMAHC beam specimen, under thermal load by resistive heating with random base mechanical excitation, are presented and discussed. For this, it is necessary the application of an electrical current through the embedded SMA wire, as described in Reis *et al* (2007), however now under random inertial loads for different electrical activation modes of the Ni-Ti SMA wires.

2. EXPERIMENTAL PROCEDURE

All the SMAHC beam vibration outcomes in this study results from forcing excitation by an electromechanical shaker specially designed for this application. The dynamic responses are evaluated at various temperatures corresponding to different stiffness states. The beam was designed to present resonance in the excitation bandwidth used in the experiments. Transducers are placed on fixture and beam in order to obtain the relative response of the SMAHC beam. During mechanical excitation a thermal load is applied to the beam as in the previous static tests (Reis *et al*, 2007), where seven actuation modes were established and tested in a cantilevered beam way. For which actuation mode the SMAHC beam will be brought to a desired temperature set point, in the same time which dynamic data will be captured. Therefore, one run will consist of capturing dynamic data at all the chosen set point through a thermal cycle from ambient to about 90ºC.

2.1. Measurement of the natural frenquency of SMAHC beam

Before running the experiments, the natural frequency for each actuation mode of SMAHC beam was measured. First, the SMAHC beam was clamped in a single cantilever mode, as showed on schema in Fig 1. Then, an impact hammer was used as excitation device to apply an impulse to the SMAHC beam. Finally, the beam starts the motion as well as oscillatory with decaying amplitude. The response of the beam is measured using an ADXL202E accelerometer supplied by Analog Devices, mounted in the edge of the beam.

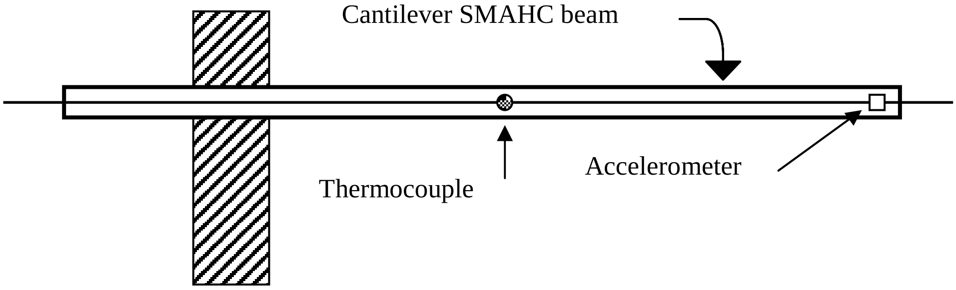

Figure 1. Schema of the experimental assembler for measurements of the natural frequency of SMAHC beam specimen.

2.2. Design and assembly of a small electromechanical shaker

A miniaturized electromechanical shaker was made using a DC electrical motor with rotating unbalance mass. This motor was characterized using a photoelectric sensor consisting of a pair transmitter-receiver infra-red ray. This sensor generates an infrared light that has left of the transmitter and reaches the receiver, making possible to identify when the infrared light is interrupted. Therefore, to measure the rotation speed, the motor was mechanically mounted in a way that the infrared ray is interrupted at each turn of its shaft, as well as pointed out in Fig 2. In this set-up, an oscilloscope was used to determine the number of interruptions by second of infrared light and thus measure the motor speed. Finally, the characterization method of the shaker consisted in connect a DC power supply at the motor and varying the voltage level from 0.4 V to 1.8 V, with steps of 0.1 V. For each value of applied voltage, the speed was written down the value of the corresponding frequency.

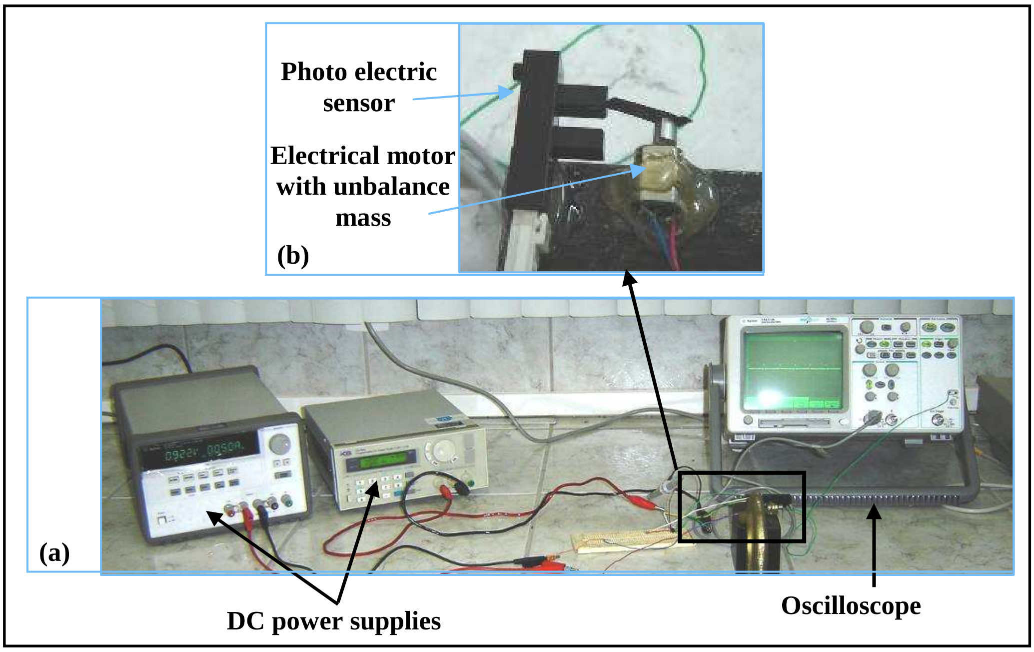

Figure 3. Assembly for the motor characterization used as electromechanical driver (small shaker). (a) General view of the developed assembly. (b) Detail of the photoelectric sensor and motor.

Figure 4 shows the characteristic curve of the mini-shaker, obtained with the assembly shown in Fig 3. It is verified that mechanical oscillation with frequencies between 50 and 200 Hz can be produced with this shaker. Thus, specific software to control the motor was made for the experiments. A voltage power supply was controlled by this softwareand consequently the motor frequency can be adjusted at any time.

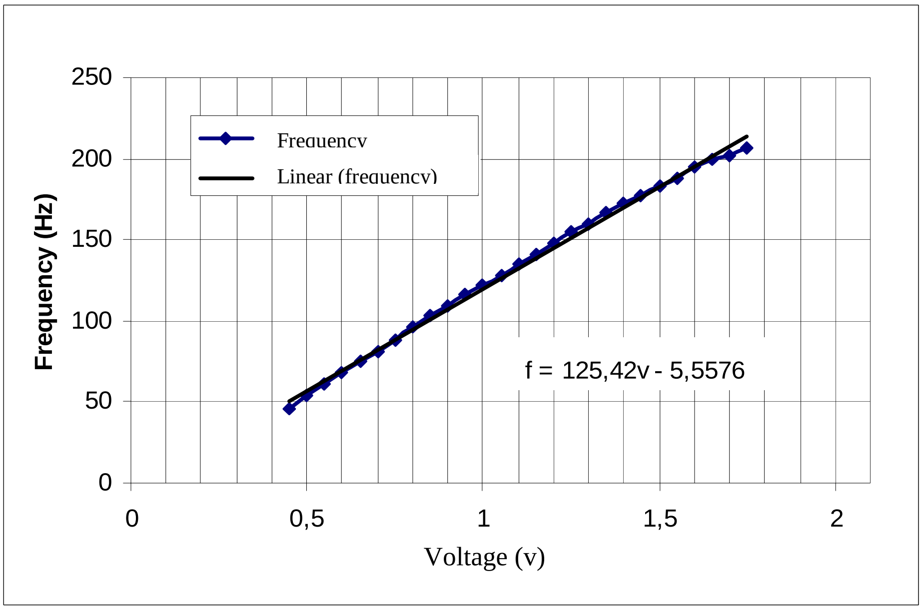

Figure 4. Relation between frequency and voltage of the DC electrical motor.

2.3. Assembly for the dynamic tests

The designed SMAHC beam has 300 x 25 x 4 mm^3 and was manufactured at ambient temperature and pressure by stretching out each trained Ni-Ti SMA (0.29 mm diameter) individually in an aluminum mold and spilling the epoxy resin on them. This active composite contains five pre-trained Ni-Ti SMA wire actuators, evenly distributed along the neutral plane of the epoxy beam, which can be activated by resistive heating. For the dynamic tests, the activation of the SMAHC beam was made in the same way described in the static tests (Reis *et al*, 2007). Figure 5 show the electrical activation schema for the cantilevered SMAHC beam specimen. It is possible to activate one (01), two (02 and 03), three (04 and 05), four (06) or five (07) Ni-Ti SMA wires.

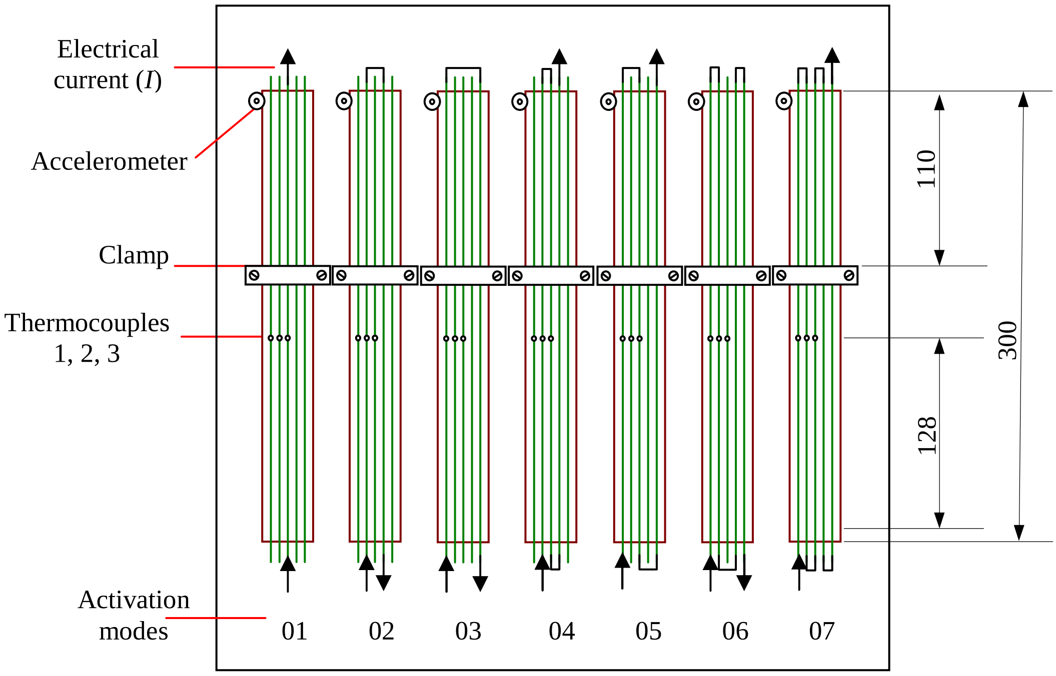

Figure 5. Different modes for electrical activation of the SMAHC beam specimen.

The SMAHC beam specimen produced as indicated above was tested in a cantilever beam mode to verify the dynamic response under electrical resistive heating of the pre-trained Ni-Ti SMA wires. Figure 6 show the experimental configuration for the SMAHC beam dynamic response. The active beam (1) is simply clamped on a rigid magnetic plate. An electrical plug (2) allows different ways for electrical activation of the Ni-Ti SMA wires and an accelerometer sensor (3) is installed to measure the excitation of the beam during operation while temperature is measured in three different points along the neutral plane of the beam using micro-thermocouples (80 μm in diameter, K type) (4) installed close to the Ni-Ti wires. A DC power supply voltage (Icel, PS 7000 model) (5) was used to drive the small shaker (6). Resistive heating is done by a programmable DC power supply (Agilent, E3633A model) (7) controlled by specific software (8), while temperatures of the beam and electrical resistance of the Ni-Ti SMA wires are stored in a data acquisition system (Agilent, 34970A model) (9). Time histories with a total length of 700 seconds were captured with a sampling rate of 1024 Hz to allow 50-frame averages with a bandwidth of 0-512 Hz and a frequency resolution of 0.25 Hz for ever set point by Cattman of HBM data acquisition Spider 8 (10).

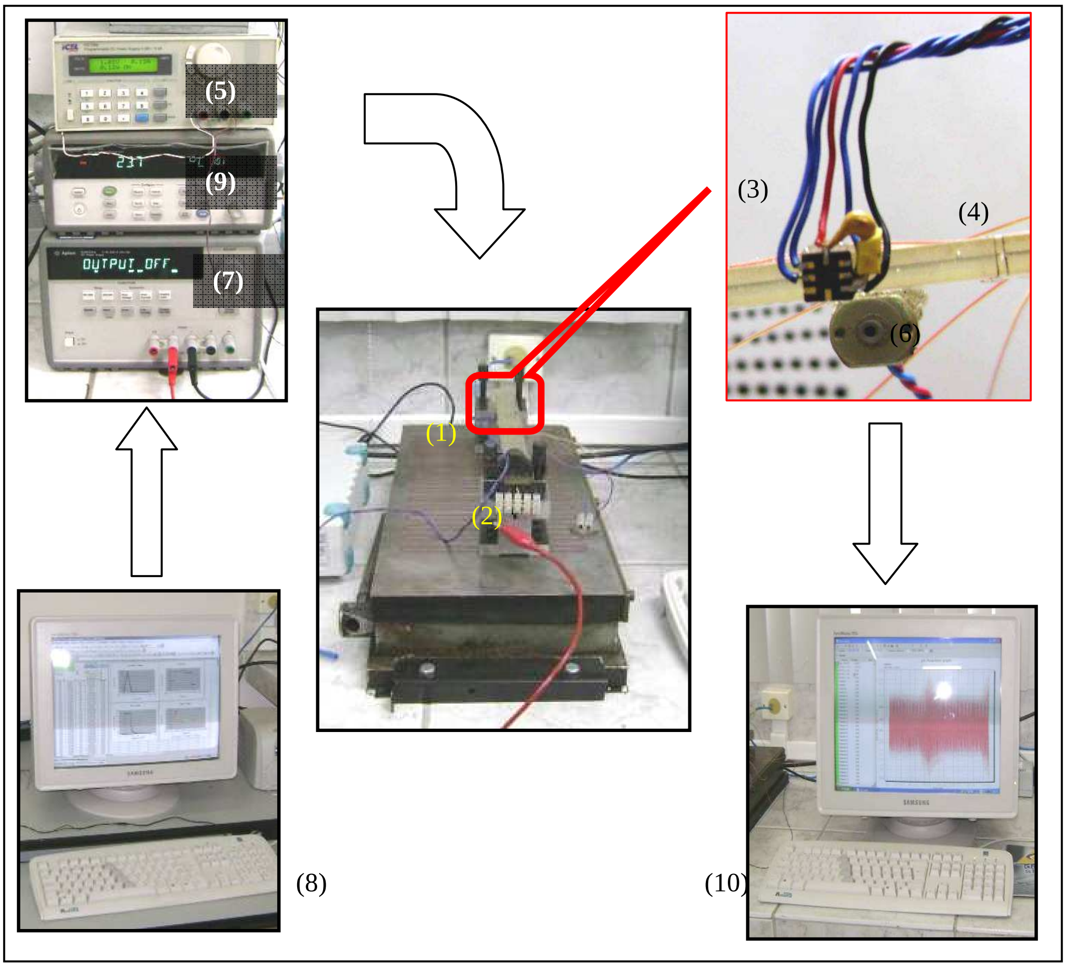

Figure 6. Experimental set-up for the SMAHC beam dynamic response.

3. RESULTS AND DISCUSSIONS

As described previously in Fig 1, the natural frequency for each one activation mode defined in Fig 5 was experimentally determined. The structure was excited by a pulse of short duration through an impact hammer and as result the time response shown in Fig. 7 was obtained. The voltage time signals from transducer were processed by Origin software to perform a Fast Fourier Transform (FFT) and change from time domain to frequency domain as show in Fig. 8.

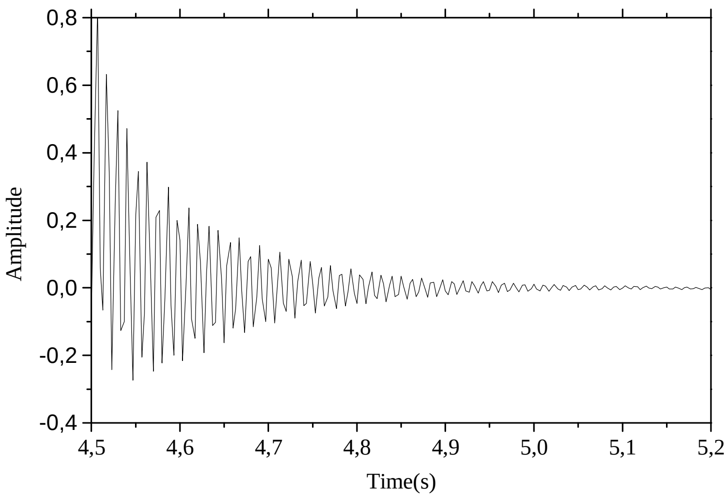

Figure 7. Time response of the SMAHC beam to a pulse impact without any activated SMA wire (room temperature).

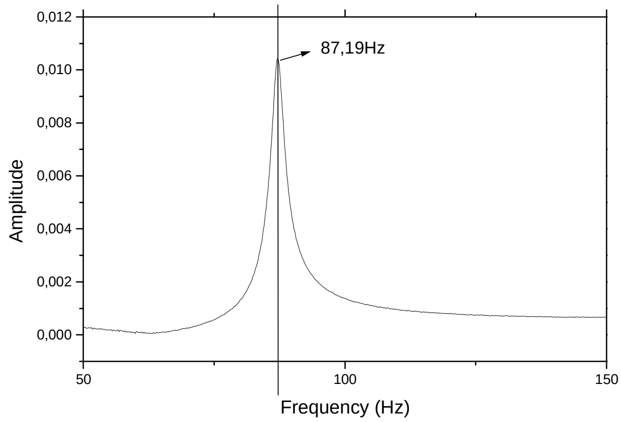

Figure 8. FFT of the voltage time signal shown in Fig 7.

In Table 1, the natural frequency values are presented as a function of activation modes defined in Fig 5 for the SMAHC beam. These results show a decrease in the natural frequency of the beam with increasing of the activated NiTi wires. Similar results were observed by other authors (Lau *et al*, 2002; Zhang *et al*, 2006) when the SMA wire fraction is below to 3%. The largest reductions occurred in natural frequency for modes 05 and 07, which were those with higher tip deflection by thermal buckling in the static study previously performed (Reis et al, 2007).

Table 1. Experimental results for natural frequency of the SMAHC beam for each activation mode.

Active mode	Frequency
No activated SMA wire(1)	87 Hz
Mode 01(2)	86 Hz
Mode 02(2)	85 Hz
Mode 03(2)	85 Hz
Mode 04(2)	84 Hz
Mode 05(2)	79 Hz
Mode 06(2)	83 Hz
Mode 07(2)	73 Hz

(1): measured at room temperature; (2): measured after heating the NiTi SMA.

The active beam can exhibit a thermal buckling tip deflection over a particular temperature range due to recover forces originated by the trained NiTi SMA wires. Within this temperature range the beam undergoes interesting dynamic responses because its stiffness can change rapidly. Then, if the beam is excited in the resonance frequency followed by the activation of NiTi wires, the amplitude response will be affected, as can be verified in Figs 9 and 10. In these figures the red line is the temperature of the SMAHC for activation mode 05 defined in Fig. 5 and in gray is the amplitude response.

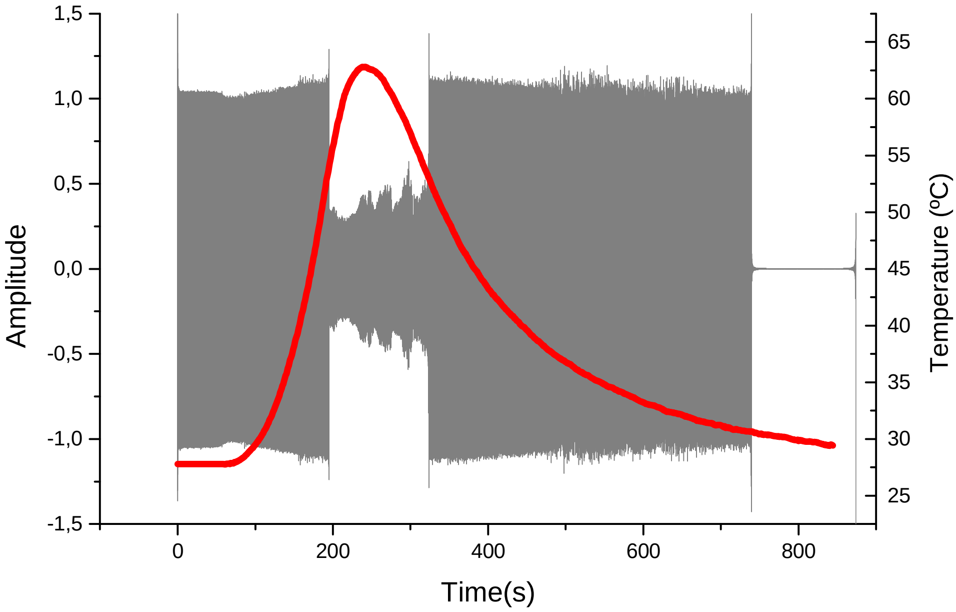

Figure 9. Amplitude response as a function of time for small shaker in the resonance frequency with activation mode 05 and evolution of the temperature of the SMAHC beam.

An opposite effect also occurs if the shaker works just below the natural frequency of the beam at room temperature. In this case, when the SMA wires are activated the vibration amplitude of the beam increases slightly, as shows in Fig 10. This behavior appears as consequence of the activation of NiTi wires decreasing the natural frequency of the SMAHC beam tuning the value close to the imposed frequency by shaker.

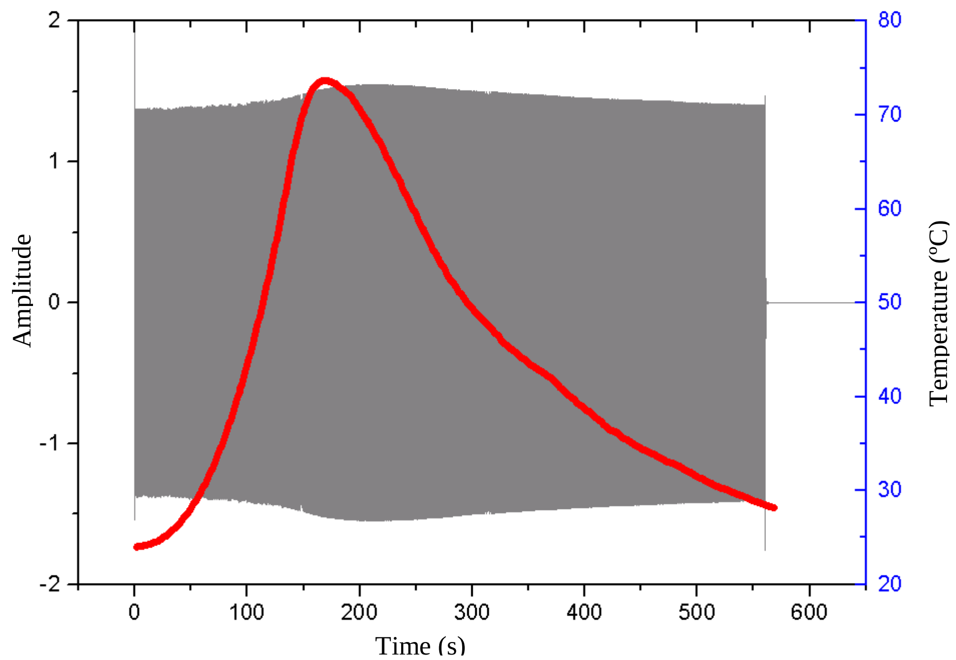

Figure 10. Amplitude response as a function of time for small shaker below the resonance frequency with activation mode 05 and evolution of the temperature of the SMAHC beam.

4. CONCLUSIONS

The SMAHC beam dynamic response with a controlled thermal loading by resistive heating, and application of mechanical excitation was experimentally investigated. The designed beam has five actuator wires evenly distributed along its neutral plane. Seven actuation modes were established and tested in a cantilevered beam way. The attractive functionality of SMA was demonstrated as an adaptive stiffening mechanism to the composite beam in all experimental cases. The experimental measurements have demonstrated that activation of SMA wires decrease the natural frequency of the SMAHC beam for all activation modes. The largest reductions occurred in natural frequency for modes 05 and 07, which were those with higher tip deflection by thermal buckling in the static study previously performed.

It was demonstrated that the variation of natural frequency for activation of the SMA wires can tune the beam to move away from or close to the resonance in a controlled way. This can be quite attractive in some real practical situations.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Ju, D., Shimamoto, A., 1999. “Damping Property of Epoxy Matrix Composite Beams with Embedded Shape Memory Alloy Fibers”, Journal of Intelligent Material Systems and Structures, Vol. 10, pp. 514-520.

Lau, K., Zhon, L., Tao, X., 2002, “Control of natural frequencies of a clamped -clamped composite beam with embedded shape memory alloy wires”, Composite Structures, Vol. 58, pp. 39- 47.

Michaud, V., 2004. “Can shape memory alloy composites be smart?,” Script. Mater., Vol. 50, pp. 249–253.

Otsuka, K., Wayman, C. M., 1998. “Shape Memory Materials”, Cambridge University Press, Cambridge, UK, 284p.

Reis, R.P.B., Rodrigues, L. F. A., Silva, M. D., de Araújo, C.J., 2007. “Static tests of an active composite beam: epoxy reinforced by trained Ni-Ti shape memory wires”. Proceedings of 19th International Congress of Mechanical Engineering (COBEM 2007), Brasília – DF, Brazil, pp. 1-8.

Trindade, M. A., Maio, C. E. B., 2008, “Multimodal passive vibration control of sandwich beams with shunted shear piezoelectric materials” , Smart Materials and Structures, Vol 17 , pp. 1-10.

Trindade, M. A., 2007, “Simultaneous Extension and Shear Piezoelectric Actuation for Active Vibration Control of Sandwich beams”, Journal of Intelligent Material Systems and Structures, Vol. 18, pp. 591-600.

Turner ,T.L.,2001 “Structural acoustic response of a shape memory alloy hybrid composite panel (lessons learned),” Smart Structures and Integrated Systems, SPIE Vol. 4701, pp. 592-603

Zhang RX, Ni QQ, Matusda A, Yamamura T, Iwamoto M., 2006. “Vibration characteristics of laminated composite plates with embedded shape memory alloys”, Composite Structures, Vol. 74, pp. 389-398.

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