

24th COBEM - 2017



24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-1973

NUMERICAL SIMULATION AND EXPERIMENTAL PROCEDURE FOR HEATING AND COOLING OF A SMA SPRING DEVICE

Andersson Guimarães Oliveira

anderssonoliveira@gmail.com

José Ricardo Ferreira Oliveira

ricardoengmec@gmail.com

Rômulo Pierre Batista dos Reis

romulopierre@ufersa.edu.br

Paulo Cesar Sales da Silva

engenheiropcsales@gmail.com

Antônio Almeida Silva

antonio.almeida@ufcg.edu.br

Celso Rosendo Bezerra Filho

celso.rosendo@ufcg.edu.br

Federal University of Campina Grande, Department of Mechanical Engineering. Aprigio Veloso Street, 882, CEP 58429140. Campina Grande, Paraíba, Brazil.

Abstract. *Response time is an important parameter for performance of devices that uses SMA (Shape Memory Alloys). SMA are special metal materials that have the ability to recover a "plastic" deformation introduced at a low temperature by means of subsequent heating above a critical temperature. Due to their characteristics, these alloys have a great application in control systems. Alloys with shape memory have been applied in various sectors of industry such as naval, aeronautical, nuclear, automotive, home appliances, robotics, medical, dental, etc. SMA response time is slow when is compared with other active materials, then is important devote studies to improve time response and applies a suitable mathematical modeling behavior to help control design systems that uses SMA. In this paper was numerically calculated the time heating and cooling of a SMA spring and compared simulation with experimental results. In the experiment, spring is heating by electrical current and cooled by forced convection. Using energy balance equation and choose most relevant parameters was verified that electrical current value and martensitic phase transformation model are the most determinant parameters to precision of modeling. The knowledge model allows verify device performance previously and adjust project parameters to achieve best results.*

Keywords: *SMA helical springs, Response Time, Modeling, Heating, Cooling*

1. INTRODUCTION

Shape Memory Alloy (SMA) is a specific kind of metallic material that changes his mechanical properties when induced by temperature (shape memory effect) or strain (superelasticity effect) (ELAHINIA, 2015). The unique characteristics of shape memory effect and superelasticity effect have made SMAs the material system of choice in applications ranging from sensing and control, vibration damping, biomedical, automotive and aerospace areas (RAO et al., 2015). SMA components can be available as wire, cables, springs, among others.

Springs are one of the most shapes used for SMA actuators. The particular behavior of SMA gives to helical springs special characteristics, for example: change stiffness or length as consequence of temperature change.

About stiffness change, as example of one of the most successful application, active vibration systems control (LIANG; ROGERS, 1993)(HOLANDA et al., 2014). There are some advantages to use SMA vibration control, for example: compact mount, low height and possibility to implement an active control vibration system with successfully results theoretical and experimental (ENEMARK; SANTOS, 2016)(BORGES, 2016).

Time response of an SMA element depends on the heating and cooling time. In most application, like actuators, is desired that this time be small as possible. An improvement of time response can be reached from the knowledge of external and internal variables that increase heat transfer (VELÁZQUEZ; PISSALOUX, 2012).

In this paper, an experimental apparatus is used to measure heating and cooling time of a SMA helical spring with shape memory effect. The experimental results are compared with numerical simulation using energy balance equation

and SMA phase transformation model where the objective is verify the effectiveness of an one dimensional mathematical model to estimate times response of SMA spring.

2. MATEMATICAL MODELLING

Based on thermal approach, SMA spring is a body that receives heat from an external source during heating and loses heat to environment during cooling. The contribution of each term of energy depends on application (CZECHOWICZ; LANGBEIN, 2015).

2.1 Nomenclature

The nomenclature of the parameters used in this article and their units are shown on the Tab. 1.

Table 1. Nomenclature used in this article.

c	Specific heat [J/kg.K]	ε	Emissivity
m	Total mass of spring [kg]	σ	Boltzmann constant [W/m^2K^4]
V	Effective spring volume [m^3]	ΔH	Latent heat for transformation [J/Kg]
T	Spring temperature [$^{\circ}C$]	ξ	Martensitic fraction [dimensionless]
T_{∞}	Environmental temperature [$^{\circ}C$]	W	Mechanical energy [J]
h	Convection coefficient [W/m^2K]	v	Electrical difference of potential [V]
S	Effective Surface spring area [m^2]	I	Electrical current [A]

2.2 Contribution of each energy portion and simplified hipotesis

Each term of energy is detailed and shown on the Tab. 2. According with the process (heating or cooling) the terms of energy may positive or negative on equation.

Table 2. Terms of the energy balance equation

Stored thermal energy	$cm \frac{dT}{dt}$
Convection	$hS(T - T_{\infty})$
Thermal Radiation	$\varepsilon\sigma S(T^4 - T_{\infty}^4)$
Latent heat for transformation	$m\Delta H \left \frac{d\xi}{dt} \right $
Mechanical energy	$\frac{dW}{dt}$
Electrical Energy	vI

Assuming that the contribution of thermal radiation and heat conduction are negligible and that there is no mechanical work (the SMA spring is attached and doesn't moves), the mathematical expression of the energy balance can be write as Eq.(1).

$$cm \frac{dT}{dt} + hS(T - T_{\infty}) + m\Delta H \left| \frac{d\xi}{dt} \right| = vI \quad (1)$$

Due to phase transformation, latent heat for transformation (ΔH) depends on martensite fraction (ξ). However, there are many numerical models to describe it. In this simulation, was used Liang & Roges unidimensional model show in Eq. (2) for $M \rightarrow A$ phase transformation. For $A \rightarrow R$ or $R \rightarrow M$ transformation is necessary change variables and use his phase transformation temperatures (LIANG; ROGERS, 1990).

$$\xi = \frac{1}{2} \left[\cos \left(\frac{\pi}{A_f - A_s} \right) (T - A_s) + 1 \right] \quad (2)$$

Transformation temperatures as also total latent heat for transformation (ΔH) was obtained from Differential Scanning Calorimetry (DSC), whose graph is shown on Fig. 1.

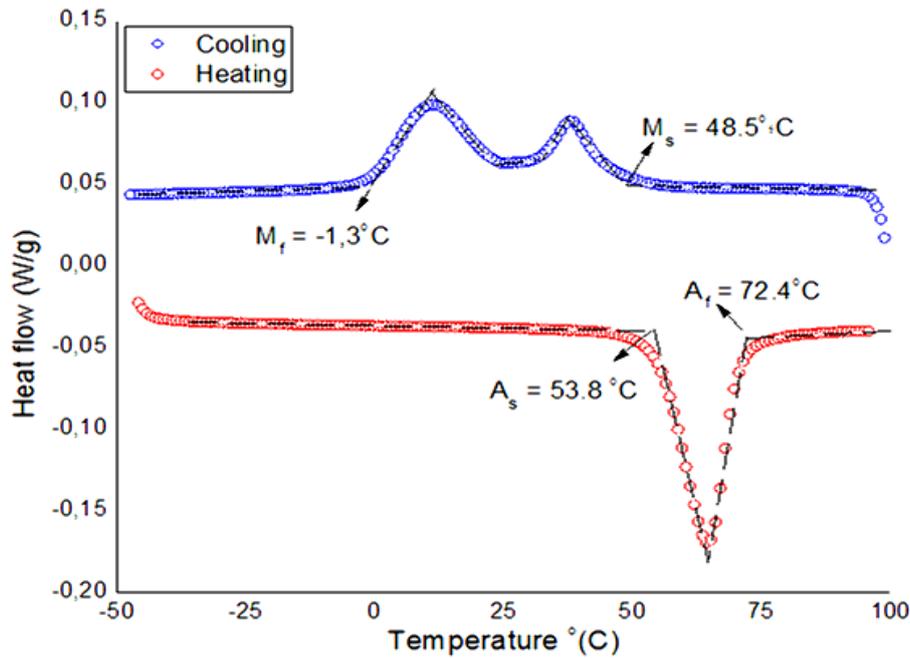


Figure 1. DSC graph: phase transformations temperatures

2.3 Numerical simulation

To obtain temperature curve during the processes of heating and cooling, it was used Matlab software to calculate differential element of temperature for each time interval from 0 seconds until 60 seconds. Using the Eq. (1) and Eq. (2), we can deduce the parameter dT , as shown at Eq. (3).

$$dT = \frac{vI - hS(T - T_{\infty})}{m \left[c_p + \Delta H \frac{1}{2} \left(\frac{\pi}{A_f - A_s} \right) \left[\text{sen} \left(\frac{\pi}{A_f - A_s} \right) (T - A_s) \right] \right]} dt \quad (3)$$

The numerical method consists in calculation of dT for each instant time. The parameters used in simulation are the same of experiment, as shown on Tab. 3.

Table 3. Experimental/Simulation parameters

Wire spring diameter (d)	1.5mm
Coil spring diameter (D)	10.0mm
Active coil	3
Difference of potential on martensitic phase (V_M)	1.4V
Difference of potential on austenitic phase (V_A)	1.2V
Continuous current (I)	12.0A

Specific heat (c)	465.2 J/Kg°C
Austenitic start (A_s) / final (A_f)	53.8°C/72.4°C
Martensitic start (M_s) / final (M_f)	48.5°C/-1.3°C
Convective coefficient (h)	$336 \frac{W}{m^2°C}$
Latent heat for transformation (ΔH) - $M \rightarrow A$ (endothermic)	8660J/Kg
Latent heat for transformation (ΔH) - $A \rightarrow R$ (exothermic)	2920J/Kg

3. EXPERIMENTAL PROCEDURE

A helical spring fabricated in NiTi wire, is fixed in two metallic supports. Each support is electrically isolated, then, electrical current flow only by spring. Current applied is continuous and fixed on 12A.

A thermocouple type K with 100 μ m diameter is fixed on spring surface and other thermocouple is positioned near structure to environmental temperature measurements. Cooling system is composed by a blower with a nozzle coupled. In metallic supports is connected a voltage sensor to register potential difference on spring. Experimental data is registered on an acquisition system to after treatment.

Figure 2 shows experimental scheme and Fig. 3 shows specimen fixed with blower positioned behind.

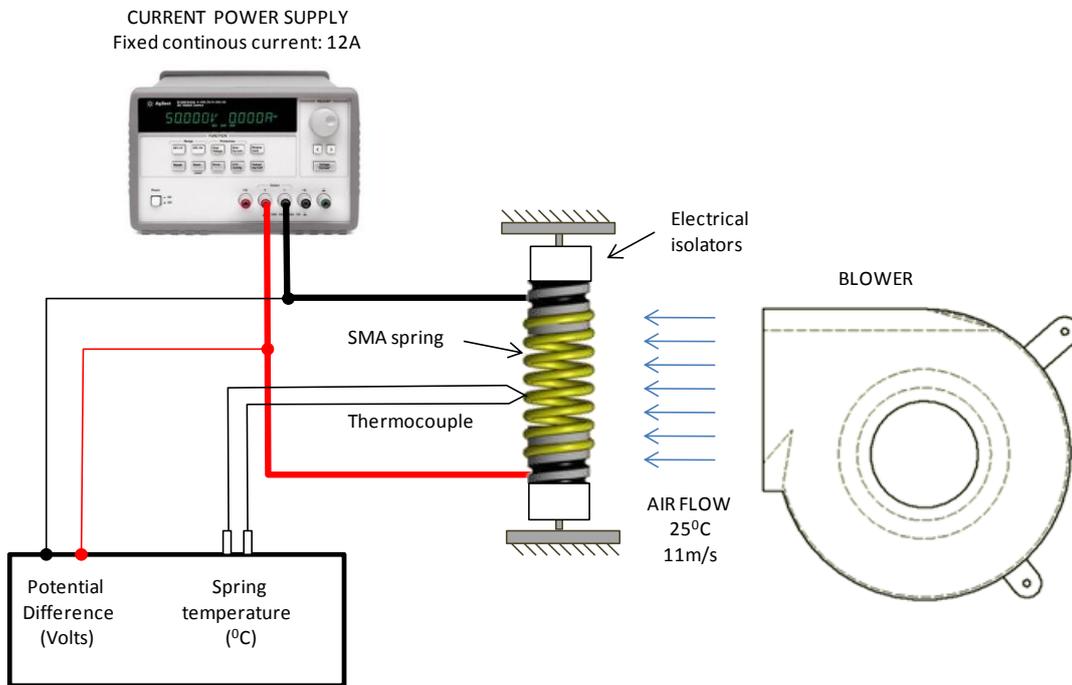


Figure 2. Experimental scheme

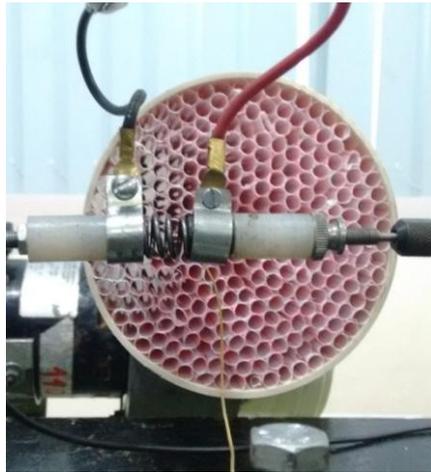


Figure 3. Front view. Spring (first plane), blower nozzle (second plane)

The experiment starts in environmental temperature (25 °C). Table 4 shows time line of experiment.

Table 4. Time line of experiment

Environmental temperature	Heating	Cooling
0 to 8.7 seconds	8.7 to 15.9 seconds	15.9 to 60 seconds
$I=0$	$I=12A$	$I=0$
Blower off	Blower off	Blower on
$T=T_{\infty}$	T : increase	T =decrease
Phase transformation: none	Phase transformation: $M \rightarrow A$ (endothermic)	Phase transformation: $A \rightarrow R$ (exothermic)

4. RESULTS AND DISCUSSION

Results of simulation and experimental are shown on Fig. 4. Transformation temperatures are marked where can be observed change of line inclination due phase transformation.

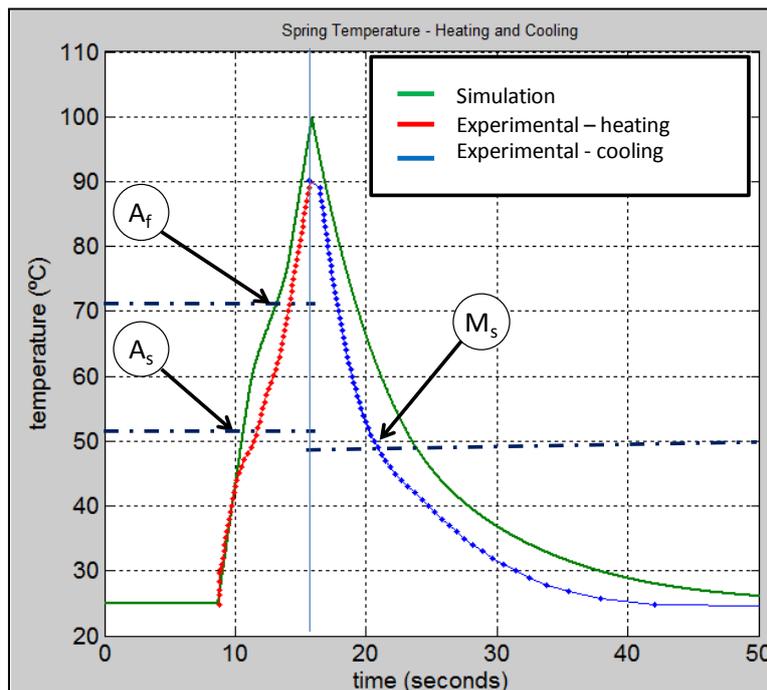


Figure 4. Comparing results between experimental and simulation

Analyses the ramp during heating, between 50 °C and 80 °C there is considerable difference between experimental and simulation curves. This difference is due martensitic fraction unidimensional model that can't represent this specific phenomenon with accuracy. Despite differences, comparing experimental and simulation line shape, the overall time response on cooling and heating can be estimated helped by simulation results because the start and the end points of both line (experimental or simulated) are next.

5. ACKNOWLEDGEMENTS

The authors thank the CAPES Brazilian Agency for funding the following research projects. CNPq Brazilian research agency. PPGEM Postgraduate Mechanical Engineer Program of Federal University of Campina Grande. LVI, Laboratory of Vibration and Instrumentation of Federal University of Campina Grande. LAMMEA Multidisciplinary Laboratory on Active Materials and Structures of Federal University of Campina Grande.

6. REFERENCES

- BORGES, J. M. *Controle de um sistema dinâmico rotativo utilizando mancais com atuadores LMF*. Campina Grande, PB: Universidade Federal de Campina Grande, 2016.
- CZECHOWICZ, A.; LANGBEIN, S. *Shape Memory Alloy Valves: Basics, Potentials, Design*. Switzerland: Springer International Publishing Switzerland, 2015.
- ELAHINIA, M. *Shape Memory Alloy Actuators: Design, Fabrication and Experimental Evaluation*. United Kingdom: John Wiley & Sons, Ltd, 2015.
- ENEMARK, S.; SANTOS, I. F. "Rotor-bearing system integrated with shape memory alloy springs for ensuring adaptable dynamics and damping enhancement - Theory and experiment". *Journal of Sound and Vibration*, Vol. 369, p. 29–49, 2016.
- HOLANDA, S. A. et al. "Study of the complex stiffness of a vibratory mechanical system with shape memory alloy coil spring actuator". *Shock and Vibration*, Vol. 2014, 2014.
- LIANG, C.; ROGERS, C. A. "One-Dimensional Thermomechanical Constitutive Relations for Shape Memory Materials". *Journal of Intelligent Material Systems and Structures*, Vol. 1, p. 29, 1990.
- LIANG, C.; ROGERS, C. A. "Design of Shape Memory Alloy Springs With Applications in Vibration Control". *Journal of Vibration and Acoustics*, Vol. 115, n. January 1993, p. 129–135, 1993.
- RAO, A.; SRINIVASA, A.R.; REDDY, J. N. *Design of Shape Memory Alloy (SMA) Actuators*. Switzerland: Springer International Publishing, 2015.
- VELÁZQUEZ, R.; PISSALOUX, E. E. "Modelling and Temperature Control of Shape Memory Alloys with Fast Electrical Heating". *International Journal of Mechanics and Control*, Vol. 13, n. 2, p. 1–8, 2012.

6. RESPONSIBILITY NOTICE

The author(s) is (are) the only responsible for the printed material included in this paper.