Experimental Platform for Obtaining Electrical Resistance of a Shape Memory Alloy Actuator

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Keywords: Deformation, Electronic Instrumentation, Electrical Resistance, Shape Memory Alloy Actuator, Strain-Gauge.

Abstract: Shape Memory Alloys (SMA) are unique metallic materials with the Shape Memory Effect (SME), which refers to a material's capacity to recover its original shape through temperature variation subjected to deformations. These alloys are commonly used as actuators to control vibration, deformation, position and have been used in several sectors in the last decades. Therefore, in order to enable a study about the behavior of the electrical resistance of an SMA actuator and the deformation measurement using strain-gauge sensors, an experiment is proposed in this work to be applied to the course of Electronic Instrumentation Laboratory of Electrical Engineering Degree at the Federal University of Campina Grande, Brazil. We used an experimental platform composed of a steel beam and an SMA actuator, and we also developed the necessary electronic system and Human Machine Interface. The experiment consists of activating the actuator by applying electric current and obtaining data corresponding to its electrical resistance and beam deformation. With the experiment's realization, the students will be able to draw the behavior curves and prepare a report with the analyses.

1 INTRODUCTION

Shape Memory Alloys (SMA) are metal alloys that, when submitted to deformations, return to their original shape after a thermal cycle. This effect is known as the Shape Memory Effect (SME), and it was discovered in 1963 by Willian J. Buehler from research developed with nickel-titanium alloys (NiTi) at the Naval Ordinance Laboratory (NOL) in Maryland, USA. In the 1960s, SME was observed in other alloys besides nickel-titanium, Cobalt (Co), and Iron (Fe). The addition of these two elements allowed a reduction in the transformation temperatures of the alloys (Lagoudas, 2008).

Later on, titanium-palladium (TiPd), titanium-platinum (TiPt), and titanium-gold (TiAu) alloys were used for high-temperature applications. However, it was only in 1980 that SMA started to be used more widely since the effect was better understood. Currently, SMA comprises a unique class of materials, which presents the capacity to recover from the original form when its temperature is increased and has the characteristic of superelasticity. When increasing the temperature, the form can be recovered from the application of high loads, which cause high densities of actuation energy (Lagoudas, 2008).

SMA actuators are widely used in sensing, impact absorption, and vibration damping applications in this context. Of the different industrial sectors that are applied, stand out: aerospace, automotive, biomedical, dental, orthopedic, robotic, and oil.

Thus, in this work, we propose an experiment to obtain an SMA wire actuator's electrical resistance behavior. Therefore, we developed an experimental platform for which a mechanical structure was used, composed of a steel beam and an SMA wire actuator. Also, we developed an electronic system and a user interface. The platform makes it possible to carry out experiments to obtain the SMA's electrical resistance and measure the beam's deformation caused by electrical current application in the actuator.

The proposed experiment is to be applied in the course of Electronic Instrumentation Laboratory of the Electrical Engineering Degree at UFCG Brazil for studies of sensors and actuators. The work's main motivation was the importance of carrying out experiments in the laboratory as a learning tool in Engineering courses, allowing students to apply the concepts presented in the classroom.

The rest of the paper is organized as follows. In

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P. da Silva, W., Cavalcanti, T., Jó da Silva, J. and Perkusich, A.
Experimental Platform for Obtaining Electrical Resistance of a Shape Memory Alloy Actuator.
DOI: 10.5220/0010438203150322
In *Proceedings of the 13th International Conference on Computer Supported Education (CSEDU 2021) - Volume 1*, pages 315-322
ISBN: 978-989-758-502-9

Section 2 we present the theoretical foundation. In Section 3 we present the developed experimental platform, and in Section 4 we describe the proposed experiment. In Section 5 we present the results and discussions, and in Section 6 we present conclusions and future work.

2 THEORETICAL FOUNDATION

This section presents the main concepts that underlie this work: the fundamentals of SMA, the strain-gauge sensors, and their use in deformation measurement.

2.1 Shape Memory Alloys

SME refers to a material's ability to recover its original shape, through temperature variation, after being submitted to mechanical deformation. This phenomenon can be perceived in special metallic materials called Shape Memory Alloys (SMA) (Elahinia, 2016).

SMA has two distinct phases, each with specific physical properties. These phases are named austenite and martensite. Austenite normally presents a cubic crystalline structure with a centered face or body-centered at high temperatures. The martensite phase can present a tetragonal, orthorhombic, or monoclinic structure at low temperatures. In the martensite phase, the crystals can be oriented in different directions; each direction is called a variant. The variants can have two directions of orientation: twinned martensite and detwinned or reoriented martensite. Self-accommodating variants form the first, and the last has a variant that is dominant in the grouping (Lagoudas, 2008).

The transformation from one phase to another can occur directly or inversely. The direct transformation refers to the change from the austenite to the martensite phase and occurs when cooling the SMA in the absence of an applied load. In the reverse transformation, in turn, when heating the same SMA, the crystalline structure undergoes a reverse transformation, returning from the martensite to austenite phase (Kumar et al., 2020).

The transformations are shown in Figure 1, in which the structures in the form of twinned martensite and austenite are presented. As can be seen, in the direct transformation, without mechanical load, the austenite phase begins the transformation to the twined martensite phase at the initial temperature of martensite (M_s) and the transition is completed at the final temperature of martensite (M_f). At this temperature, the alloy will be completely transformed into the twinned martensite form, thus completing the direct transformation. When heating the alloy, the process of reverse transformation begins at the initial temperature of austenite (A_s). Furthermore, the transition is completed at the final temperature of austenite (A_f).

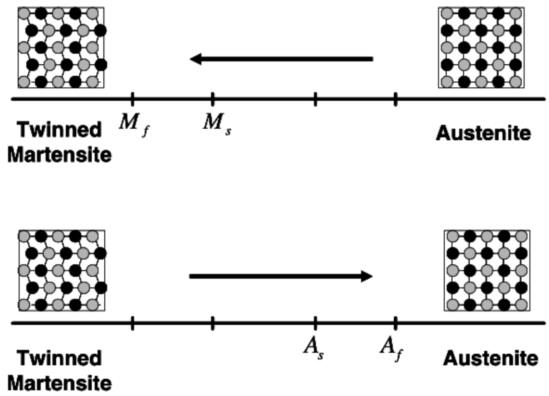

Figure 1: Representation of the Phase Transformation of an SMA (Lagoudas, 2008).

2.2 Deformation Measurement with Strain-Gauge

The physical deformation of a material occurs through the application of forces, which causes changes and can be defined as the relation between the variation in the length of a material and its original length. A common type is flexion deformation, which is caused by applying a linear force in the vertical direction, resulting in a deformation of one side of the material by contraction of the opposite side (Instruments, 2019).

Deformation measurement is essential for the correct understanding of how a given object reacts to different applied forces. For this purpose, strain-gauge sensors can be used, which are devices that vary their electrical resistance when they undergo deformation. They consist of a small grid formed by metal sheets that can be fixed to the surface of a component or structure to be measured, with a layer of adhesive that serves to transmit the structure's deformations to the sensor.

The strain-gauge is capable of measuring small deformations in the range of 0 to 50 μm/m with an accuracy of $\pm 0.15\%$, typically presenting nominal electrical resistance of 120 Ω, 350 Ω and 1000 Ω.

The electrical resistance of a strain-gauge is measured using a Wheatstone Bridge circuit. A generic Wheatstone Bridge, illustrated in Figure 2, consists of a network formed by resistive arms and an excitation voltage, V_{EX} that is applied at the entrance to the bridge.

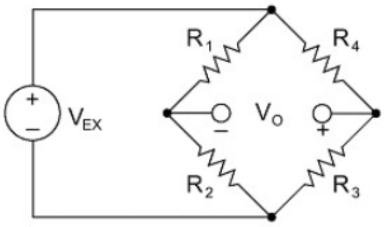

Figure 2: Wheatstone Bridge Circuit Diagram (National Instruments, 2019).

Thus, the deformation ε of the device is proportional to the output voltage of the circuit V_0, as described by Equation 1.

$$V_0 = \left(\frac{R_3}{R_3 + R_4} - \frac{R_2}{R_2 + R_1} \right) * V_{EX} \tag{1}$$

In turn, the Wheatstone bridge is considered electronically balanced, $V_0 = 0$, when it has the following relations: $\frac{R_1}{R_2} = \frac{R_4}{R_3}$. Therefore, a variation in one of the resistors (ΔR) causes a change in the output voltage value. For example, if replacing R4 with an active strain gauge, any change in its resistance unbalances the bridge and produces a nonzero output voltage, which is a function of deformation (National Instruments, 2019).

Depending on the application, it is possible to have one, two, three, or four bridge elements whose resistance varies depending on the measured physical quantity. For the application presented in this work, the resistance variation occurs in two opposing active elements: two strain-gauge. Thus, the output voltage at the bridge is given by:

$$V_0 = \frac{V_{EX}}{2} \left(\frac{\Delta R}{R} \right) \tag{2}$$

An essential parameter in the characterization of a strain-gauge is the Gauge Factor (GF), which refers to measuring the relative variation of the device's electrical resistance when it undergoes deformation. For magnetic strain-gauges, this parameter is around 2. The GF is calculated according to the relation presented in Equation 3.

$$GF = \frac{\Delta R / R}{\Delta L / L} = \frac{\Delta R}{R.\varepsilon} \tag{3}$$

where: R is the electrical resistance, ΔR is the variation in resistance , L is the length of the strain-gauge, ΔL is the variation in length and ε is deformation.

3 EXPERIMENTAL PLATFORM

For the development of this work, an experimental platform developed by (Lima et al., 2012) and optimized by (Patriota et al., 2018) was used. This platform has an SMA wire actuator fixed to the free end of a beam so that in the initial condition, the beam is deformed by its own balance weight, thereby stretching the actuator. An electric current is applied to activate it, and when doing so, the SMA recovers the original shape by heating by joule effect. Consequently, the actuator applies sufficient force to the beam to return it to the desired position.

For the proposed experiment, we used the platform to analyze the electrical resistance behavior in the SMA wire and the beam's deformation by varying the electric current in the actuator. Therefore, this section will present the mechanical and electronic systems and HMI that make up the platform.

3.1 Mechanical System

Figure 3 illustrates the platform's mechanical structure by the isometric view. It consists of a rectangular iron base; a support column with a rectangular area; a steel beam, with one end attached and the other free; an SMA wire attached to the top of the support column and the free end of the beam; and a support for possible application of external load weights.

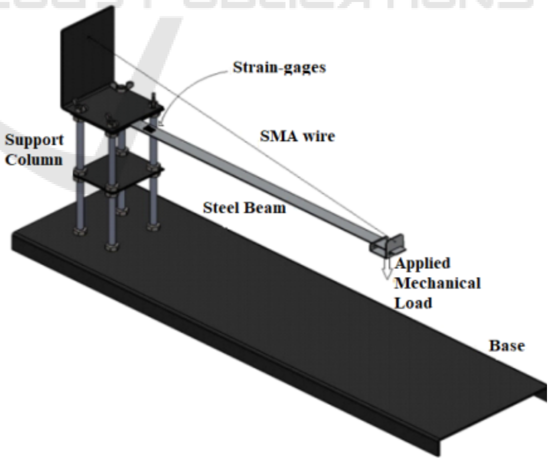

Figure 3: Representation of the Mechanical System (Patriota et al., 2018).

3.2 Eletronic System

The platform's electronic system, adapted and implemented for this work, consists of two strain-gauge sensors, Wheatstone bridge and gain adjustment circuits, an SMA wire actuator, NI DAQ USB-6212 data acquisition system from National Instruments, the current driver for actuating the SMA wire actuator, and circuit for measuring the voltage in the actuator. The block diagram of the electronic system is shown in Figure 4, and each subsystem is described as follows.

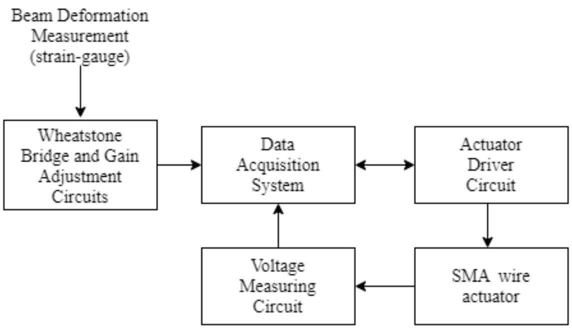

Figure 4: Electronic System Block Diagram.

3.2.1 Strain-Gauge and Wheatstone Bridge

At the fixed end of the beam, two strain-gauge were fixed, one located at the top and the other at the bottom, to measure the flexion deformation at that point. The two strain-gauge were positioned at the same distance from the platform support column and under the same axis to obtain a correct measurement. When one strain-gauge is tensioned, the other is compressed following the same proportion so that the resistance variation of the two sensors has the same module, with different signals, as shown in Figure 5.

The strain-gauge used are the model PA-06-125-BA-350-LEN from Excel Sensors, of the collatable type and recommended for steel surfaces. It has simple unidirectional resistance with a traditional shape of 350 Ω and a gauge factor of 2.1.

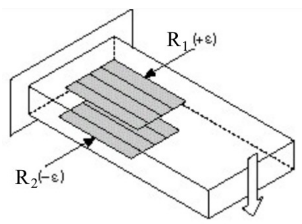

Figure 5: Representation of the Deformation Measurement Scheme Used. (National Instruments, 2019).

As the measurement of flexion deformation involves the resistance variation of two opposing elements, a Wheatstone bridge circuit was used in the half-bridge configuration and the output voltage given by Equation 2. Performing the appropriate mathematical manipulations with Equations 3 and 2, Equation 4 was obtained for the deformation.

$$\varepsilon = \frac{2.V_0}{V_{EX}.GF} \tag{4}$$

The variation in the resistance of the strain-gauge is less than 1%. Therefore, as the bridge's output voltage is directly proportional to this variation, it will also be practically negligible. Thus, it is necessary to apply a high gain (G) to amplify the value of V_0 and enable the data acquisition board's digital-analog converter to carry out the signal acquisition. Therefore, the acquired voltage is $V_{acquired} = G.V_0$. Rewriting Equation 4 we get that:

$$\varepsilon = \frac{2.V_{acquired}}{V_{EX}.GF.G} \tag{5}$$

3.2.2 SMA Wire Actuator

The SMA wire used as an actuator is a NiTiNOL alloy of the type FLEXINOL TCF1140, manufactured by Dynalloy, Inc. It has the two-way shape memory effect and was thermomechanically trained by Patriota (2018). According to the manufacturer manual, it has the characteristics listed in Table 1.

Table 1: Features of SMA Wire Actuator.

Parameter	Value
Diameter	$0.2\,mm$
Density	$6,450\,kg/m^3$
Specific heat	$837\,J/kg.K$
Thermal conductivity	$1,800\,W/(m.K)$
Resistance	$29\,\Omega/m$
Cooling time	between $2.7\,s$ and $3.2\,s$

3.2.3 Data Acquisition System

We used the NI DAQ USB-6212 multifunctional device from National Instruments (see Figure 6) as the data acquisition system (Instruments, 2009). The device performs the acquisition of the analog readings and sends them to the LabVIEW software, in which they will be processed and made available to the user. It is also responsible for sending the activation commands to the actuator driver.

3.2.4 Actuator Driver and Voltage Measurement Circuits

The NI DAQ USB-6212 sends the SMA wire actuator's activation signal to the current driver input. The driver receives a DC signal ranging from 250 mV a 5 V. The circuit is powered using a 12 V DC source,

Figure 6: Image of the NI DAQ USB-6212 Data Acquisition Device (National Instruments).

capable of supplying up to 1 A, sufficient current to drive the actuator.

In order to measure the voltage on the SMA wire actuator, was implemented a differential measurement circuit. The circuit consists of two stages. The first corresponds to the preamplifier with unit gain, consisting of two voltage followers that isolate the input voltage signals, thus increasing the circuit's input impedance. The second stage consists of a differential amplifier designed to have a gain of 1/3.

3.3 Human Machine Interface

To allow the student to interact with the platform system and visualize the process outputs numerically and graphically, we developed a Human-Machine Interface (HMI) using the LabVIEW software (an acronym for Laboratory Virtual Instrument Engineering Workbench).

Figure 7 shows the front panel of the VI developed in LabVIEW.

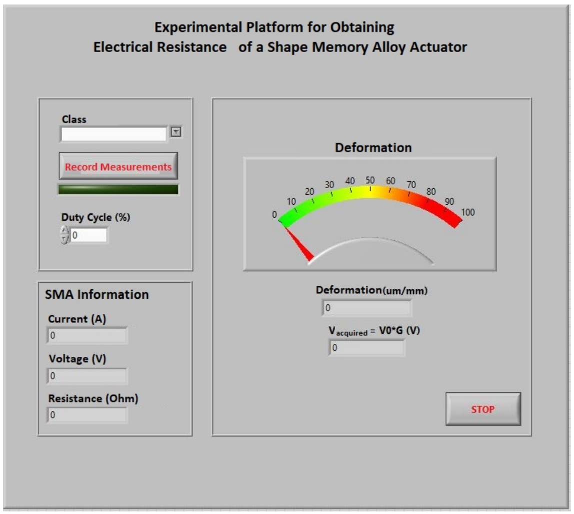

Figure 7: Representation of the HMI.

The developed software performs the acquisition of the measurements corresponding to current and voltage in the SMA actuator and the acquired voltage to calculate the beam deformation. These values are mathematically treated to be displayed in the user interface.

With the acquisition of the voltage value at the output of the Wheatstone Bridge gain adjustment circuit, the deformation calculation is performed using Equation 3. Furthermore, with the SMA's voltage and current values, the corresponding electrical resistance value is calculated. According to the percentage of DC voltage entered by the user, the SMA activation signal is sent to an analog output of the DAQ NI USB-6212. This sending is done using the DAQ Assistant block, and the analog output is connected to the current driver circuit.

The HMI also allows the student to select his class and record a txt file with the measurements to analyze later.

4 PROPOSED EXPERIMENT

In Engineering courses, the execution of experiments in laboratories is an essential tool for student learning. Specifically, for the Electrical Engineer training, it is required to understand how the measurement systems interact with the environment and provide information, which can be treated and applied in solving the most varied problems.

In this context, the course of Electronic Instrumentation Laboratory offered by the Electrical Engineering Degree at UFCG, Brazil, addresses the content of great importance for the formation of the future professional of Electrical Engineering, since it introduces the basic techniques and the main methods to perform measurements using sensors or transducers. The course has activities in the laboratory, where students perform practical experiments using experimental platforms and data acquisition systems. With that, the student can analyze several types of conditioning circuits and know the operation of different types of sensors.

Thus, in this work, an experiment is proposed to be applied to the Electronic Instrumentation Laboratory course to enable a study about the electrical behavior of SMA wire actuator and deformation measurement using strain-gauge sensors. For this, the experimental platform presented in Section 3 is used. Figure 8 shows a photograph of the mechanical and electronic systems.

The proposed experiment consists of varying from 5% to 100% the actuator signal's duty cycle value, which is the percentage of the DC voltage signal ap-

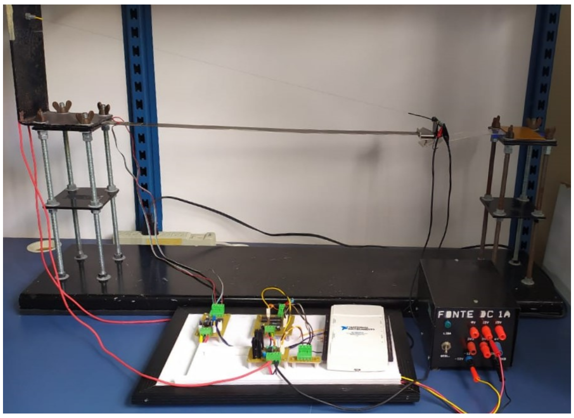

Figure 8: Experimental Platform Photography.

plied at the current driver input. The deformation, current, voltage, and resistance values corresponding to each measurement must be noted or saved in a txt file using the "Record Measurements" button present on the HMI. However, it is necessary that before saving the data, the student must select his class.

When it reaches 100% of the actuator's activation signal, the experiment should be ended. With the data collected, the student will be able to draw the Resistance versus Current and Deformation versus Current behavior curves and prepare a report with the results and analyses achieved.

5 RESULTS AND DISCUSSIONS

Table 2 presents real measurement data using the developed system to exemplify the analyses that can be performed with the proposed experiment. This table is the values stored in the txt file for the twenty measurements made during the experiment. The values correspond to the measurements of beam deformation (D), current (I), and voltage (V) measured in the SMA and the resistance (R) calculated from the SMA.

The electrical resistance of an SMA sample increases as the current increases until it reaches the current value at which the phase transformation begins. From that current value, the resistance starts to decrease. Therefore, analyzing the last column of Table 2, it can be seen that the resistance value changed during the experiment, resulting in a variation of approximately 1.85 Ω. The resistance variation is directly related to the current applied to the alloy, so an increase in resistance is observed as the current increases, up to a current value of 240.63 mA. From that value, the resistance starts to decrease with the increase of the current. Thus, one can observe that the phase transformation began when the current applied

Table 2: Experimental Data.

CT (%)	D ($\mu m/m$)	I (mA)	V (V)	R (Ω)
5	0.4064	23.0087	0.5689	24.7254
10	0.4099	42.7998	1.0631	24.8389
15	0.4264	62.5595	1.5586	24.9139
20	0.4488	82.3349	2.0558	24.9688
25	0.4653	102.1104	2.5584	25.0552
30	0.5194	121.9485	3.0586	25.0811
35	0.5548	141.6613	3.5643	25.1607
40	0.5830	161.4368	4.0686	25.2024
45	0.6125	181.2437	4.5791	25.2649
50	0.6831	201.0035	5.0735	25.2409
55	0.7149	220.8104	5.5814	25.2769
60	0.7561	240.6330	6.0715	25.2314
65	0.7773	260.4086	6.4891	24.9189
70	0.8021	280.2312	6.8421	24.4159
75	0.8480	299.9912	7.1618	23.8734
80	0.9834	319.7513	7.5629	23.6524
85	1.8831	339.5270	7.9162	23.3154
90	3.0784	359.2714	8.3166	23.1485
95	5.1204	379.0629	8.7003	22.9521
100	7.7866	398.9639	9.1261	22.8745

in the alloy is greater than 240 mA. Using the MATLAB software, the resistance versus current curve was constructed, which describer this behavior (see Figure 9).

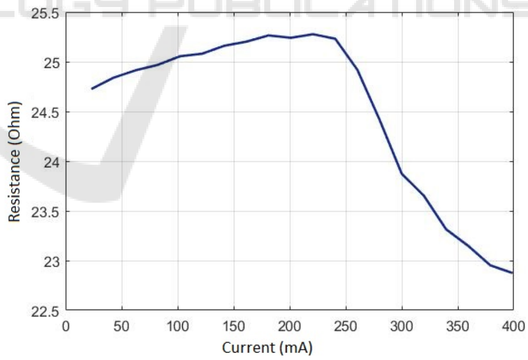

Figure 9: Representation of Resistance versus Current Behavior.

To apply the experiment in the Electronic Instrumentation Laboratory course, the student may also determine an approximate mathematical model that best describes this behavior. The best approximation found for the Resistance versus Current curve was a tenth-degree polynomial for the results presented. As described by Equation 6, in which $f(x)$ corresponds to resistance and x corresponds to current.

$$f(x) = p1*x^{10} + p2*x^9 + p3*x^8 + p4*x^7 + p5*x^6 + p6*x^5 + p7*x^4 + p8*x^3 + p9*x^2 + p10*x + p11 \quad (6)$$

where: p1 = $2.1572*10^{-22}$; p2 = $-4.0457*10^{-19}$; p3 = $3.1871*10^{-16}$; p4 = $-1.3718*10^{-13}$; p5 = $3.5183*10^{-11}$; p6 = $-5.5046*10^{-09}$; p7 = $5.1505*10^{-07}$; p8 = $-2.6684*10^{-05}$; p9 = 0.00059919; p10 = 0.004991; p11 = 24.504.

With this information, the polynomial approximation graph was plotted, shown in Figure 10.

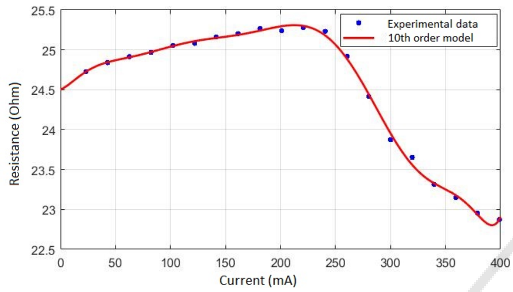

Figure 10: Representation of Resistance versus Current - Approximate Model.

The analysis of the behavior of the electrical resistance of an SMA is fundamental when we want to use it as an actuator. This behavior can be considered to study the performance criteria before implementing the actuator. It is possible to determine the best SMA operating region, analyzing which currents provide the phase transformation. Thus, one can choose which type of SMA best attends to the needs of the desired application.

Regarding the deformation measurement behavior in the beam, we observed that when lower currents are applied to the SMA actuator, not enough force was applied to the beam to vary its position since the actuator has not started to contract yet. Consequently, the measurement of the strain-gauge in this range does not show very significant variations. However, for higher current values, above 300 mA, the alloy starts to contract and has enough force to lift the beam from the initial position. Thus, the deformation measurement begins to increase according to the applied current, as shown in Figure 11.

The best approximation of the deformation versus current behavior was a ninth degree polynomial, which is described in Equation 7.

$$f(x) = p1*x^9 + p2*x^8 + p3*x^7 + p4*x^6 + p5*x^5 + p6*x^4 + p7*x^3 + p8*x^2 + p9*x + p10 \quad (7)$$

where: p1 = $6.1361*10^{-21}$; p2 = $-1.4801*10^{-17}$; p3 = $1.4118*10^{-14}$; p4 = $-7.04*10^{-12}$; p5 = $2.0258*10^{-09}$; p6 = $-3.4738*10-07$; p7 = $3.5114*10^{-05}$; p8 = -0.0019751; p9 = 0.055351; p10 = -0.1668.

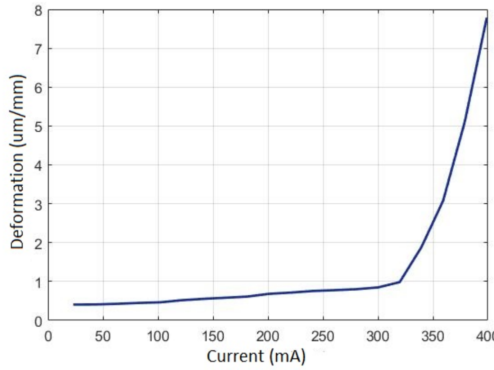

Figure 11: Representation of Deformation versus Current Behavior.

With this information, the polynomial approximation graph was plotted, shown in Figure 12.

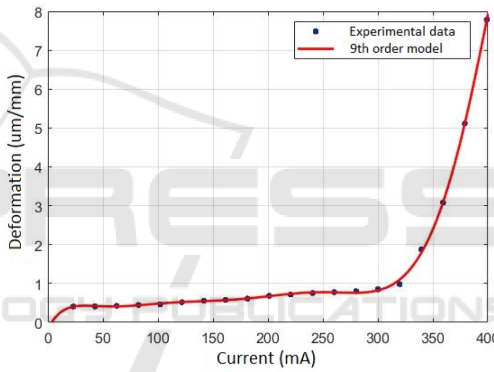

Figure 12: Representation of Deformation versus Current Behavior - Approximate Model.

6 CONCLUSIONS

In this work, we present an experimental platform for studying an SMA wire actuator. The platform allows experiments to be executed to obtain the characteristic of the SMA's electrical resistance and deformation of a beam. For this, we first described the concepts and characteristics of the SMA and the strain-gauge sensor. Then, we presented the main tools and procedures performed to develop and use the experimental platform. In this way, we explained the components that make up the mechanical system, the electronic system, and the HMI. After, the experiment proposal was presented to be applied in the Electronic Instrumentation Laboratory course.

With the analysis of the results obtained experimentally, we conclude that the platform satisfies the requirements that it was intended to achieve. The SMA resistance behavior analysis through the application of current in the alloy is a study of great relevance for using material as an actuator since it makes it possible to determine the best operating region, according to the phase transformation.

Besides, we found a relationship between the SMA's performance and the beam deformation, measured by strain-gauge sensors. We verified that when low currents are applied to the SMA wire actuator, not enough force is applied to the beam to vary its position. However, for higher current values, the alloy starts to contract and consequently has enough force to lift the beam from its initial position.

Thus, the proposed experiment can be used in the Electronic Instrumentation Laboratory course to complement the experiments carried out on sensors and actuators.

We plan the use the experimental platform developed to investigate the phase transformation and the SMA wire actuator hysteresis behavior during the heating and cooling process. For this, we intend to estimate the SMA wire temperature from the electrical parameters data resulting from the proposed experiment.

ACKNOWLEDGEMENTS

The authors thank the support of the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazil (CAPES), Electronic Instrumentation and Control Laboratory and Programa de Pós-Graduação em Engenharia Elétrica (COPELE), UFCG.

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